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Representative values of thermal effects for concrete bridges in EC1, Part 2.5

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Summary

The influence of the environmental conditions on the thermal effects in concrete bridges is considered. The representative values of thermal effects (the uniform temperature component and the linear temperature differences) are determined by means of the representative values of climatic actions (incoming solar radiation and shade air temperature), which are obtained with the help of statistical analysis and the theory of extremes.

1. Introduction

According to the system of Eurocodes characteristic value of an action is its main representative value. For thermal actions the characteristic value is taken as the value having a return period of 50 years.

According to [1] - [3] three design situations have to be considered for the serviceability limit state (SLS) and three corresponding representative values of actions have to be determined:

- infrequent (return period of occurrence is one year)
- frequent (return period of occurrence is two weeks)
- quasi-permanent.

These representative values can be obtained with the help of reduction coefficients Ψ, which - multiplied by the characteristic value, lead to the level of action with the given return period.

$\Delta T_1' = \Psi_1' \cdot \Delta T_K$ (infrequent value of thermal effect),

$\Delta T_1 = \Psi_1 \cdot \Delta T_K$ (frequent value of thermal effect),

$\Delta T_2 = \Psi_2 \cdot \Delta T_K$ (quasi-permanent value of thermal effect),

where ΔT_K - characteristic value of thermal effect.

2. Thermal effects in the bridge deck

The environmental conditions which have the greatest influence on the temperature of a bridge are shade air temperature, and radiation (incoming total solar radiation (TSR)). Wind speed may also play an important role; this may be reflected in the value of the heat transfer coefficient used for an analysis and entered not directly as a parameter.

These environmental conditions cause a non-linear temperature profile through the depth of the bridge deck. This distribution is active in producing strains of varying magnitude. It can be subdivided into three parts:

- *Bridge effective temperature range* T_N (or an uniform temperature component $\Delta T_N = T_N - T_0$, where T_0 is the datum temperature: effective bridge temperature at the time that the structure is restrained). This is the range of temperature which is used to determine the amount of movement due to expansion and contraction that the bridge must be able to accommodate and the uniform axial strains (and hence forces) induced in the structure due to restraint at bearing positions.

- *Linear temperature differences* ΔT_M. This is a linearly varying part of temperature profile through the depth of the bridge deck which is active in producing curvatures and strains of varying magnitude (and hence moments) where appropriate restraints are present.

- *Non-linear temperature distribution* ΔT_E. This is a non-linear part of temperature profile through the depth of the bridge deck which causes internal, non-linear selfequilibrating stresses which produce no net load effect on the structural element.

For concrete bridges, the uniform temperature component and the linear temperature differences play an important role. The non-linear temperature distribution may be not taken into account.

For positive differential temperature profile (only this profile is considered) the values of the temperature effects outlined above are dependent on differing environmental processes. For linear temperature differences, incoming total solar radiation (TSR) is the dominant variable rather than shade air temperature range. On the contrary, shade air temperature has the main influence on the effective bridge temperature.

Therefore, it is possible to consider the extreme values of effective bridge temperature as a function of the extreme values of shade air temperature range and average values of incoming total solar radiation (TSR), while the extreme values of linear temperature differences can be considered as a function of extreme values of TSR and average ranges of shade air temperature.

Large positive temperature difference profiles may occur within a structure during a day with high solar radiation, and a large range of shade air temperature. These conditions typically occur in the Middle Europe during the months of June, July or August. Thus, period of observations from 1st June till 31st August is considered.

3. Temperature profile through the depth of the bridge deck

The calculation of temperature distribution through bridge decks has been considered by numerous authors (see for example [4] - [8]). It was shown in [4], [5] that for concrete bridge decks, heat flow through the depth of a concrete deck can be considered to be effectively one-dimensional because of a large thermal inertia and relatively low diffusivity of concrete. Therefore, the temperature difference distribution for concrete decks can be derived using the iterative, one-dimensional heat flow model. Based on these investigations the computer program [9] was developed. The finite difference equations are solved at 50 mm increments through the entire depth of a bridge deck and at 15 minutes time increments during one day (24 hours).

The program uses the following data as input:

1. Solar radiation
   - The time of sunrise.
   - The duration of the solar day i.e. the number of hours of sunlight for the day considered.
   - The total daily value for TSR.

2. Temperature
   - The daily maximum shade air temperature.
   - The daily minimum shade air temperature.
   - The time at which the maximum value occurs.
   - The time at which the minimum value occurs.
   - The bridge effective temperature at starting time (at 08:00 a.m.).

3. Geometrical characteristics of bridge cross section (heights of all parts of the concrete deck).

4. Thermal and material properties of concrete deck
   - The coefficient of absorptivity
   - The coefficient of emissivity
   - The heat transfer coefficient of the surface
   - Thermal conductivity
   - The specific heat
   - Density

In order to begin calculations, the initial temperature in the bridge, which is unknown, must be defined. To overcome this, a start time must be chosen at which the temperature distribution through the section is considered to be the most uniform. For the climate of Middle Europe , it has been shown in [4, 5] that during the summer, this condition exists when the bridge reaches it's minimum effective temperature, which, for concrete decks occurs typically at 08:00 a.m.. Therefore, a one-day calculation cycle begins at eight o'clock in the morning.

For wind conditions of Middle Europe the heat transfer coefficient of the upper surface appears to be equal to 19 - 23 W/m^2 and the one of the lower surface is equal to 9 W/m^2.

According to [4] - [6] there is no significant benefit derived from allowing for slight difference in the thermal properties of surfacing to those of concrete and therefore for concrete decks, the surfacing is simply modelled as an additional thickness of concrete. All results are calculated for surfacing 50 mm. The influence of other surfacing on linear temperature differences is also investigated (see below Chapter 7).

Three groups of bridge cross sections are considered as the most useful in praxis (they are shown in Annex A):

box girder
- type 1.0 (bridge Lucka), total depth 1.95 m
- type 1.1, total depth 2.0 m
- type 1.2, total depth 3.3 m
- type 1.3, total depth 4.7 m

T-beam
- type 2.1, total depth 1.2 m
- type 2.2, total depth 1.8 m
- type 2.3, total depth 2.4 m

slab
- type 3.1, total depth 0.6 m
- type 3.2, total depth 0.9 m
- type 3.3, total depth 1.2 m

For each type of cross section the upper width is 14.2 m with the exception of type 1.0 (bridge Lucka in Thüringen, Germany), which has an upper width of 9.12 m. The bridge Lucka is considered because of available experimental data which are used for comparison of results.

4. Statistical analysis of thermal effects

Statistical analysis of thermal effects has been performed by some authors. In [10] available data was the experimental ones of bridge Lucka. This data was recorded for the period 1984-1985. Then three-day maxima of thermal effects were taken to establish the sample of independent events. This is because of shade air temperature and solar radiation have a three-day period of independence. Then representative values (see Chapter 1 above) of thermal effects have been calculated.

The theoretical investigation for bridge Lucka also was performed in [11] - [12]. The climatic data from Middle Germany (meteorological station Giessen) was used. The values of thermal effects were obtained by means of program [9] for each day from 1st June till 31st August for ten years period 1981 -1990. Then three-day maxima of thermal effects were determined and the representative values and coefficients Ψ (see above) were obtained with the help of statistical analysis and extreme values theory. The comparison with [10] gave a good coincidence, that shows that the using of program [9] is reasonable for concrete bridges.

It was reported that the results of 1982 are very close to results for all ten years 1981 - 1990. It was the reason for using only the climatic data of 1982 for all other cross sections (types 1.1 -3.3, see Chapter 3 above). In [11] - [12] the representative values of thermal effects for these types of cross section were calculated. Although this method gives very good results, it needs plenty of work and time because the program [9] calculates temperature profile only for one day, but for statistical analysis it is necessary to obtain the temperature profiles for some hundreds, even thousands of days.

5. Statistical analysis of environmental conditions

Shade air temperature and solar radiation are the non-stationary stochastic processes. However, it appears, that during three summer months, these processes may be considered as the stationary ones.

The climatic data for the period of 1981 - 1990 is available from meteorological station Giessen (Hessen, Germany). This station is in the middle of Germany and Europe and can be considered as a representative place for Middle Europe. The data is:

- hourly values of solar radiation,
- hourly values of shade air temperature.

First of all the daily maximum and daily minimum of shade air temperature, and daily value of total solar radiation are obtained for all days during the months of June, July, and August for the above mentioned period. Then two different procedures for two different thermal effects can be used.

5.1 Linear temperature differences

Because for linear temperature differences incoming total solar radiation (TSR) is the dominant variable, only for total solar radiation the maximum for each three days is taken. For shade air temperature range (maximum and minimum of daily shade air temperature) only associated values are taken, i.e. maximum and minimum of shade air temperature which are observed on the same day in which the maximum of TSR occurs. Three days is a minimal interval of independent random events (TSR and shade air temperature). Thus, 30 values per summer are obtained for maximum of TSR and associated shade air temperature range, and 300 values are available for 10 years. According to [9] some supplementary input parameters need to be calculated for summer months (mean values):

- The time at which the daily maximum of shade air temperature occurs	15:00 p.m.
- The time at which the daily minimum of shade air temperature occurs	04:00 a.m.
- The time of sunrise	04:00 a.m.
- The duration of solar day	16 hours

Then parameters of random sample for maximum TSR and for associated shade air temperature range can be calculated (for period 1981 -1990):

- three-day maximum of TSR: mean value $M(R) = 5831.8\ W/m^2$
  standard deviation $s(R) = 1368.5\ W/m^2$

- associated values of shade air temperature range:
  mean value of maximum shade air temperature $M(T_{max})_{ass} = 23.7\ ^0C$
  mean value of minimum shade air temperature $M(T_{min})_{ass} = 11.9\ ^0C$

Almost the same values are obtained for year 1982 (see [11]). Only for the standard deviation of TSR the value ($1165.3\ W/m^2$) is a little different. This data is used for the types 1.1 - 3.3, so that results can be compared with results obtained by the „exact" method in [11] (see Chapter 4 above).

The probability distribution function of the three-day maximum of TSR can be assumed to fit a type III extreme value distribution (for the maximum). This distribution is limited in the tail to an upper cut-off value of x_0, because solar radiation has a physical upper limit (for Middle Germany this value is equal to $10150\ W/m^2$):

$$F_X(x) = \exp \{ - [(x_0-x) / (x_0-u)]^c \} \tag{1}$$

where: c,u - the parameters of the distribution, which connect with mean value M_X and standard deviation σ:

$$M_X = x_0 - (x_0-u)\, \Gamma(1+1/c) \tag{2a}$$

$$\sigma^2 = (x_0-u)^2 [\Gamma(1+2/c) - \Gamma^2(1+1/c)] \tag{2b}$$

where: Γ - Gamma function.

Knowing the parameter c, u, x_0 and using the inverse probability distribution function

$$x = \Phi(P) = x_0 - (x_0-u) [- \mathrm{Ln}\,(P)]^{1/c}, \qquad P = [0,1] \tag{3}$$

it is possible to calculate fractile values for different return periods of the random variable R (three-day maximum of TSR).

For ultimate limit states (ULS) the return period is 50 years. Corresponding probability of not exceeding of the fractile value of action is (30 three-day intervals per year):

$$P = 1 - 1 / (30\times50) = 0.999333$$

For serviceability limit states (SLS) it is necessary to determine three different values of action (see Chapter 1):

- infrequent value (return period 1 year),

- frequent value (return period 2 weeks),
- quasi-permanent value (return period seems to be assumed as 6 days, because available statistical data of TSR is three-day maxima).

For these three situations the fractile values are calculated with the following probabilities of not being exceeded:

T_{return} = 1 year: $P = 1 - 1/30 = 0.966667,$ (4a)

T_{return} = 2 weeks: $P = 1 - 1/4.67 = 0.785867,$ (4b)

T_{return} = 6 days: $P = 0.5.$ (4c)

With the help of (3) the representative values of TSR can be obtained:

Characteristic value	R_K	=	9557.6	W/m^2
Infrequent value	R_1'	=	8327.3	W/m^2
Frequent value	R_1	=	6955.6	W/m^2
Quasi-permanent value	R_2	=	5828.1	W/m^2

5.2 Bridge effective temperature

For bridge effective temperature the shade air temperature range is the dominant variable, therefore three-day maxima of shade air temperature range are determined. For TSR only associated values are taken, i.e. the value of TSR which is observed on the day in which the maximum of shade air temperature range occurs. Thus, 30 values per summer are available for the maximum value of shade air temperature range and the associated value of TSR, so that 300 values are available for 10 years. The supplementary input parameters are the same as in Chapter 5.1 (see above).

The parameters of random sample for maximum shade air temperature range and for associated value of TSR are (for period 1981 -1990):

- three-day maximum of shade air temperature range:

mean value M(T): - maximum shade air temperature = 24.8 ^{0}C
- minimum shade air temperature = 12.7 ^{0}C

standard deviation s(T): - maximum shade air temperature = 4.3 ^{0}C
- minimum shade air temperature = 2.8 ^{0}C

- associated value of TSR:

- mean value $M(R)_{ass}$ = 5417.0 W/m^2

Almost the same values are obtained for 1982 (see [12]). This data is used for cross sections types 1.1 - 3.3 which results can be compared with results obtained by the „exact" method in [12] (see Chapter 4 above).

The probability distribution function of the three-day maximum of shade air temperature range can be assumed to fit a type III extreme value distribution (see above Chapter 5.1, eq. (1), (2a), (2b)). The upper cut-off value of x_0 for Middle Germany is equal to 40.0 °C for maximum shade air temperature and the one for minimum shade air temperature is equal to 30.0 °C.

With the help of the eq. (3), (4a) - (4c) the representative values of shade air temperature range are determined:

Characteristic value:	- maximum	$T_{K\,(max)}$	=	37.3 °C
	- minimum	$T_{K\,(min)}$	=	23.2 °C
Infrequent value:	- maximum	$T_{K\,(max)}$	=	32.8 °C
	- minimum	$T_{K\,(min)}$	=	18.4 °C
Frequent value:	- maximum	$T_{K\,(max)}$	=	28.2 °C
	- minimum	$T_{K\,(min)}$	=	14.8 °C
Quasi-permanent value:	- maximum	$T_{K\,(max)}$	=	24.7 °C
	- minimum	$T_{K\,(min)}$	=	12.4 °C

6. Calculation of representative values of thermal effects

6.1 Linear temperature differences

To obtain the representative values of linear temperature differences it is necessary to perform the calculations with the help of the program [9] only for 4 different design situations (characteristic, infrequent, frequent, quasi-permanent) using appropriate values of TSR and associated mean values of other input parameters.

A very high value of linear temperature differences occurs usually in a day with a very high total solar radiation and average range of shade air temperature, following one or two not very warm days. Program [9] uses a one-day cycle, therefore, the initial mean temperature of the bridge (see Chapter 3) in a given day can be considered as the final temperature of the previous day. Because two previous days were not very warm the initial temperature in the given day can be supposed to be close to the air temperature at the same time, i.e. at 08:00 a.m.. This value is close to the daily minimum air temperature and can be estimated as 12.0 °C (see Chapter 5.1) for the calculation of the characteristic value of linear temperature differences. Because other representative values (infrequent, frequent, and quasi-permanent) are smaller than the characteristic one, the two previous days need to be not so cold for these situations. It means that the mean bridge temperature is greater than the temperature of the surrounding air at 08:00 a.m. in a given day, and the initial effective bridge temperature can be derived by running the bridge model for the particular set of environmental conditions of interest for a period of 2 - 3 days. The starting initial mean bridge temperature can be assumed again as 12 ^{0}C.

The calculations are performed for 10 types of bridge cross sections (types 1.0. - 3.3.) and results are shown in Table 1 (ΔT_M in ^{0}C).

Depth (m)	ΔT_{MK}	$\Delta T_{M1}'$ Ψ_1'	ΔT_{M1} Ψ_1	ΔT_{M2} Ψ_2
Box girder				
1.95 (Lucka)	11.4	9.3 *0.82*	7.4 *0.65*	5.8 *0.51*
2.0	11.5	9.4 *0.82*	7.4 *0.64*	6.0 *0.52*
3.3	10.3	8.3 *0.81*	6.5 *0.63*	5.2 *0.50*
4.7	9.6	7.6 *0.79*	5.9 *0.62*	4.7 *0.49*
T-girder				
1.2	19.0	14.8 *0.78*	11.7 *0.62*	9.5 *0.50*
1.8	16.0	12.2 *0.76*	9.5 *0.59*	7.7 *0.48*
2.4	14.1	10.6 *0.75*	8.2 *0.58*	6.5 *0.46*
Slab				
0.6	18.0	15.2 *0.84*	12.5 *0.69*	10.4 *0.58*
0.9	13.8	11.6 *0.84*	9.5 *0.69*	7.8 *0.57*
1.2	10.8	9.1 *0.84*	7.3 *0.68*	6.0 *0.56*

Table 1. Representative values of linear temperature differences.

ΔT_{MK} , $\Delta T_{M1}'$, ΔT_{M1} , ΔT_{M2} are characteristic, infrequent, frequent, and quasi-permanent values of the linear temperature differences.

The comparison with the results in [11] obtained by the statistical analysis of linear temperature differences shows a very good coincidence. For characteristic situation the values from Table 1 are a little smaller (but the difference is only 0.5 - 2.5 %), for other representative situations the results are practically identical.

Reduction coefficients Ψ are determined as:

$\Psi_1' = \Delta T_{M1}'/\Delta T_{MK}$ for infrequent value of the action,

$\Psi_1 = \Delta T_{M1}/\Delta T_{MK}$ for frequent value of the action,

$\Psi_2 = \Delta T_{M2}/\Delta T_{MK}$ for quasi-permanent value of the action.

Values of these coefficients are shown also in Table 1.

Considering all results in Table 1 it is possible to propose the following values for the reduction coefficients Ψ:

$\Psi_1' = 0.8$
$\Psi_1 = 0.6$
$\Psi_2 = 0.5$

The same values are in [11].

6.2 Effective bridge temperature

To obtain the representative values of effective bridge temperature it is necessary to perform the calculations with the help of the program [9] only for 4 different design situations (characteristic, infrequent, frequent, quasi-permanent) using appropriate values of shade air temperature range and associated mean values of other input parameters.

A very high value of effective bridge temperature occurs usually in a day with a very high range of shade air temperature and average total solar radiation, following one, two or three very warm days with very warm nights. Because of the thermal inertia the mean bridge temperature rises during these days and, therefore, the starting mean bridge temperature is very high at 08:00 a.m. in a day considered. Analysis undertaken in [12] showed that this value can be assumed as $T_{rep,max}$ - 3 ^{0}C (where $T_{rep,max}$ - the representative value for the situation of interest).

The calculations are performed for 10 types of bridge cross sections (types 1.0. - 3.3.) and results are shown in Table 2 (ΔT_N in ^{0}C).

ΔT_{NK} , $\Delta T_{N1}'$, ΔT_{N1} , ΔT_{N2} are characteristic, infrequent, frequent, and quasi-permanent values of the uniform temperature component.

The comparison with [12] shows that for characteristic situation the values are almost the same for box girders and a little smaller for T-girders and slabs (0.5 - 4.0 %), for other representative situations the values from Table 2 are a littler higher (on the safe side) for box girders and slabs (2 - 8 %) and very close for T-girders.

Depth (m)	ΔT_{NK}	$\Delta T_{N1}'$ Ψ_1'	ΔT_{N1} Ψ_1	ΔT_{N2} Ψ_2
Box girder				
1.95 (Lucka)	26.6	22.0 *0.82*	17.5 *0.65*	14.1 *0.53*
2.0	27.9	23.5 *0.84*	19.2 *0.68*	16.0 *0.57*
3.3	27.4	23.0 *0.84*	18.7 *0.63*	15.4 *0.56*
4.7	26.9	22.6 *0.84*	18.3 *0.68*	15.0 *0.56*
T-girder				
1.2	28.5	24.1 *0.84*	19.8 *0.69*	16.6 *0.58*
1.8	27.8	23.4 *0.84*	19.1 *0.68*	16.0 *0.57*
2.4	27.3	22.9 *0.83*	18.6 *0.68*	15.4 *0.56*
Slab				
0.6	27.6	22.2 *0.80*	18.8 *0.68*	15.6 *0.56*
0.9	26.5	22.1 *0.83*	17.8 *0.67*	14.5 *0.55*
1.2	25.9	21.6 *0.83*	17.3 *0.66*	14.0 *0.54*

Table 2. Representative values of the uniform temperature component $\Delta T_N = T_N - 10\,^0C$.

Reduction coefficients Ψ are determined as:

$\Psi_1' = \Delta T_{N1}'/\Delta T_{NK}$ for infrequent value of the action,

$\Psi_1 = \Delta T_{N1}/\Delta T_{NK}$ for frequent value of the action,

$\Psi_2 = \Delta T_{N2}/\Delta T_{NK}$ for quasi-permanent value of the action.

Values of these coefficients are shown also in Table 2.

In [12] coefficients Ψ calculated with the help of statistical analysis of uniform temperature component are proposed as:

$\Psi_1' = 0.8$
$\Psi_1 = 0.6$
$\Psi_2 = 0.5$

7. Influence of surfacing on the values of linear temperature differences

All results given above are obtained for surfacing of 50 mm. The variation of the thickness of surfacing affects only on linear temperature differences. For other values of thickness the procedure given above can be also used and conversion factor k may be proposed:

surface thickness (mm)	factor k
0	1.5
50	1.0
100	0.7
150	0.5

Table 3. Influence of surface thickness.

For other values of thickness factor k can be found by interpolation.

Thus, all representative values of linear temperature differences from Table 1 must be multiplied by factor k if the surfacing is other than 50 mm.

8. Conclusions

The statistical analysis of extreme values of environmental conditions (incoming total solar radiation and shade air temperature) is performed. According to the philosophy of Eurocodes four design situations and correspondingly four representative values of thermal effects in bridges are defined. The thermal effects in a concrete bridge deck can be derived from the difference temperature profile through the depth of the deck. The representative values of thermal effects (linear temperature differences and uniform temperature component) may be obtained using directly the appropriate representative values of environmental conditions. These latter ones are calculated with extreme values theory using extreme value distribution type III. The reduction coefficients Ψ and surfacing factors k are also obtained. This procedure can be used for different climatic zones. The results based on meteorological data from central Germany are performed for typical bridge cross sections and can be considered as valid for the middle of Europe.

The characteristic values of linear temperature differences and values of surfacing factor are incorporated in Eurocode 1, Part 2.5 „Thermal Actions“. The values of coefficients Ψ are included in Eurocode 1, Part 3 „Traffic Loads on Bridges“.

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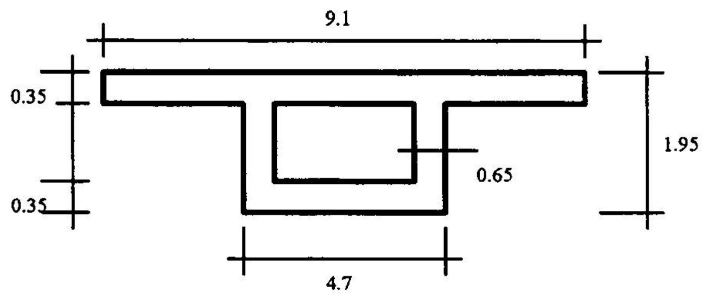
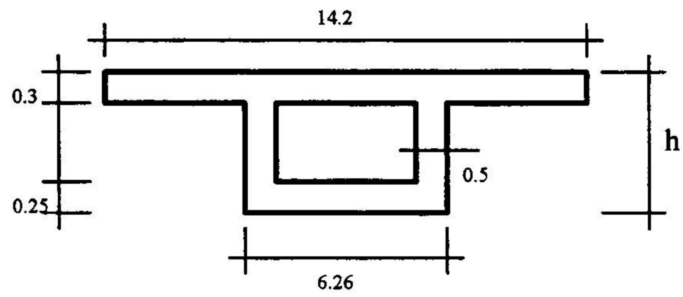
ANNEX A

Bridge Cross Sections

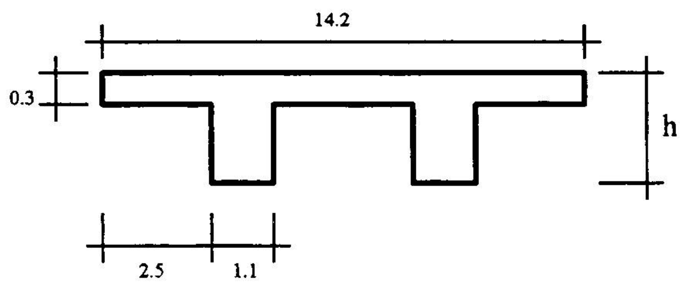
Box Girder Type 1.0



Type 1.1 (h=2.0 m), Type 1.2 (h=3.3 m), Type 1.3 (h=4.7 m)



T-girder Type 2.1 (h=1.2 m), Type 2.2 (h=1.8 m), Type 2.3 (h=2.4 m)



Slab Type 3.1 (h=0.6 m), Type 3.2 (h=1.2 m), Type 3.3 (h=1.8 m)