

# Temperature distribution in concrete bridge decks

*Duen Ho and Chi Ho Liu*

*Proc. Instn Civ. Engrs Structs & Bldgs*, 1993, **99**, May, 233–235

Paper 9715

**A. J. Harris & B. W. Smith, Flint & Neill Partnership**

The work reported by the Authors is a summary of the comprehensive study undertaken by them for the Highways Department, Hong Kong (HDHK). As a result of their work, concern was expressed regarding the general applicability of the thermal loadings defined in BS 5400, Part 2,<sup>7</sup> to Hong Kong conditions. The Flint & Neill Partnership was subsequently commissioned by the HDHK to undertake a study of temperature effects for all bridge superstructure groups and surfacing thicknesses covered in the British Standard, for application to Hong Kong climatic conditions and taking account of appropriate local material parameters. During the above study, the Authors' work proved to be an invaluable source of data, relating specifically to the region. While the analyses undertaken as part of our study were based on a one-dimensional heat flow model similar to that used by the Authors, our approach differed in several key areas. We would welcome the Author's views on these.

60. Because of the nature of global solar radiation  $Q$ —although it is a random process—for any fixed point on the Earth's surface, there will be an absolute maximum value for the amount of incoming radiation which will be experienced in any single day under ideal conditions. As a result, we consider that a Type III extreme distribution is more appropriate than the Type I that has been adopted by the Authors (§ 28).

61. While we agree that bridge effective temperature is a function of  $Q$  (or by night, re-radiation  $R$ ) and shade air temperature  $T_a$ , our analyses have confirmed the conclusion drawn by a number of other authors on the subject, that the maximum temperature difference profiles are a function of  $Q$  (or  $R$ ) and the diurnal range of shade air temperature ( $\Delta T_a$ ). A high value of  $T_a$  will produce high deck temperatures; but for a fixed daily range  $\Delta T_a$ , the magnitude of the temperature difference through the depth of the deck will not change from that experienced at a lower absolute value of  $T_a$ . This is somewhat supported by the Authors in their treatment of reverse temperature differences, which takes into account a negative temperature range in excess of that calculated by way of the expressions that they have presented in reference 8 relating  $T_{a(\max, \min)}$  and  $\Delta T_a$ . Because these relationships are the

result of a curve-fitting exercise, they must therefore yield only representative values of  $\Delta T_a$ . Our investigations, based on Royal Observatory data, indicated that the extreme values of  $\Delta T_a$  encountered are considerably higher than the values yielded by the above expressions.

62.  $Q$  and  $\Delta T_a$  are independent processes, and it is highly unlikely that both will reach their maxima at the same instant in time. Bearing in mind that there are bound to be modelling inaccuracies—on account, firstly, of the simplifying assumption of one-dimension heat flow, secondly, of assumptions regarding the initial conditions, and, thirdly, of assumptions regarding material parameters and boundary conditions—we considered that the pragmatic approach proposed by Turkstra<sup>12</sup> was appropriate when the extreme loading event was being examined. The basis of the approach is that an extreme value of an individual loading process is, in turn, combined with 'usual' or average values of other loading processes.

63. The results of our study confirmed that increases in the magnitudes of the positive temperature difference profiles relative to those presented in BS 5400 are appropriate for the Hong Kong region, and that this is attributable to the significantly higher levels of  $Q$  experienced at the reduced latitude of Hong Kong relative to the UK. The case of an extreme value of  $Q$  (with associated nominal value of  $\Delta T_a$ ) produced the governing load effects, and, as a result, our recommended design profile for an unsurfaced, trafficked concrete deck is similar in form to that described by the Authors. Revisions to the reverse temperature difference profiles are far less significant. This is illustrated by the Authors' observation that the British code estimated reasonably well their winter thermal loadings, where the values of  $\Delta T_a$  and  $R$  used for their analysis were similar to those used during the derivation of the BS 5400 curves. However, one point that we would make with regard to the validity of the Authors' comparison with BS 5400 is that the temperature distribution against which their results are compared appears to be that for unsurfaced concrete. We have been advised that these values were derived on the assumption that the surface of the concrete is as cast (i.e. not discoloured) and would hence have an absorptivity value  $\alpha$  of the order of 0.5, which is considerably less than the figure of 0.75 for

Paper published:  
*Proc. Instn Civ. Engrs*, Part 2, 1991, **91**, Sept., 451–476

unsurfaced trafficked concrete adopted by the Authors. We therefore consider the BS 5400 values for waterproofed decks (where  $\alpha = 0.85$ ) to be a more valid comparison.

64. With regard to the Authors' comments in § 15 regarding the absence of a reverse temperature gradient at the deck soffit for positive temperature difference profiles, we would suggest that this is a result of the reduced shade air temperature ranges considered and of the fact that only the unsurfaced condition was examined. If surfacing is considered, it has the effect of delaying the time at which the top of the structural element reaches its maximum temperature. As a result of this time lag, the surrounding shade air temperature may change significantly, resulting in the small reverse gradient typical of the BS 5400 curves. It should be added that this effect, although observed, was very small in magnitude and would have a relieving effect on  $M_t$ . The effect becomes far more pronounced when larger ranges of shade air temperature are considered.

65. During the course of our study, a number of inconsistencies within BS 5400 became apparent. Firstly, it became evident that while the bridge effective temperatures derived are based on 120 year return period events, the temperature difference profiles presented do not represent extreme events but approximate to thermal events which might occur during a typical UK year. Secondly, because the temperature difference profiles are based on recorded data for a limited number of bridges, in order to reproduce these events, the environmental data used were varied depending on the form of construction being considered. While we acknowledge that different construction groups will react at differing rates to environmental stimuli, we consider that the approach adopted to temperature difference profiles within BS 5400 is not consistent with the statistical approach adopted for other forms of loading.

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*Mr Harris* and *Mr Smith* assume that the temperature difference in a deck depends on daily global solar radiation  $Q$  and daily range of shade air temperature  $\Delta T$ . The design temperature profile is then determined based on the 50 year value of  $Q$  and an average value of  $\Delta T$ . No analysis was carried out on bridge effective temperature  $T_e$ .

67. Harris and Smith's approach is, as they have pointed out themselves, only a 'pragmatic' one. The probability of occurrence of the value obtained is not known. It is obvious that many other combinations of  $Q$  and  $\Delta T$  could produce a worse profile. Meanwhile, analyses based on the 50 year value of  $\Delta T$  and the average value of  $Q$  seem equally valid. For

example, in the analysis of effective bridge temperatures which depend on both  $Q$  and the daily maximum shade air temperature  $T_{\max}$ , what should be assumed?

68. Our analysis is based on the assumptions that in summer

- (a) the thermal loadings, including both effective temperature and the temperature profile  $M_t$ , depend on  $Q$  and  $T_{\max}$ ; the influence of  $\Delta T$  is included in the relation between  $T_{\max}$  and  $\Delta T$
- (b) the extreme values of the thermal loadings are assumed to be functions of the extreme values of these two climatic parameters.

Assumption (b) implies that extreme values of  $Q$  and  $T_{\max}$  occur simultaneously, which is not necessarily the case. As we pointed out in the discussion on reference 13, such an assumption is a necessary simplification pending a detail statistical analysis on  $Q$  and  $T_{\max}$ .

69. We agree that with an upper bound, the assumption of a Type III extreme distribution would be more logical. However, our extreme analysis is not based on a Type I distribution for  $Q$  but on the sample statistics of  $Q$ .<sup>13</sup> The 50 year value of  $Q$  in the Paper was quoted for reference only.

70. The validity of the above assumptions is checked by comparison with simulation analysis. Results of the two analyses are quite close,<sup>13</sup> the present analysis overestimated the extreme thermal loadings by only a few percent. It is based on this comparison (and not on any intuitive argument) and that we accepted the assumptions as 'reasonable'.

71. Similarly, in our analysis, the parameters such as the value of absorptivity  $\alpha = 0.75$  were determined from a comparison of the calculated and measured statistics of the thermal loadings (Table 4 in Paper). As the bridges from which measurements were taken have been opened to traffic for several years, it is unlikely that their deck surface would still remain fresh and clean. Besides, the parameters, which were empirical, should be treated as a set, e.g.  $\alpha = 0.75$  should be used together with  $h_t = 24.5 \text{ W/m}^2 \text{ per K}$ . For a different value of  $\alpha$ , a different value of  $h_t$  would have to be assumed to give best fit to the measured data. Hence an assumption of  $\alpha = 0.5$  is not justifiable without corresponding changes in the other parameters.

72. Comparison with BS 5400 should be based on the physical condition and not on the parameters used in the two calculations. If  $\alpha = 0.75$  is different from  $\alpha = 0.5$  used for the unsurfaced deck in BS 5400, so is  $h_t$  and other parameters. Should one also adjust for these differences before comparison?

73. Our comment on the reverse gradient at deck soffit in § 15 refers to measured results.

The observation is therefore unrelated to 'the reduced  $\Delta T$  considered', etc.

74. Finally, as measurements have been carried on unsurfaced concrete decks only, we have limited our discussion to this type of deck. Calculation on other types of construction can be carried out using available computer programs. However, as neither the parameters used nor the results obtained could be verified, we do not think it is appropriate to extend our comments to such cases.

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