Forth Road Bridge: temperature measurements

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(The work was originally requested by the Forth Road Bridge Joint Board)

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Executive Summary

The temperature differences to which a structure is subjected during its life cause thermal stresses within the materials of construction. These stresses act as loads on the structure, and, together with dead load, live load and wind load, must be taken into account in a load assessment. The data on bridge temperatures contained in current Standards include information on likely values of minimum and maximum temperatures, and magnitudes of temperature differences, for different forms of construction. However, the forms of construction do not include orthotropic steel decks on an open truss/plate girder construction, vertical steel boxes, or cables, all of which can be components of a suspension bridge. The Forth Road Bridge is a suspension bridge.

Some years ago, Consultants W A Fairhurst & Partners were asked by the Forth Road Bridge Joint Board to carry out a load assessment of the bridge. In the absence of guidance in the Standards on temperatures associated with some components of the bridge, W A Fairhurst & Partners decided that the temperatures of these areas should be measured in order that realistic data could be used in the assessment. The advice and assistance of TRRL (now TRL) was requested regarding the instrumentation required for the measurement and recording of these temperatures, and the analysis and interpretation of the data which were collected. All the measurements were carried out between 1984 and 1986, a number of years before the strengthening works on the bridge were started.

As well as measured temperatures and temperature differences, information was required on the effects of extremes of temperature likely to be experienced during the life of the bridge. It was thus necessary to develop a combination of empirical and theoretical methods by which measured temperatures could be extrapolated to those likely to occur during 1 in 120 year extreme conditions.

The areas where temperatures were measured included: (a) the deck plates and associated stiffeners, (b) other components of the open truss/plate girder construction, (c) the vertical steel plates which form the five cells of the main tower legs, (d) one of the main suspension cables, and (e) two of the hangers.

The main findings regarding: (a) measured temperatures and corresponding calculated temperatures, (b) temperature differences, and (c) theoretical 1 in 120 year extreme temperatures, are summarised in the report. The majority of the data are concerned with maximum temperatures and large temperature differences, for these data are important for a load assessment. However, data on minimum temperatures are also included.

The temperatures measured on vertical surfaces, and on one of the main (suspension) cables, are of particular interest, for published information on such data is scarce. Two of the highest measured temperatures in these areas were 51°C on the west facing face of one of the main tower legs, and 40°C on the main cable. One of the highest temperatures measured on the undersurface of one of the deck plates was 39°C. Measured minimum temperatures lay between -3°C and -6°C.

Temperature differences of 35°C and 24°C were measured between the north and south, and east and west facing surfaces respectively of one of the main tower legs. A temperature difference of 24°C was measured between two sides of the main cable.

Temperatures were also calculated, and, for locations unaffected by shadow, the agreement between measured and calculated temperatures was usually good. Extrapolations of the theory to calculate 1 in 120 year temperatures suggested that some areas of the bridge might experience ranges of temperature in excess of 80°C under these extreme conditions.

Although the data apply to a specific bridge in a specific location in the UK, there is no reason why, provided that adequate meteorological data are available, the temperatures of the decks, towers and cables of bridges in other areas of the world cannot be estimated.

Some of the data are to be used as the basis for expanding the information given in the temperature clauses of BD 37/88 and Part 2 of BS 5400. Some information has already been used to assist with the preparation of data for Eurocodes.

1 Introduction

The temperature differences to which a structure is subjected during its life cause thermal stresses within the materials of construction. These stresses act as loads on the structure, and, together with dead load, live load and wind load, they must be taken into account in a load assessment. Current Standards which deal with temperature loading provide information and guidance on likely values of minimum and maximum temperatures, and magnitudes of temperature differences, for different forms of construction. However, the forms of construction do not include orthotropic steel decks on an open truss/plate girder construction, vertical steel boxes, or cables.

Some years ago, Consultants W A Fairhurst & Partners were asked by the Forth Road Bridge Joint Board to carry out a load assessment of the Forth Road Bridge, a suspension bridge near Edinburgh. Areas of the bridge to be included in the assessment were the main span of the suspended superstructure (orthotropic steel deck plates on an open truss/plate girder framework), the main towers (vertical multi-cell steel boxes), the main (suspension) cables and the hangers. Because of the lack of guidance in the Standards, W A Fairhurst & Partners decided that the temperatures of these areas should be measured in order that realistic data could be used in the load assessment. The advice and assistance of TRRL (now TRL) was requested regarding the instrumentation required for the measurement and recording of these temperatures, and the analysis and interpretation of the data which were collected.

As well as measured temperatures and temperature differences, information was required on the extremes of temperature likely to be experienced by the bridge during its life. It was thus necessary to develop a combination of empirical and theoretical methods by which measured temperatures could be extrapolated to those likely to occur during 1 in 120 year extreme conditions.

The circumstances under which the work was carried out were different from previously reported TRRL temperature investigations. The work was instigated in response to a request for specific information and guidance, rather than as part of a wider-ranging research programme. The data have therefore been analysed and reported in accordance with these requirements.

All the measurements were carried out a number of years before the strengthening works on the bridge were started. All times mentioned are GMT.

The details of the work and the results obtained were reported initially in three unpublished TRRL Working Papers which were written some years ago. This TRL report summarises the main findings regarding: (a) measured temperatures and corresponding calculated temperatures; (b) temperature differences; (c) theoretical 1 in 120 year extreme temperatures. The results relate to the suspended superstructure of the main span, the main towers, the main suspension cables and the hangers.

One of the current trends in the transport world is towards an increase in the construction of suspension and cable-stayed bridges. The size of the bridges is also increasing. However, published data on temperatures measured on steel open truss decks, steel towers, suspension cables and hanger ropes, are sparse. It is hoped that the results presented in this report will be of use in illustrating the levels of temperature and the magnitudes of temperature differences which can exist in such structures, and the levels of 1 in 120 year temperatures to which a structure might be subjected.

Although the data in the report apply to a specific bridge in a specific location in the UK, there is no reason why, provided that adequate meteorological data are available, the temperatures of the decks, towers and cables of bridges in other areas of the world cannot be estimated.

Some of the data contained in the report are to be used as the basis for expanding the information given in the temperature clauses of BD 37/88, 'Loads for highway bridges', and in BS 5400, 'Steel, concrete and composite bridges: Part 2: Specification for loads'. Some information has already been used to assist with the preparation of data for Eurocodes.

2 The Forth Road Bridge

2.1 General description

The Forth Road Bridge is a suspension bridge situated to the north-west of Edinburgh, carrying the A90 in an almost due north/south direction over the Firth of Forth. It was opened to traffic in September 1964.

The suspended superstructure of the main span consists of orthotropic steel deck panels on a steel open truss/plate girder framework. The side spans are formed from concrete deck slabs on steel stringers, supported by the same steel open truss/plate girder framework. The approach viaducts consist of concrete deck slabs on two longitudinal steel box girders with transverse beams. The main towers are formed from steel multi-cell boxes. A general elevation of the bridge, including the side spans and approach viaducts, is shown in Figure 1. A detailed description of the design and construction of the bridge may be found elsewhere (Proceedings of the Institution of Civil Engineers, 1965). A brief summary of salient points, including steel and surfacing thicknesses, is given in Sections 2.2, 2.3 and 2.4 below. These data relate to the bridge before the strengthening works were started, and when the original surfacing was still in place.

At the time the temperatures were being measured, the paint on all the steelwork (including the main cable wrapping) was a light grey 'micaceous' iron oxide.

2.2 The suspended superstructure of the main span

The steel structure suspended from the main cables is an open rectangular framework 23.8m (78ft) wide and 8.4m (27.5ft) deep, braced on all four sides, and designed for torsion as well as vertical and horizontal bending. The four corners of the framework, namely the east and west upper and lower chords, are formed from welded box members approximately 0.61m (24in) square in section. At the positions at which the temperatures were measured the steel plates forming the east and west vertical faces of

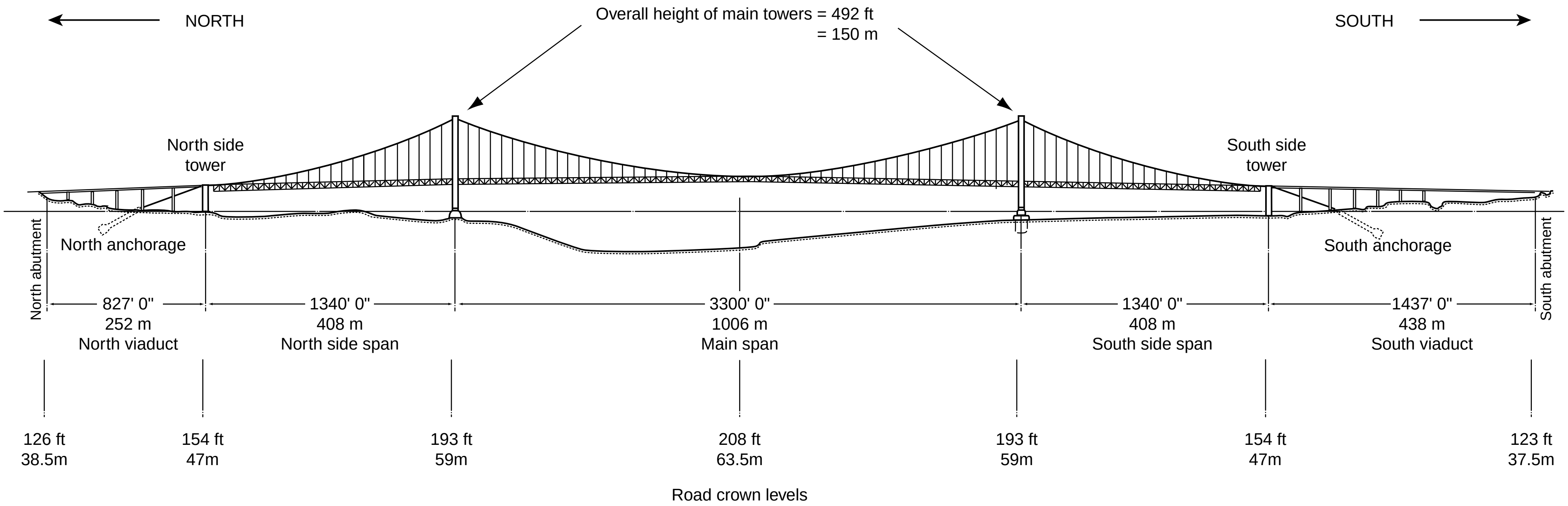


Figure 1 Forth Road Bridge: general elevation

these chords are 17.5mm (11/16in) thick, and the plates forming the top and bottom faces are 19mm (0.75in) thick. The layout of the deck panels, and the stiffening truss and cross bracing of the framework is shown in Figure 2.

The standard main span roadway deck panels are orthotropic mild steel plates 12.7mm (0.5in) thick with longitudinal trapezoidal stiffeners and transverse plate girders. Most of the panels are approximately 18.3m (60ft) long. They are located on the top of the open rectangular framework described in the previous paragraph. The longitudinal stiffeners are manufactured from 6.3mm (0.25in) mild steel plate, and have 203mm (8in) sides and a 203mm (8in) wide base. At the time the temperature work was carried out, the surfacing on all the panels consisted of a rubber bitumen primer, a 3mm (0.125in) thick layer of rubber bitumen, and a layer of mastic asphalt which brought the total thickness of material to 38.1mm (1.5in).

2.3 The main towers

The section of each tower leg is composed of five cells formed by three prefabricated boxes joined by four connecting plates. The plates are stiffened longitudinally. The size of the centre box and the spacing between the boxes are maintained for the full height of each tower, as is the breadth of the boxes. The width of the outer boxes is greater at the base of each tower leg than it is at the top. A diagrammatic cross-section of a tower leg at level 5C, the level at which the temperatures were measured, is shown in Figure 3. Level 5C is approximately 15m (49ft) above the roadway. The vertical sides of the tower legs face approximately north, south, east and west. At the positions at which the temperatures were measured, the east and west plates are 22.2mm (0.875in) thick, and the north and south plates are 25.4mm (1.0in) thick. The instrumented area was in the west leg of the south main tower, i.e. the SW tower leg.

2.4 The main suspension cables and the hangers

Using a 5mm (0.196in) diameter wire, each of the two main cables was spun in a series of bundles or strands. The strands were organised in the form of a hexagon, this being the nearest approach to the circular form into which the cable was to be compacted. The hexagonal arrangement is shown in Figure 4(a). The final circular shape was formed by mechanically compacting the cable and wrapping it with mild steel galvanising wire. It was estimated that after compaction and wrapping approximately 20 per cent of each cable consisted of voids. The outside diameter of each completed cable (including the wrapping) is approximately 584mm (23in).

The vertical hangers are in pairs, bent round two grooves in the upper surfaces of the main cable bands. The hangers in the main span are formed from 44mm (1.75in) diameter wound steel rope. In the side spans the diameter of the rope is 54mm (2.125in). The cable band and hanger assembly is shown in Figure 4(b).

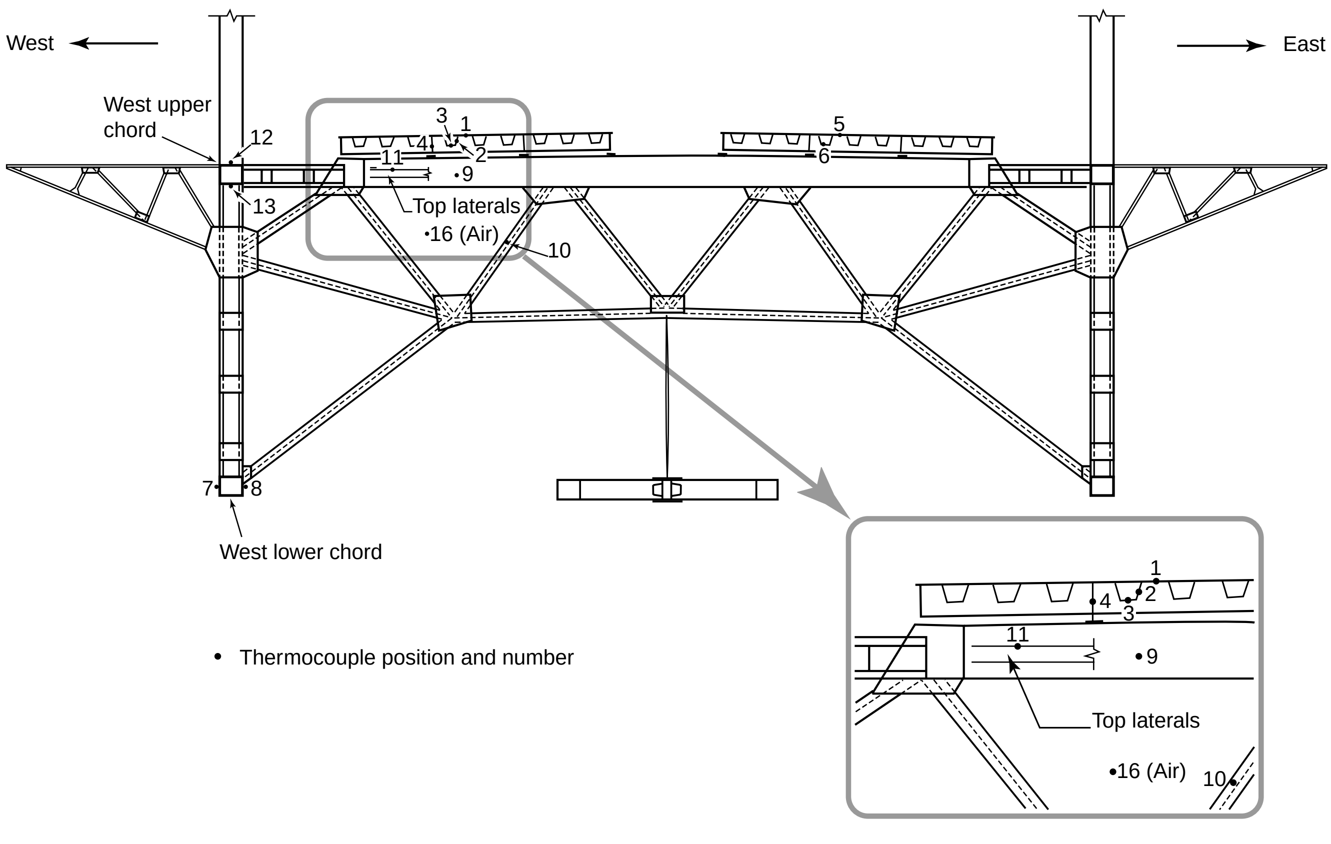


Figure 2 Cross-section of the suspended superstructure of the main span showing thermocouple locations

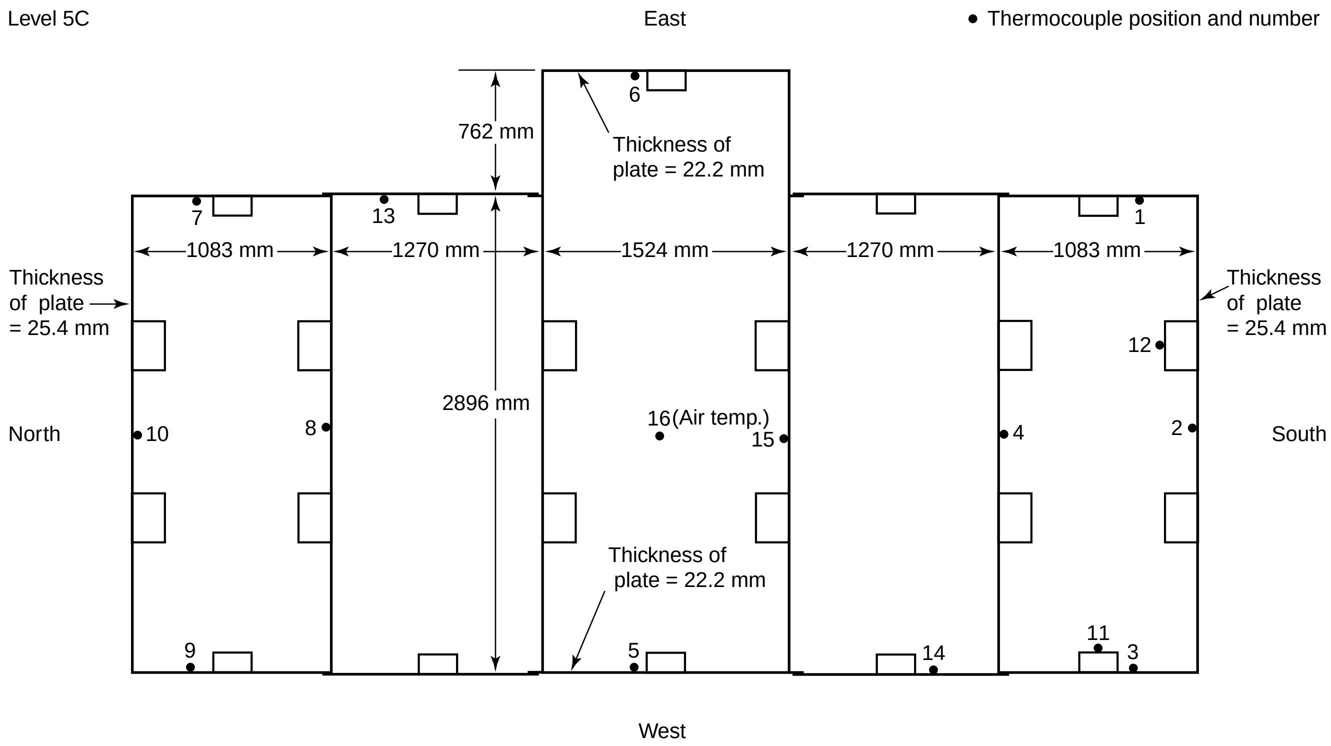


Figure 3 Diagrammatic cross-section of SW tower leg showing thermocouple locations

3 Instrumentation

The instrumentation of the bridge for the measurement of temperature was carried out by steel riggers from the bridge maintenance crew and personnel from W A Fairhurst & Partners. Advice on the locations at which the temperatures should be measured, and on the method of recording, was given by TRRL.

With one exception all the temperatures were measured using copper-constantan thermocouples connected to potentiometric chart recorders. (The exception, identified in Section 3.4, was one of the measurements of the shade temperature.) Each chart recorder could measure 16 temperatures in continuous rotation, one rotation taking just over 5 minutes to complete. The recorders were run almost continuously for periods ranging between 1 and 2.5 years, thus providing comprehensive data on temperature variations.

A full description of the method used to fix thermocouples to steel can be found elsewhere (Capps, 1968). Brief details in relation to the Forth Road Bridge are that each thermocouple junction was ‘insulated’ from the steel by a strip of insulating tape, and it was also ‘insulated’ from the surrounding air by a substantial thickness of adhesive tape.

The insulation of the thermocouples from the steel is a precaution against the possibility of interference with the microvolt outputs of the thermocouples by spurious voltages within the steel. This was a problem which had arisen in the past at other bridge sites. The insulation of the thermocouple junction from the surrounding air is in order that the temperature measured is that of the steel and not the air. (The ‘true’ temperature of an exposed surface can be difficult to measure.)

3.1 The suspended superstructure of the main span

The temperatures of the deck plates and associated stiffeners, and other girders, were measured at six locations, as shown in Figure 2. Four of the thermocouples were positioned beneath the northbound carriageway in the vicinity of the NE tower leg, and two were beneath the southbound carriageway.

The temperatures of three members of the open truss/ plate girder framework were also measured. The locations are also shown in Figure 2.

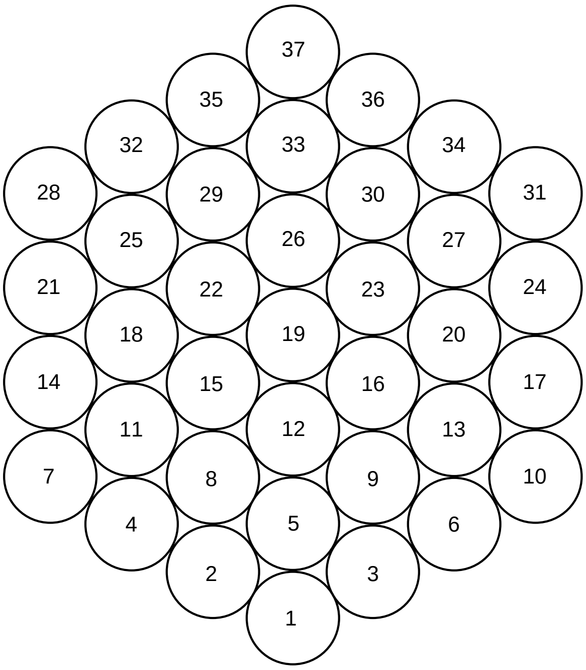
The temperatures of the main chords of the open truss/ plate girder framework were measured at two positions on each of the upper and lower main chords on the west side of the bridge. As can be seen from Figure 2, the thermocouples were located on the horizontal top and bottom faces of the upper chord, and on the vertical east and west faces of the lower chord.

All the thermocouples were connected to a chart recorder situated on one of the permanent access platforms beneath the deck panels. Temperature recording started in August 1984 and ended in January 1987.

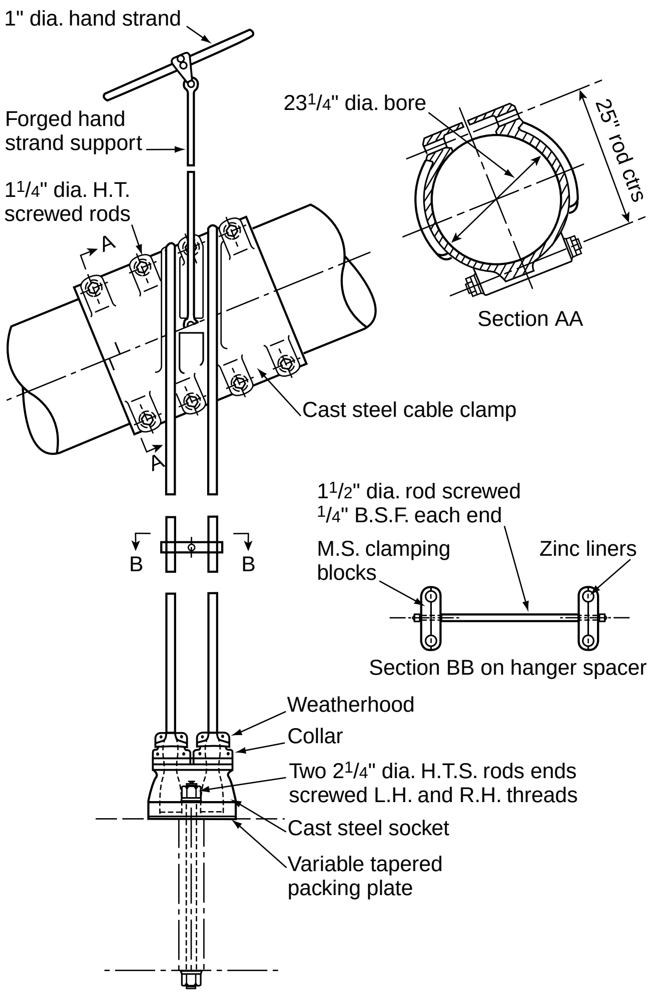
3.2 The SW tower leg

As mentioned in Section 2.3, the temperatures of the steel plates which form the SW tower leg were measured at level 5C. The thermocouples were attached to the plates and stiffeners at the locations shown in Figure 3, and were connected to a chart recorder situated inside the tower leg. The chart recorder was run continuously from June 1984 to the end of December 1986. Some minor losses of data were experienced as a result of equipment malfunction.

The temperature of the air inside the tower leg was also measured using a thermocouple suspended in the centre box of the leg.



(a) Pattern of strands in cable before compacting



(b) Cable band and hanger assembly

Figure 4 Detail of main cables and hangers

3.3 The main suspension cables and the hangers

The temperatures of the main cable on the east side of the bridge were measured at the eight locations shown in Figure 5(a), four on the main span section of the cable and four on the north side span section. The thermocouples were attached to the outside of the cable wrapping, and were connected to a chart recorder situated inside the top of the NE tower leg.

Recording of the temperatures of the main span section of the east main cable started in June 1984, and on the north side span section in August 1984. Temperature recording at both locations terminated in August 1985.

The hanger temperatures were measured at the four locations shown in Figure 5(b). Each thermocouple junction was recessed into the twists of the hanger rope at a distance of approximately 1m below the main cable. One of the hangers was on the main span section of the main cable, and the other was on the north side span section. The thermocouples were also connected to the chart recorder situated inside the top of the NE tower leg, and the periods of temperature recording were the same as those mentioned in the previous paragraph for the main cable.

3.4 Shade temperature

The shade temperature was measured using a thermocouple located beneath the deck plates in the vicinity of the NW tower leg and another thermocouple located at the top of the NE tower leg. In addition, a thermograph was installed to measure the temperature at the top of the SW side tower. Shade temperature data were also obtained from Edinburgh Airport (Turnhouse), which is approximately 5 miles from the bridge.

4 Temperatures

As first indicated in Section 1, all times mentioned are GMT.

4.1 Shade temperature

Before the measurements of bridge temperatures are discussed, it is first necessary to comment on the shade temperature, for shade temperature values are used in the calculation and estimation of bridge temperatures.

Comprehensive data on the relationship between the shade temperature measured in the vicinity of a bridge and the shade temperature measured at the nearest Meteorological Station to a bridge have already been published (Emerson, 1976a, b). One of the findings was that shade temperatures measured in the vicinity of a bridge are likely to be influenced by the proximity of the thermal mass of the bridge. This can result in daily minimum temperatures which are artificially elevated, and this in turn reduces the values of daily ranges of shade temperature. It is thought that both these effects, as well as the moderating influence of the sea, occurred at the Forth Road Bridge site.

One example in support of the above hypothesis can be seen in that the lowest shade temperature recorded in the vicinity of the bridge was -4°C, while the lowest shade

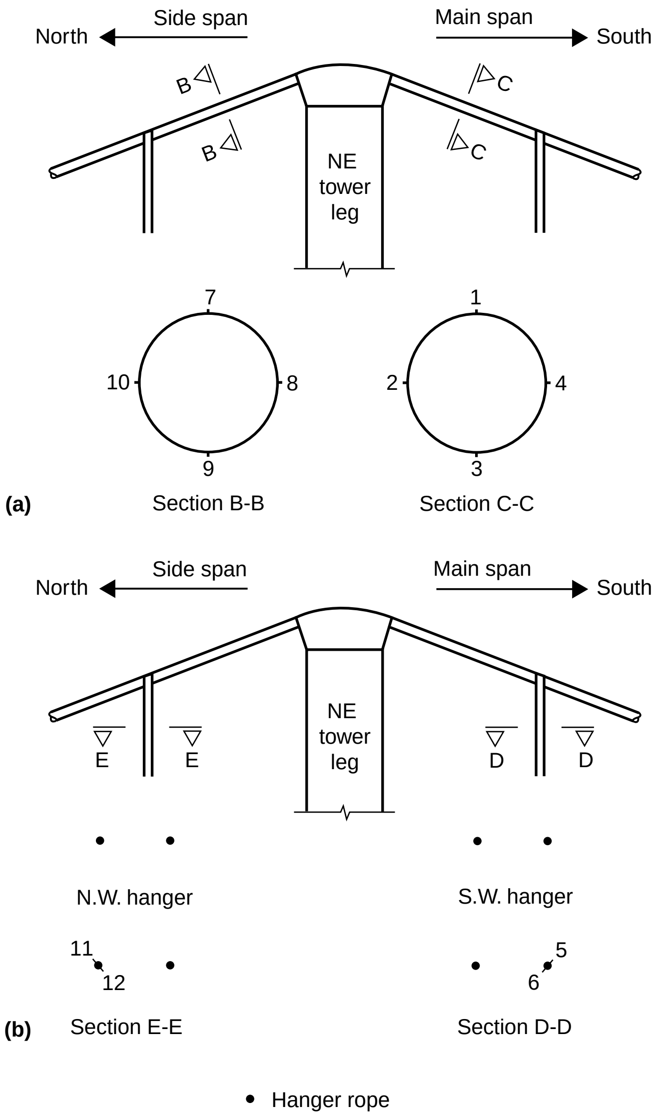


Figure 5 Main cable and hangers: thermocouple positions and numbers

temperature recorded at Edinburgh Airport on the same day was -12°C. (This was also the lowest temperature recorded at the airport during the period that bridge temperatures were being measured.) Indeed, there were many occasions when the daily minimum shade temperature at the airport was considerably lower than the corresponding daily minimum shade temperature in the vicinity of the bridge. The largest difference between these two temperatures was 8°C.

It should therefore be noted that the predicted 1 in 120 year minimum value of the shade temperature in the Edinburgh area of -18°C (Hopkins & Whyte, 1975; British Standards Institution, 1978; Department of Transport, 1988), while appropriate to inland areas, might be too ‘extreme’ for the location of the bridge. Unfortunately, none of the data from previous research related to a bridge in such an exposed location spanning a large sea inlet, and so no estimation of these effects can be provided. The theoretical 1 in 120 year minimum temperatures of various components of the bridge presented in this report have therefore been related to the statistically derived minimum shade temperature of -18°C mentioned above.

The lowest shade temperatures recorded at the bridge, all occurring at approximately 0600h on 27 January 1985, were:

at the top of the NE tower leg :	-4°C;
beneath the deck plates :	-3°C;
at the top of the SW side tower:	-2°C.

Daily maximum shade temperatures recorded at the bridge and at Edinburgh Airport showed better agreement. However, with regard to maximum conditions, there are four further points to consider. The first is that very high temperatures in exposed components of a bridge are more likely to be the result of very high solar radiation than very high shade temperatures. The second is that very high solar radiation does not necessarily occur on the same day as a very high shade temperature (Emerson, 1976b). Thus shade temperature values are less important in the determination of 1 in 120 year maximum temperatures for the components of a bridge than they are for the minimum situation. This is particularly the case for steel constructions.

The third point is that a 1 in 120 year maximum shade temperature is most likely to occur during June, July or early August. While these months might be the times when a horizontal surface could be expected to achieve its highest temperature, this is not necessarily the case for vertical surfaces. For example, as will be discussed more fully later in the report, a south facing vertical surface will receive its highest solar radiation during the months of March and September. These are not the months during which a 1 in 120 year maximum shade temperature can be expected to occur.

The fourth point is that the moderating influence of the sea may have kept maximum temperatures slightly lower than they would have been had the bridge been over land.

The predicted 1 in 120 year maximum shade temperature for the Edinburgh area (Hopkins & Whyte, 1975; British Standards Institution, 1978; Department of Transport, 1988) is 31°C. The highest value of the shade temperature recorded at the bridge was measured beneath the deck plates, and was 26°C. It occurred at 1500h on 19 August 1984. The maximum shade temperature recorded at Edinburgh Airport on 19 August 1984 was 27°C.

A final comment: the thermocouple recording the shade temperature at the top of the NE tower leg appears to have caught the early morning sun, with the result that the recorded temperatures at this time were not strictly 'shade' temperatures. In addition, during the day, the temperatures recorded at this location were higher than the temperatures measured beneath the deck plates, and the temperature trace showed more fluctuation than is normal in the author's experience. Both of these effects are thought to be because of the inevitable convection from the top of the tower leg. As a result, shade temperatures measured at the top of the NE tower leg were rarely used in the data analysis.

4.2 Bridge temperatures: general comments

All of the TRRL research into bridge temperatures published in the past was concerned with the temperatures of exposed horizontal surfaces such as bridge decks, and the variation of temperature in a vertical direction through the depth of the deck. Thus associated temperature differences were also in a vertical direction.

The research confirmed that the environmental factor which has by far the greatest influence on the daytime temperature of a horizontal steel member is the amount of global solar radiation (described in previous work as total solar radiation) incident on the steel (Capps, 1968; Emerson, 1973). This is because the thermal conductivity of steel is high, and, as a result, its temperature can change very quickly. For example, at the Beachley Viaduct/Wye Bridge, where solar radiation was measured on site, variations in the temperature of the steel deck plate were observed as clouds passed across the sun. The shade temperature has a less dramatic influence. The highest steel temperatures occur during clear, hot, sunny, windless days.

During the night the factors of greatest influence are the outgoing radiation to the night sky, and the shade temperature. The lowest steel temperatures occur during clear, cold, windless nights[1].

The global solar radiation incident on a horizontal surface which was used in the earlier research is well documented (Capps, 1968; Emerson, 1973; Jones, 1976, 1977; IHVE, 1970). It related to latitude 52°N, and so a small adjustment has been made to it in this current work to accommodate the 56°N latitude of the Forth Road Bridge.

As well as horizontal surfaces, the measurements at the Forth Road Bridge also involved vertical surfaces and associated temperature differences, these latter being in a horizontal direction. The global radiation incident on north, south, east and west facing vertical surfaces is shown in Figure 6. The source of the data is the Institution of Heating and Ventilating Engineers (IHVE) Guide, Book A (1970). Again the radiation relates to latitude 52°N, and so, when used in the calculations discussed later, it was adjusted to allow for the more northerly location of the bridge.

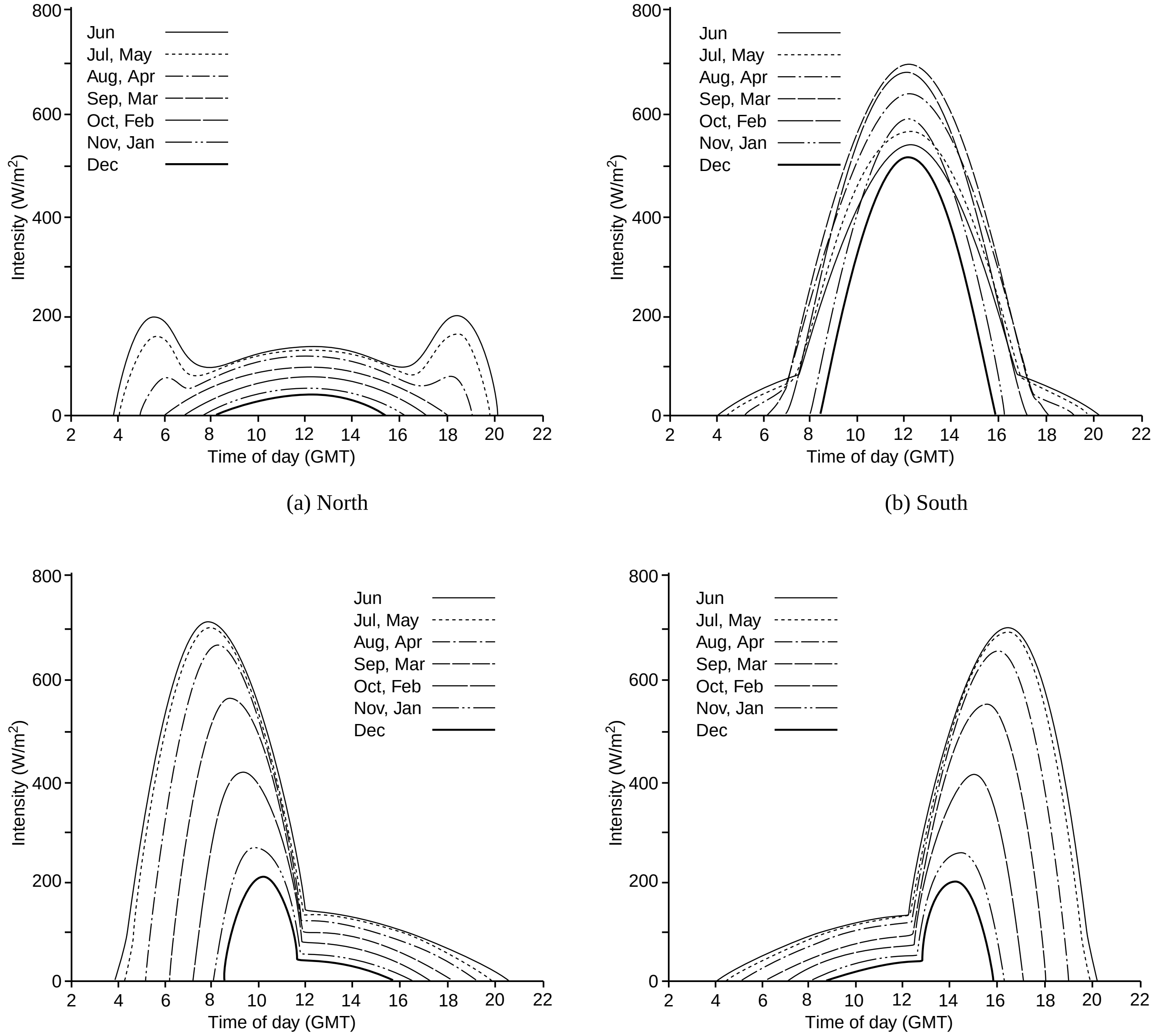
Because of the configuration of the steelwork of the bridge, it was inevitable that the locations of some of the thermocouples would, at different times of the day, fall into shadows cast by other areas of the superstructure. This caused 'blips' of varying degrees of magnitude in the temperature records. As at the Beachley Viaduct/Wye Bridge, other 'blips' were caused by the passage of clouds across the sun.

The temperature information required for the load assessment concerned the highest and lowest measured and calculated temperatures for the various components of the bridge, the magnitudes of large positive temperature differences[2] within or between the components, and 1 in 120 year extreme temperatures. Some general comments are given below, before the temperatures are discussed in more detail in following Sections of the report.

It can be inferred from Figure 6 that on clear, sunny days, the vertical surfaces of the tower legs and of the main chords of the stiffening truss will achieve their maximum temperatures at different times of the day and at different times of the year, depending on their orientation. This means that large temperature differences between, for example, east and west faces[3], will occur not only when the east face is hotter than the west face in the morning, but also when the west face is hotter than the east face in the afternoon. In addition, prior to the measurements being made, it was thought that the largest positive temperature differences[2] would occur only during the spring, summer or autumn months. In the event, the largest positive south/north temperature difference recorded on the SW tower leg occurred during the month of February.

Large reversed temperature differences[2] usually occur during the night - in the hours just before dawn, and they can exist at any time of the year. Some weather conditions, such as a heavy rainstorm during a hot day, can also induce reversed temperature differences. Again, the orientation of the components will have an effect. However, for a steel bridge, reversed temperature differences which occur during the night should rarely exceed 8°C.

Temperature differences of the same magnitude can be caused by more than one combination of environmental conditions, and they can also occur at different levels of temperature. Thus the highest maximum temperature (or the lowest minimum temperature) does not necessarily occur on the same day (or night), or at the same time of the year, as the largest positive or reversed temperature difference. For these reasons it is not easy to assign a return period to the occurrence of large temperature differences.



(a) North (b) South

(c) East (d) West

Figure 6 Global radiation intensity on N, S, E and W faces (IHVE Guide)

Theoretical methods from past work, or developed from past work, have been used to calculate the temperatures of some of the major components of the bridge. The main areas of the original theory which required adjustment for Forth Road Bridge calculations were associated with: (a) the intensity of solar radiation on vertical surfaces of different orientations; (b) the heat loss to the sky from vertical surfaces; (c) the heat gain/loss at both the top and the bottom surfaces of the horizontal deck plates; (d) the heat gain/loss at both the inner and outer surfaces of the vertical sides of the tower legs.

Item (a) was dealt with by using the solar radiation values shown in Figure 6 for vertical surfaces of different orientations. Item (b) was accommodated by consideration of the following argument, to which Note 1 on page 33 also relates:

Heat loss to the sky occurs during both day and night. The temperature of the sky as 'seen' by an exposed surface is very much lower than the temperature of the surrounding environment. This is why, during a cloudless night, the temperature of a surface exposed to the sky can fall below the temperature of the surroundings – for heat is being re-radiated to a 'body' at a much lower temperature. A vertical surface will 'see' less of the sky than a horizontal surface, and so will lose less heat to it. Thus during a clear night, an exposed vertical surface should remain slightly warmer than an exposed horizontal surface facing upwards.

The orientation of a vertical surface (i.e. N, S, E, W, etc.) should have no effect on the amount of heat lost to the sky.

Items (c) and (d) were dealt with by adjustments to the values of the surface heat transfer coefficients which quantify the heat gains/losses by convection and radiation from the various surfaces of the steel. In previous work, values of surface heat transfer coefficients derived from measurements showed good agreement with values published by Billington (1952), and Billington's values were used in the temperature calculations on which current Standards are based. However, these values relate more directly to circumstances where the surface of the body under consideration is not affected by heat loss from any other surfaces of the body – as was the situation for the concrete bridges and some areas of the composite bridge studied in past work. The steel bridge of previous work had a large trapezoidal box deck which was full of still, or poorly circulating air. This meant that the four sides of the box were effectively 'thermally isolated' from each other, for air is a good insulator, and Billington's surface heat transfer coefficients were relevant.

In the case of the Forth Road Bridge, the steel plates forming the outside surfaces of the towers will be subject at their outer surfaces to the usual heat exchange with the environment. However, the air inside the towers will not be still, for variable convection currents will develop as the sides of the towers warm up at different times of the day. In addition the warmest air will rise towards the top of the tower leg. Thus the inner surfaces of the plates will also be subject to heat exchange.

In order to accommodate this situation, heat transfer coefficients for both surfaces were derived from measurements and then combined into a single coefficient (one for each plate of each orientation) for use in the calculations. While the coefficients so derived fell within the ranges of values published by Billington for vertical surfaces of different orientations, they did not always follow the trends of the published values. There is thus a 'degree of uncertainty' attached to the coefficients used in some of the temperature calculations. Further work might help to resolve this problem.

The situation for the main chords of the stiffening truss is slightly different, for the air inside the chords will be either still or poorly circulating. This will reduce the heat flow between the inside faces of the chord. Thus only the heat flow at the external surfaces is of relevance. However, in comparison with a 'full size' bridge deck, the chords are small (approximately 0.61m square in section), and this may have some influence on the temperatures achieved by the four faces.

In addition, it should be remembered that because of the rapid response of steel to changes in solar radiation, the use of solar radiation values which were not measured on site will inevitably introduce errors into the calculations.

However, in spite of these uncertainties, a large proportion of the calculated temperatures showed good agreement with measured values. In some situations calculated temperatures could be used to indicate the level measured temperatures would have achieved had a particular location not been affected by shadow. Where there was satisfactory agreement between theory and measurement, the calculations were extrapolated to determine likely 1 in 120 year maximum temperatures[4].

All calculated temperatures are associated with daytime conditions. This is because from the point of view of the assessment of the bridge, minimum temperatures were not so important, and so no calculations were carried out. However, measured minimum temperatures are identified, and comment is made about the likely values of 1 in 120 year minima[4].

4.3 The suspended superstructure of the main span

4.3.1 Deck panels and other components

4.3.1.1 Measured and calculated temperatures

Some of the highest temperatures measured at the locations shown in Figure 2 are illustrated in Figures 7(a), (b), (c) and (d). It can be seen from Figure 7(a) that the maximum temperature achieved by the deck plate on 31 May 1985 was 39^{o}C (thermocouple 5). This was the highest deck plate temperature measured during the period of recording. The corresponding daily maximum shade temperature was 20^{o}C. Had there been full solar radiation on that day, or had the shade temperature been higher, or both, the maximum temperature achieved by the deck plate would have exceeded 40^{o}C. It should be remembered that 39^{o}C is a temperature measured beneath 50.8mm of steel and surfacing, and that the surface of the surfacing would be hotter than this, possibly by up to 8^{o}C.

Figure 7(a) also shows that there can be a temperature difference approaching 9^{o}C between the deck plate and the base of a trapezoidal stiffener (thermocouples 1 and 3). It can also be seen in both Figure 7(a) and Figure 7(c) that there are differences in temperature between the two deck plates (thermocouples 1 and 5, and 3 and 6) – a situation which had also occurred at the Beachley Viaduct/Wye Bridge. There are a number of possible reasons for such differences. Some examples are: the effect of shadow, the effect of small differences in the thickness of the surfacing system at different locations, and the effect of different orientations of the surface towards the sun.

Figures 7(b) and 7(d) show the temperatures recorded on some of the steelwork below the deck plates. For most of the day these areas are shielded from incident solar radiation, but they are permanently exposed to free-flowing air (as opposed to the poorly circulating air inside a steel box). It is therefore not surprising that their temperatures are much the same as the shade temperature measured beneath the deck plates. The highest measured temperature was 29^{o}C (thermocouple 11). The highest shade temperature recorded beneath the deck plates was 26^{o}C. Both occurred on 19 August 1984, and are shown in Figure 7(d).

Using methods developed for previous work (Emerson, 1973, 1976b, 1977), with adjustments to allow for the circulation of air on both upper and lower faces, the temperature of the deck plate was calculated for a number of sunny days. The solar radiation values used were as for previous work, but with the small adjustment mentioned in Section 4.2 for the more northerly latitude of the bridge. Some of the results are shown in Figures 8(a) and (b). The calculated maximum temperature of the deck plate on 31 May 1985 was 41^{o}C. The temperature of the surface of the surfacing could be up to 8^{o}C higher than this.

Figure 8(a) illustrates one of the difficulties caused by the rapid thermal response of steel to changes in the surrounding environment. At 1230h the solar radiation incident on the deck plate of the northbound carriageway was interrupted, and the deck plate temperature began to fall. The calculated temperatures suggest what might have happened if full solar radiation had persisted. Figure 8(b) shows the agreement which can be achieved between measured and calculated temperatures when sunshine is almost uninterrupted.

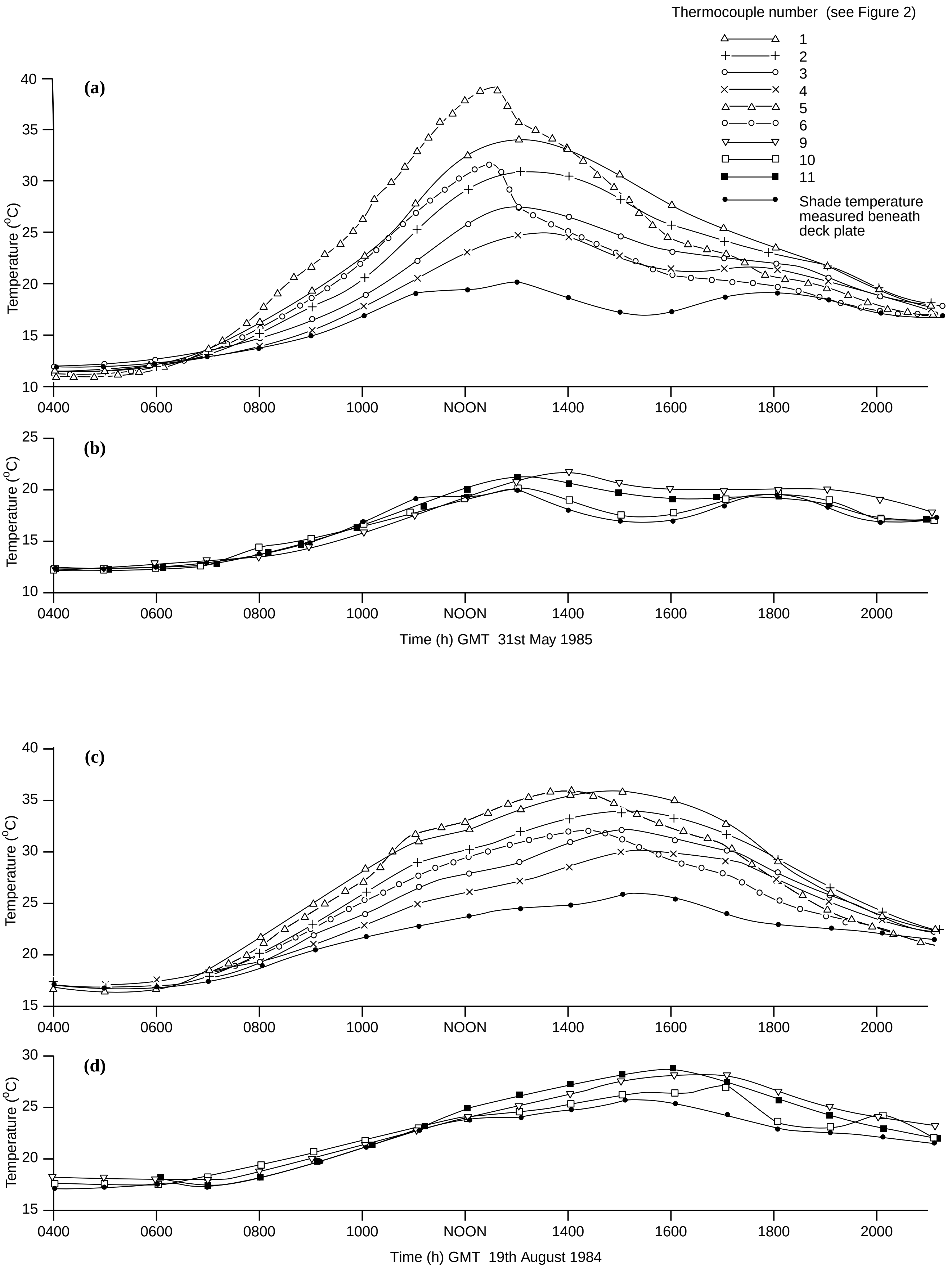
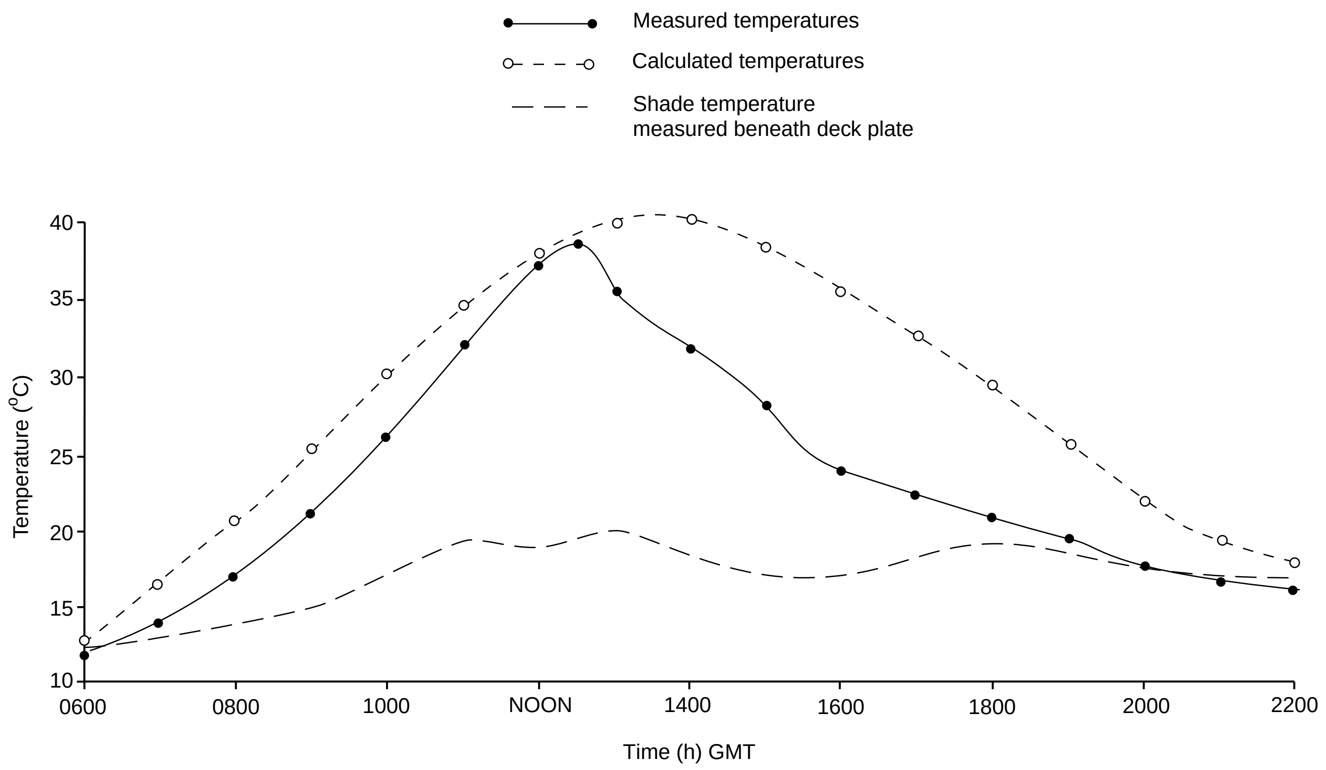
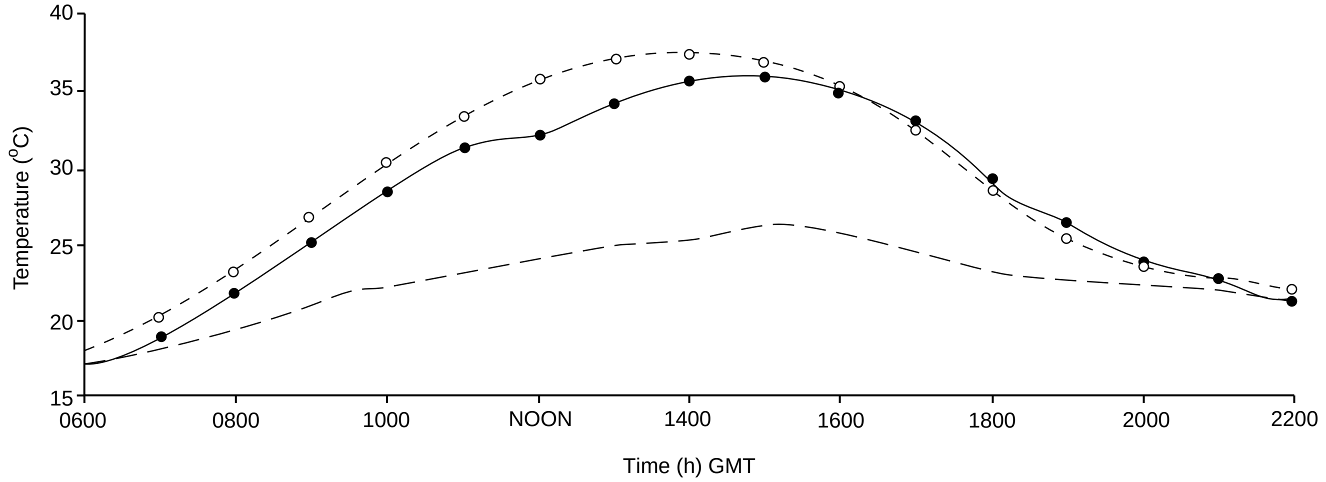


Figure 7 Measured temperatures of deck panels and cross-bracing



(a) 31st May 1985



(b) 19th August 1984

Figure 8 Measured and calculated deck plate temperatures

Temperatures were not calculated for any of the steelwork beneath the deck plates.

During cold nights the temperatures of the deck plates, stiffeners, and all areas of the open truss/plate girder framework were so similar that it was frequently almost impossible to identify the individual traces on the temperature records. It was also frequently impossible to identify the shade temperature, its trace being 'buried' within the traces of the steel temperatures. The lowest recorded steel temperature was -5^{o}C, and it occurred during the early morning of 27 January 1985. The corresponding minimum shade temperature measured beneath the deck plates was also the lowest recorded, namely -3^{o}C.

The range of measured temperatures experienced by the deck plates was 44^{o}C, from -5^{o}C to 39^{o}C. The range of measured temperatures of the steelwork beneath the deck plates (ignoring the stiffeners) was 34^{o}C, from -5^{o}C to 29^{o}C.

Previous research has shown that the calculated minimum temperature of a horizontal deck plate is usually between 5^{o}C and 6^{o}C below the value of the corresponding minimum shade temperature. Thus a calculated minimum temperature of the deck plate for 27 January 1985 would probably be in the region of -8^{o}C.

4.3.1.2 Theoretical 1 in 120 year temperatures

Using previous calculation methods, with amendments as discussed in Section 4.2, the likely 1 in 120 year maximum temperature of the deck plates was determined. The results are shown in Figure 9, where it can be seen that the maximum temperature of the steel plate is 52^{o}C. The maximum temperature of the surface of the surfacing could be at least 8^{o}C higher than this, i.e. in the region of 60^{o}C.

Based on previous work, the likely 1 in 120 year minimum temperature of the deck plates should be in the region of -24^{o}C (i.e. 6^{o}C below the minimum shade temperature for these extreme conditions). However, the comments in Section 4.1 relating to minimum shade temperatures and the moderating influence of the sea should be borne in mind.

The range of theoretical 1 in 120 year temperatures for the deck plate is thus estimated as 76^{o}C, from -24^{o}C to 52^{o}C.

Maximum and minimum 1 in 120 year temperatures for the various components of the open truss/plate girder framework are likely to be in the region of 37^{o}C and -18^{o}C respectively, bearing in mind the comments in Section 4.1 about minimum temperatures. The maximum temperature, 37^{o}C, is derived from 31^{o}C + 4^{o}C + 2^{o}C, i.e. the maximum shade temperature plus the 4^{o}C by which the temperature of the steelwork exceeds the shade temperature in Figures 7(b) and (d), plus 2^{o}C to allow for a 'factor of ignorance' under 1 in 120 year conditions. The minimum temperature of the steelwork is not likely to fall much below the minimum shade temperature of -18^{o}C as the steelwork is shielded by the deck plates and so will not lose heat to the night sky.

The range of theoretical 1 in 120 year temperatures for the steelwork below the deck plate is thus estimated as 55^{o}C, from -18^{o}C to 37^{o}C.

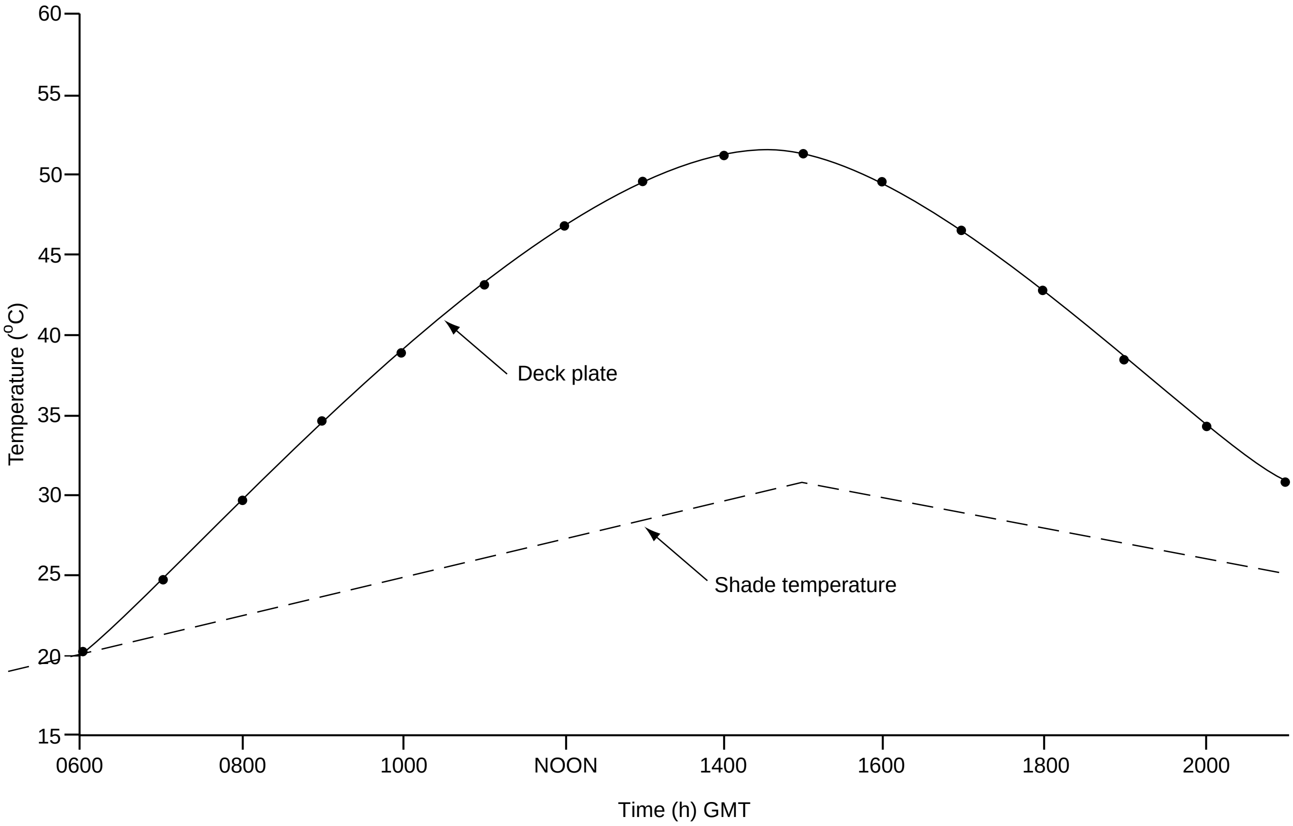


Figure 9 1 in 120 year maximum deck plate temperatures

4.3.2 West upper chord, top and bottom faces

As mentioned in Section 4.2, all the previous research was related to temperatures associated with heat flow in a vertical direction through the horizontal upper and lower surfaces of bridge decks. The top and bottom faces of the west upper chord fit into this category. Thus approaches developed for the earlier work can be applied to these two surfaces, but see also the comments about the size of the chords in Section 4.2.

4.3.2.1 Measured and calculated temperatures, and temperature differences

The configuration of the steelwork, including the parapets (which are not shown in Figure 2), is such that the top face of the chord was more often in shadow than in sun, resulting in daily maximum temperatures which were not particularly high. The highest measured temperature was 36°C, occurring at 1400h on 19 August 1984. It is shown in Figure 10. Also shown in Figure 10 are the calculated temperatures for the top face, assuming that the face is in full sun. The maximum calculated temperature is 49°C. The difference between the measured and calculated maximum temperatures gives some indication of the effect of shadow.

It is interesting to note that the measured maximum temperature for the deck plates on 19 August 1984 was also 36°C (Figure 7(c)), even though the 'thermal environment' of the deck plates is quite different from that of the top face of the chord. The difference in the thermal environments is illustrated when calculated temperatures are compared. As mentioned above, the maximum calculated temperature of the top face of the chord on 19 August 1984 was 49°C, while the maximum calculated temperature for the deck plates, for the same day, was only 37°C, (Figure 8(b)).

There a number of reasons for the difference of 12°C between the two calculated maximum temperatures for horizontal steel for the same day. Two of the main reasons are:

i the deck plates had 38mm of surfacing above them. The maximum temperature of the surface of the surfacing would have been in the region of 45°C;

ii the deck plate/surfacing system would be losing heat from both surfaces. This is not the case for the chords, where the air trapped inside them would have the effect of reducing the heat loss from their inside surfaces. A horizontal plate losing heat from one surface only will achieve a higher maximum temperature than a horizontal plate losing heat from both surfaces.

The bottom face of the chord receives no direct solar radiation. However, warming of the air inside the chord when the other faces are in the sun will raise the temperature of the bottom face a few degrees above the shade temperature. The highest measured temperature of the bottom face occurred on 19 August 1984, and is shown in Figure 10. It was 28°C, occurring at 1600h. Calculation of the temperature of the bottom face gives a maximum value of 32°C, which is also shown in Figure 10. The maximum shade temperature on 19 August 1984 was 26°C.

Measured and calculated positive temperature differences for 19 August 1984 are shown in Figure 11, where it can be seen that the maximum measured difference on that day was approximately 9°C, occurring at 1245h. Calculated positive temperature differences

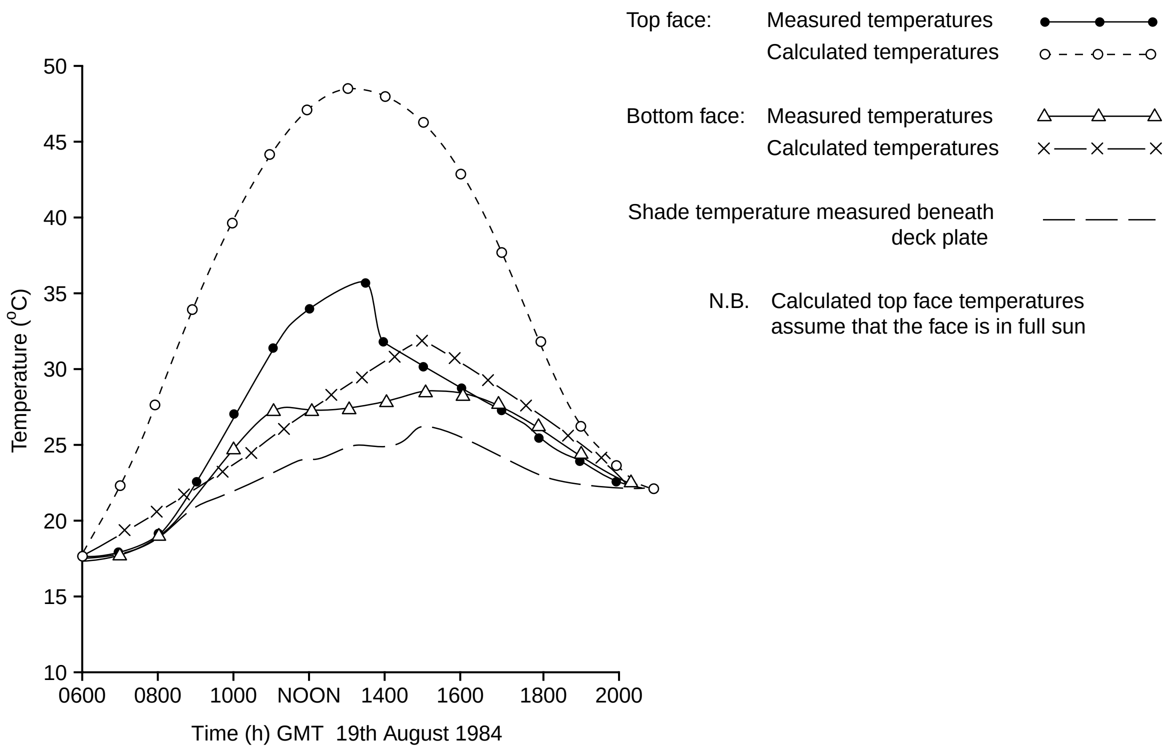


Figure 10 Measured and calculated temperatures of top and bottom faces of west upper chord

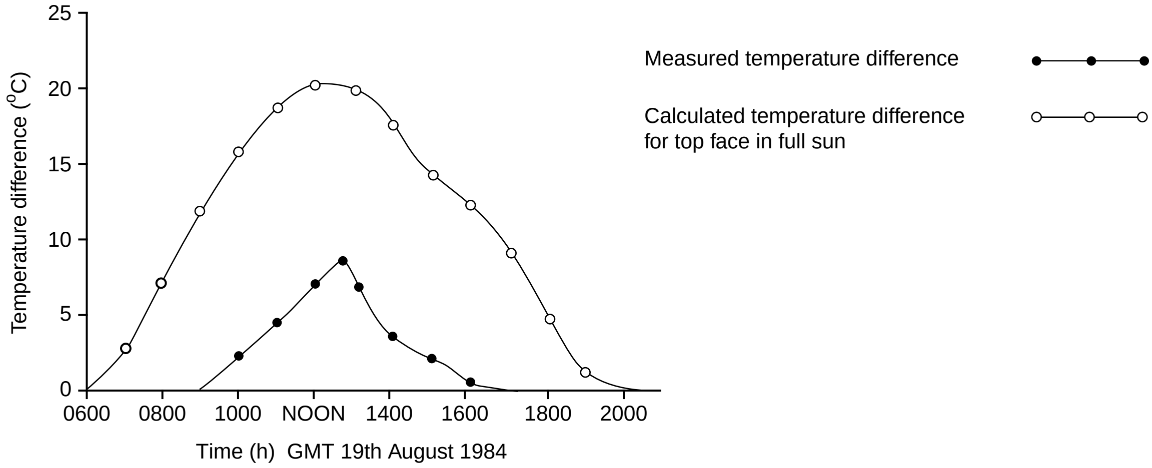


Figure 11 Measured and calculated temperature differences between top and bottom faces of west upper chord

assuming the top face to be in full sun are naturally much larger (maximum value, 20°C), as can also be seen from Figure 11. The difference between the measured and calculated maximum temperature differences again illustrates the effect of shadow.

The largest measured positive difference occurred at 1215h on 22 April 1985. It was 13°C.

Analysis of the records showed that during clear, cold nights, the minimum temperature of the top face of the chord was approximately 2°C below the corresponding minimum shade temperature measured beneath the deck plates. The temperature of the bottom face of the chord was very similar to the shade temperature. The lowest temperatures measured were -5°C for the top face and -3°C for the bottom face. Both temperatures occurred during the early morning of 27 January 1985, when the minimum shade temperature measured beneath the deck plates was -3°C.

Because the temperatures of the top and bottom faces were so similar during cold, clear nights, reversed temperature differences were very small (no more than 2°C to 3°C).

The ranges of measured temperatures for the top and bottom faces of the chord were 41°C for the top face (from -5°C to 36°C, remembering the effect of shadow), and 31°C for the bottom face (from -3°C to 28°C).

4.3.2.2 Theoretical 1 in 120 year temperatures

Using methods described for previous work (Emerson, 1973, 1976b, 1977), 1 in 120 year temperatures were calculated for the top and bottom faces of the chord. The results are shown in Figure 12, where it can be seen that the 1 in 120 year maximum temperatures are, for the top face, approximately 57°C, and for the bottom face, approximately 37°C.

Based on previous work, likely 1 in 120 year minimum values should be in the region of -24°C for the top face and -18°C for the bottom face, bearing in mind the comments in Section 4.1 about minimum shade temperatures and the moderating influence of the sea.

The ranges of theoretical 1 in 120 year temperatures for the top and bottom faces of the chord are thus estimated as 81°C for the top face (from -24°C to 57°C), and 55°C for the bottom face (from -18°C to 37°C).

4.3.3 West lower chord, east and west faces

It can be seen from Figures 6(c) and (d) that east and west facing vertical surfaces receive the greatest amounts of global radiation during the months of April, May, June, July and August. These should therefore be the months when the two faces achieve their highest temperatures, and analysis of the records confirmed that this was the case. Unfortunately there were no occasions when the highest east face temperature occurred on the same day as the highest west face temperature. The east and west face maximum temperatures are therefore reported for different days.

4.3.3.1 Measured and calculated temperatures, and temperature differences

By virtue of its location, it was inevitable that the east face of the chord was in shadow at various times of the day, as consideration of Figure 2 will show. Indeed, the face was in uninterrupted sunshine for only a few brief periods during the morning of a sunny day.

In full sun, an east facing vertical surface will achieve its highest temperature in the early morning, soon after the peak of the incident radiation at approximately 0800h. Unfortunately, this was the time that the location at which the temperature was being measured went into shadow. This can be seen quite clearly in Figure 13, where measured and calculated temperatures during 8 September 1986 are compared.

In previous research, daytime calculations of steel temperatures had been started at 0600h. However, the calculation of the temperature of an east face has necessarily to be started earlier than this, for an east face is exposed to global radiation almost as soon as the sun rises. This earlier calculation starting time is illustrated by the presence of part of the graphs on the left of the temperature axis in Figure 13 (and Figure 16).

The rapid thermal response of steel to global radiation is also illustrated in Figure 13, where it can be seen that the

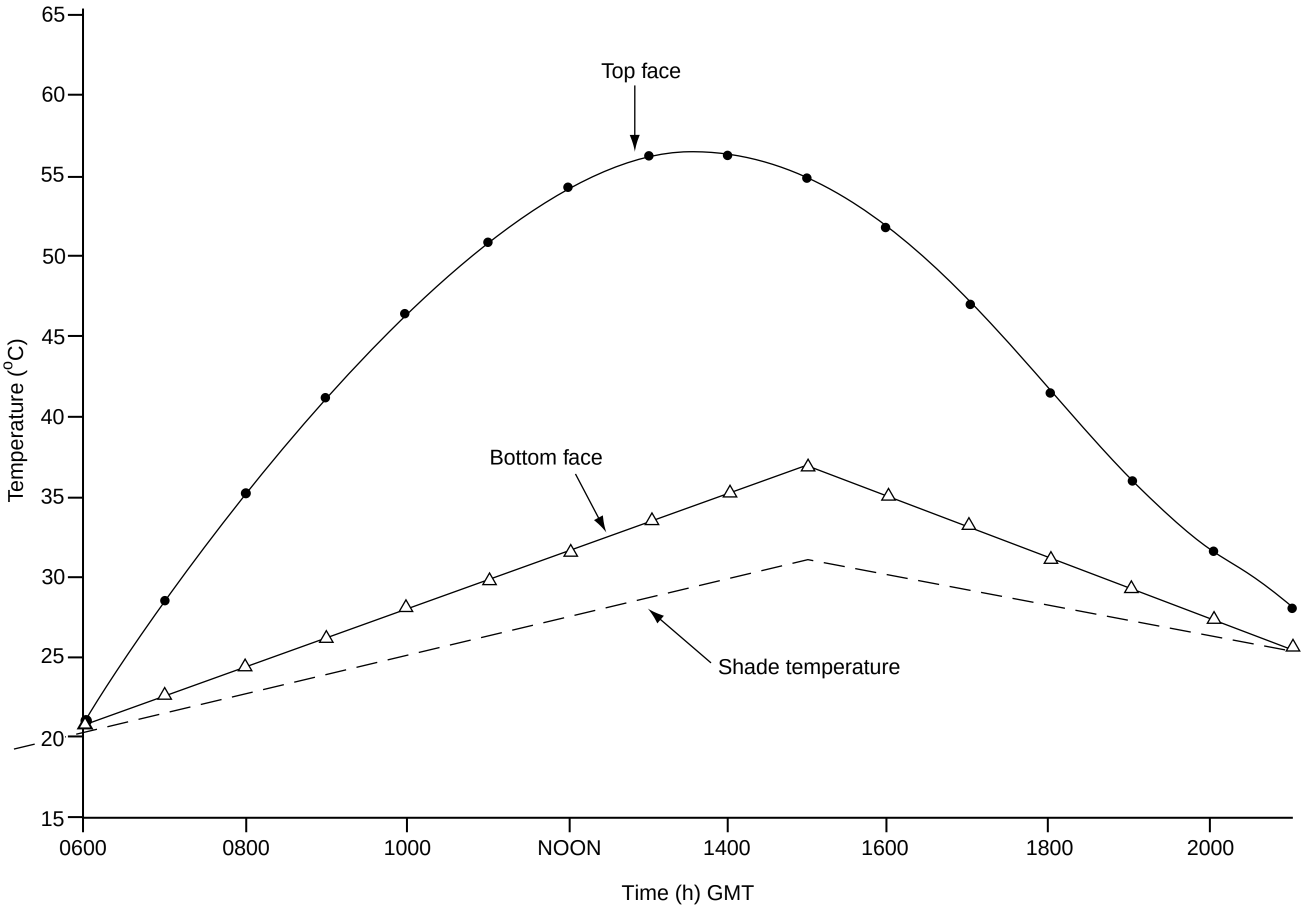


Figure 12 1 in 120 year maximum temperatures: top and bottom faces of west upper chord

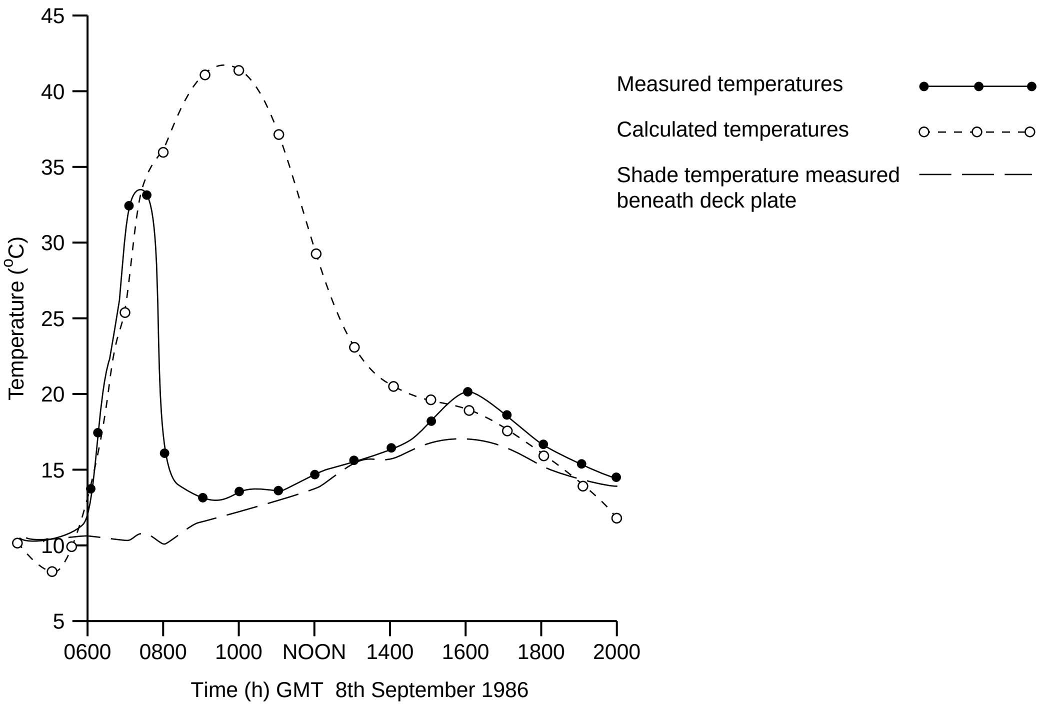


Figure 13 Measured and calculated temperatures of east face of west lower chord

temperature of the steel rose by approximately 23°C in just over two hours. Similar temperature increases also occurred on other days.

Another very much smaller temperature increase which occurred on more than one day can also be seen in Figure 13. It is the small 'peak' in the measured temperatures between approximately 1500h and 1700h. The cause may be an effect already mentioned in Sections 4.2 and 4.3.2.1, namely the influence of the temperature of another face of the chord – in this case probably the west face. On a sunny day the maximum temperature of the west face will occur at approximately 1700h.

The east face temperature of 33°C shown in Figure 13 was the highest that was recorded. It occurred at 0730h. However, it can be seen from the calculated temperatures that had the face remained in full sun, it might have achieved a temperature approaching 42°C. For comparison, the highest temperature recorded on the east face of the SW tower leg (which also went into shadow in the early morning) was 39°C, occurring in the months of July and August (see Section 4.4.1).

Apart from periods when in the shadow of the cantilevered cycle track and footpath, the west face is relatively unobstructed. An example of the temperatures measured during a warm, sunny day is shown in Figure 14. The temperature of 52°C, occurring at approximately 1730h on 3 September 1986, was the highest recorded. For comparison, the highest measured temperature of the west face of the SW tower leg was 51°C (see Section 4.4.1).

The value of the shade temperature at the time the steel achieved its maximum temperature of 52°C was 18°C.

Calculated steel temperatures are also shown in Figure 14. The maximum calculated value was 53°C. While there is good agreement between measured and calculated maximum temperatures, it can be seen from the shape of the graph of measured temperatures that there was not full sunshine on the day. This accounts for the less good agreement between measured and calculated temperatures at other times of day. Calculations for some other days (not illustrated) showed better agreement with measurements, but the temperatures were not as high.

A further example of the rapid thermal response of steel can be seen in Figure 14, with another temperature rise of 23°C in two hours. An even more rapid response occurred on 11 September 1986, when the steel temperature rose approximately 30°C in 1.5 hours.

One of the largest measured temperature differences between the east and west faces, with the east face the hotter, was 21°C. (It is not illustrated.) However, because of the problem of the east face going into shadow, actual temperature differences experienced by the chord will be in excess of this. One of the largest measured temperature differences with the west face the hotter was 29°C, occurring on 3 September 1986. It is illustrated in Figure 15.

Calculated temperature differences for 3 September 1986, for both the east face the hotter and the west face the hotter, are also shown in Figure 15. Full sun was assumed for both calculations. The maximum differences are 30°C and 35°C respectively.

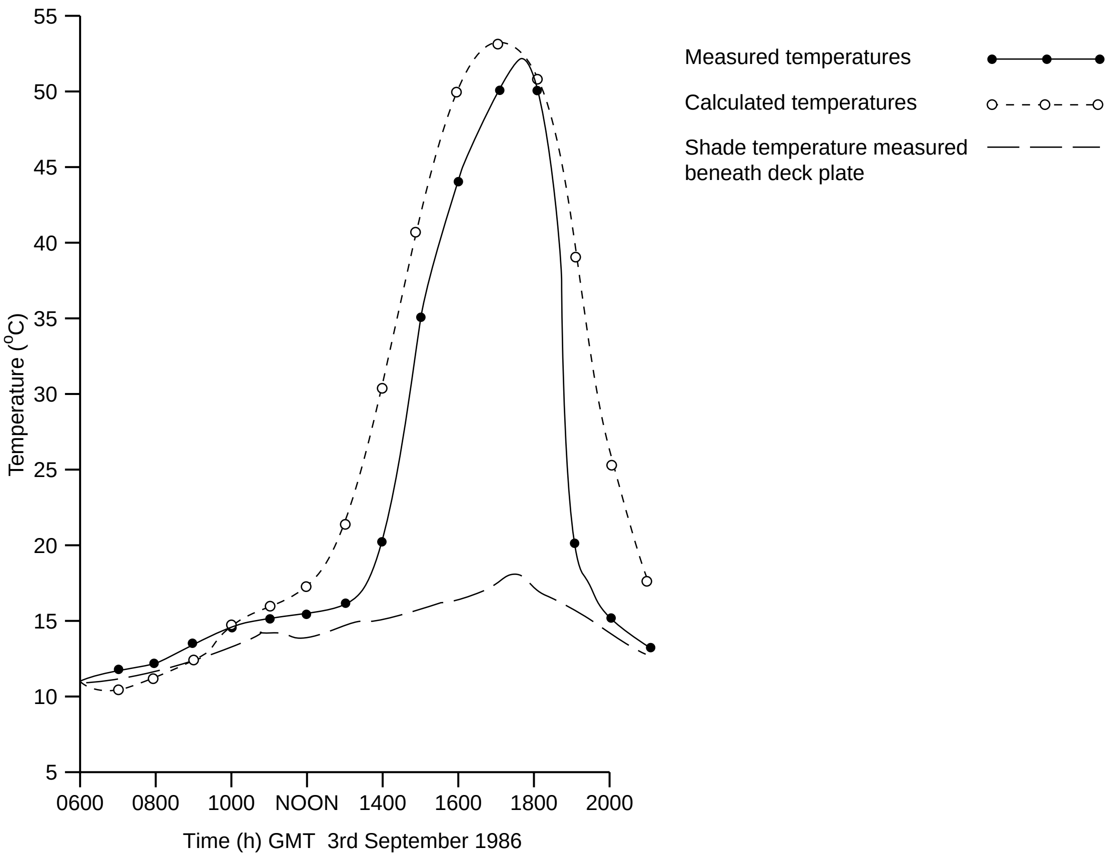


Figure 14 Measured and calculated temperatures of west face of west lower chord

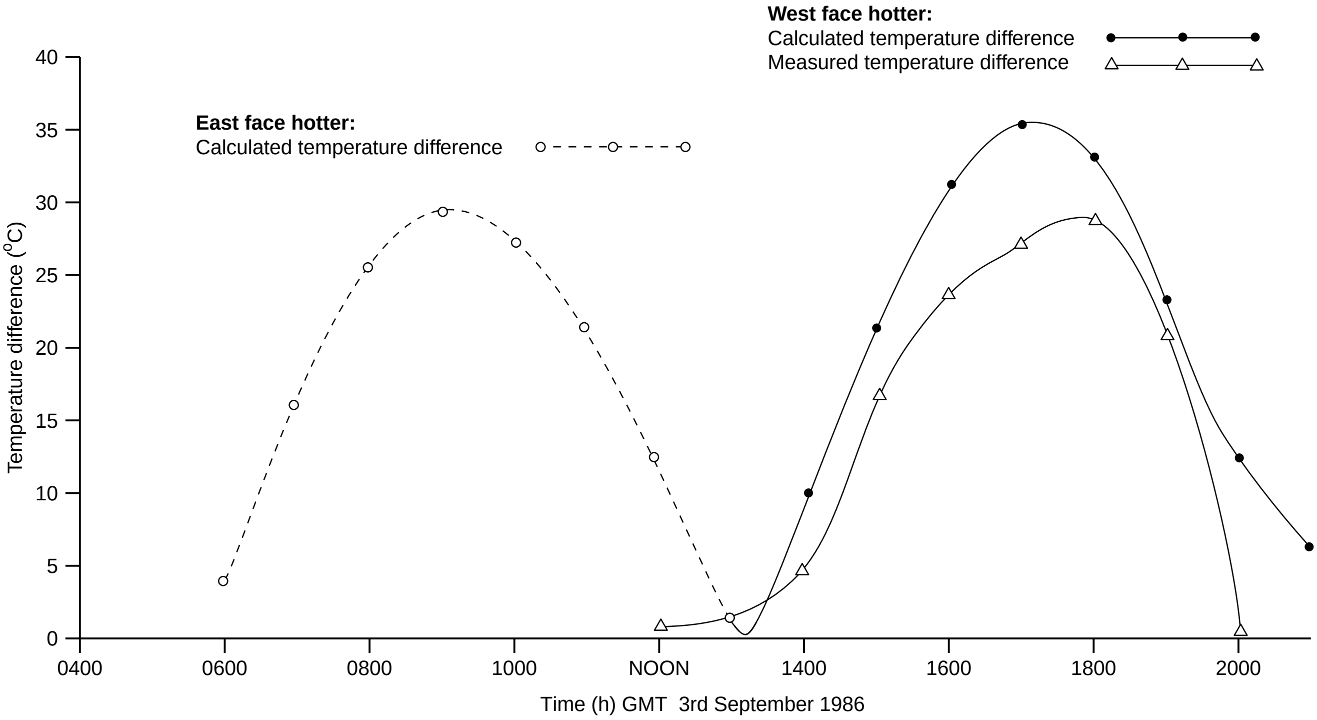


Figure 15 Measured and calculated temperature differences between east and west faces of west lower chord

Analysis of the temperature records showed that during cold, clear nights, the minimum temperatures of the east and west faces of the chord were both within 2°C to 3°C of the corresponding minimum shade temperature measured beneath the deck plates. The lowest temperature recorded on both faces was -4°C, occurring during the early morning of 27 January 1985. The minimum shade temperature at this time was -3°C.

The ranges of measured temperatures experienced by the east and west faces of the chord were 37°C for the east face (from -4°C to 33°C, remembering the effect of shadow), and 56°C for the west face (from -4°C to 52°C).

4.3.3.2 Theoretical 1 in 120 year temperatures

The calculations were carried out assuming that the 1 in 120 year maximum temperatures of both the east face and the west face occurred on the same day. The solar radiation used was as shown in Figures 6(c) and (d) for the month of June. The results are illustrated in Figure 16, where it can be seen that the 1 in 120 year maximum temperature for the east face is 57°C and for the west face is 65°C. It should be remembered that the calculations assumed that neither face was affected by shadow.

The heat lost by re-radiation to the night sky will be less for a vertical face than for a horizontal face. Therefore the temperature of a vertical face will be depressed below the minimum shade temperature by a smaller amount. (For a horizontal surface, a depression of approximately 6°C occurs during very extreme conditions.) Thus the likely 1 in 120 year minimum temperature of both faces is estimated as being in the region of -21°C. The comments in Section 4.1 about minimum shade temperatures are relevant.

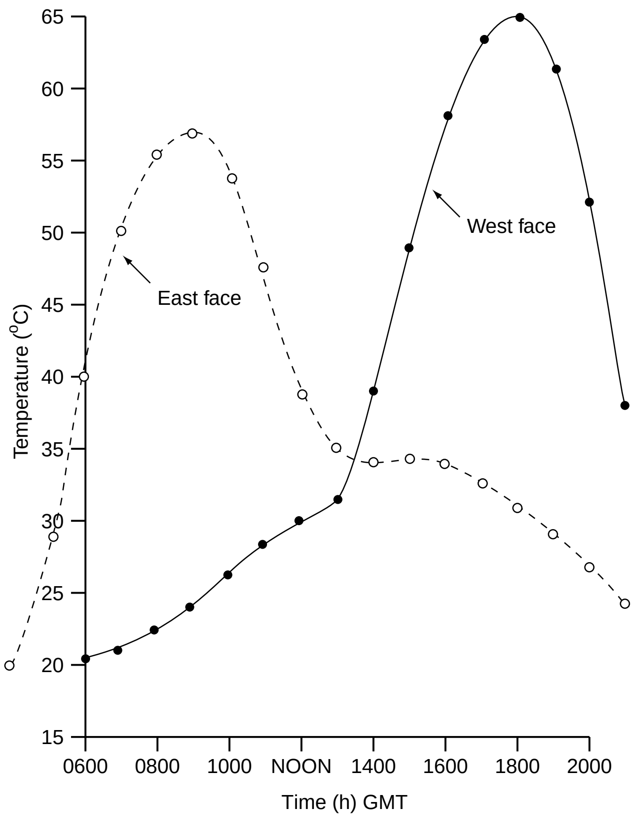


Figure 16 1 in 120 year maximum temperatures: east and west faces of west lower chord

The ranges of theoretical 1 in 120 year temperatures for the east and west faces of the chord are estimated as 78°C for the east face (from -21°C to 57°C), and 86°C for the west face (from -21°C to 65°C).

4.4 The SW tower leg

4.4.1 Measured and calculated temperatures, and temperature differences

It can be seen from Figure 6(a) that a north facing surface receives the highest intensities and highest daily totals of global solar radiation during the months of May, June and July. Corresponding months for a south facing surface are February, March, September and October, as shown in Figure 6(b). These months should therefore be the times during which the north and south faces of the tower leg achieved their maximum temperatures. Analysis of the temperature records showed that this was indeed the case.

As was the case for the east and west faces of the west lower chord, the east and west faces of the tower leg achieved their maximum temperatures during the summer months. This is in accordance with the solar radiation values shown in Figures 6(c) and (d). Unfortunately the locations at which the east face temperatures were being measured went into shadow during the early morning, and this affected the maximum temperatures achieved. The west face was unobstructed.

It can be seen from Figure 3 that temperatures were measured at four locations on each of the east and west faces. The temperatures recorded showed some differences within each group of four, particularly on sunny days. For the purposes of this report, the temperatures of the east and west faces of the centre box (thermocouples 6 and 5 respectively) have been used in the analysis of the results.

Examples of temperatures measured during a clear, sunny day are shown in Figure 17 for the north and south faces, and in Figure 18 for the east and west faces. The two days illustrated are not the days during which the highest measured temperatures were achieved.

The highest measured temperatures were:

north face, 28°C;

south face, 45°C;

east face, 39°C, (remembering the effect of shadow);

west face, 51°C.

The temperatures of the vertical faces of the SW tower leg were calculated for a number of sunny days. Results for two of these days can be seen in Figures 17 and 18, where they are compared with measured temperatures. The agreement is good. The effect of the east face falling into shadow is clearly illustrated in Figure 18.

The measured temperature differences between the north/south and east/west faces on the two days illustrated

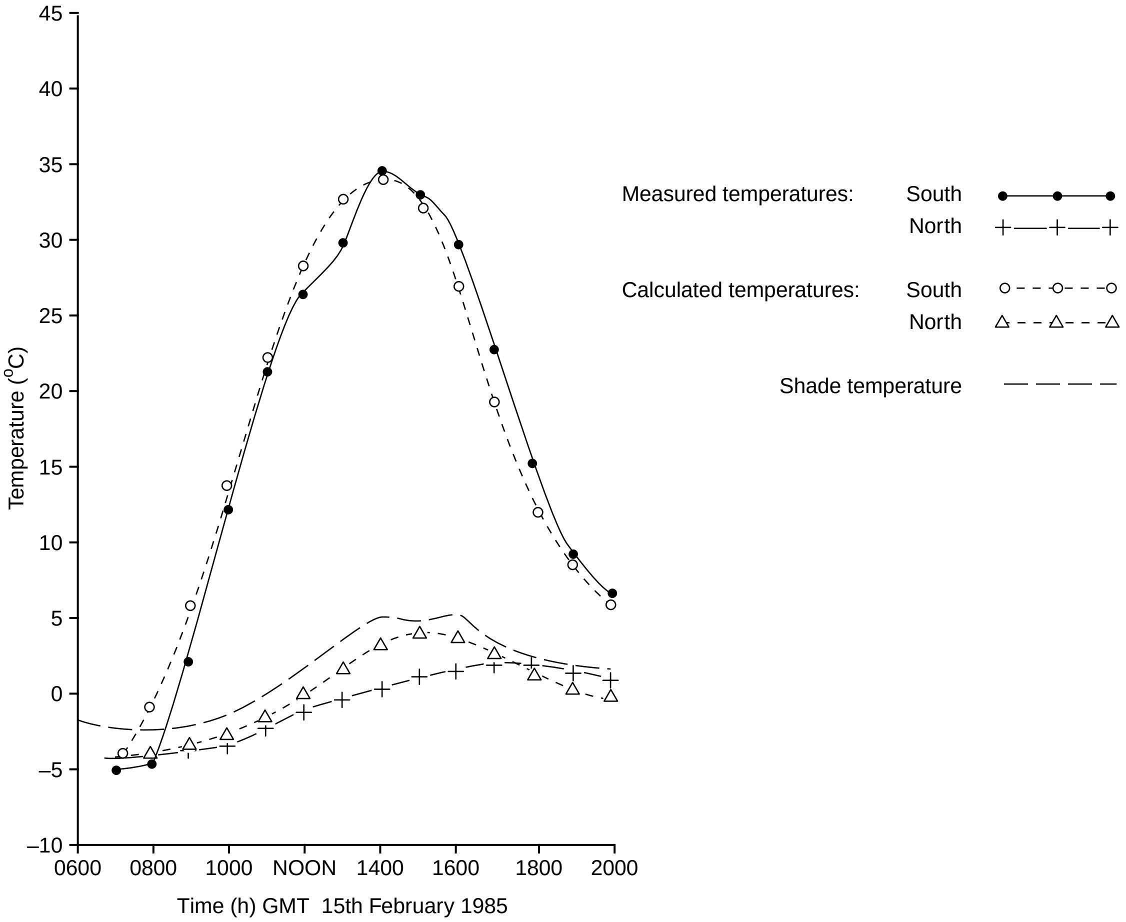


Figure 17 Comparison of measured and calculated temperatures: north and south faces: SW tower leg

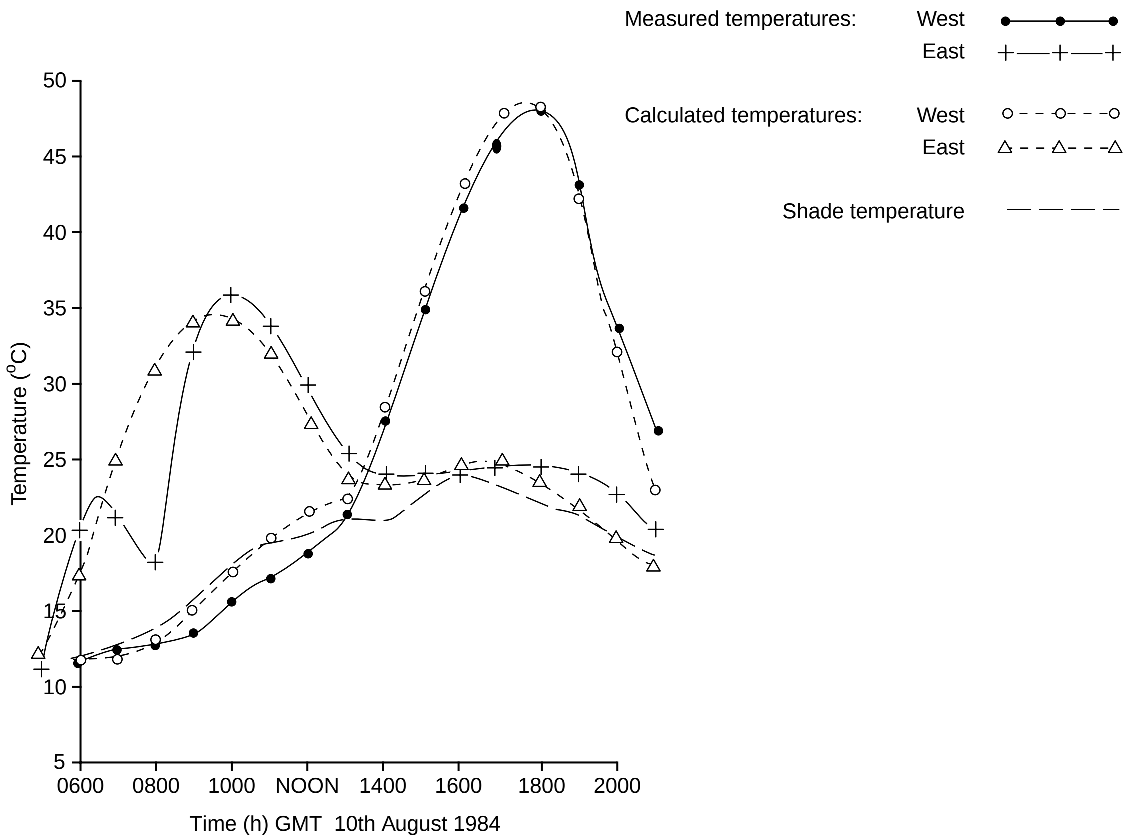


Figure 18 Comparison of measured and calculated temperatures: east and west faces: SW tower leg, centre box

in Figures 17 and 18 are shown in Figures 19 and 20 respectively, where it can be seen that:

a a temperature difference of 35°C occurred between the north and south faces on 15 February 1985. The south face was at the higher temperature. It was the largest measured difference;

b a temperature difference of 20°C (remembering the effect of shadow) occurred between the east and west faces during the morning of 10 August 1984. The east face was at the higher temperature. The largest measured temperature difference with the east face the hotter was 24°C. It occurred during March 1986;

c a temperature difference of 24°C occurred between the east and west faces during the afternoon of 10 August 1984. The west face was at the higher temperature. It was the largest measured difference.

Temperatures were also measured on some of the internal plates of the tower leg, and on one of the stiffeners. The locations are identified in Figure 3. The temperatures recorded at these locations on 15 February 1985 are shown in Figure 21(a), and a diagrammatic representation of the temperature differences between them is shown in Figure 21(b). For completeness, the temperatures of the north and south external faces of the tower leg have also been included.

During the winter months, the lowest temperature recorded on all four faces of the tower leg was -6°C. It occurred at 0600 ± 1h on 27 January 1985. The air temperature inside the centre box at 0600h on this date was -4°C. The minimum shade temperature measured below the deck plates was -3°C.

From the information given above, it can be seen that during the period of recording, the four faces of the tower leg experienced the following ranges of temperature:

north face: 34°C, from -6°C to 28°C;

south face: 51°C, from -6°C to 45°C;

east face: 45°C, from -6°C to 39°C (remembering the effect of shadow);

west face: 57°C, from -6°C to 51°C.

Some of the data on the tower leg temperatures have already been published (Simpson, 1991).

4.4.2 Theoretical 1 in 120 year temperatures

The calculation of 1 in 120 year maximum temperatures is not straightforward. For example, the highest totals of solar radiation incident on a south face occur during February, March, September and October, and so the highest steel temperatures are likely to occur during these months. However, the highest shade temperatures usually occur during June, July, or August. Thus to use a 1 in 120 year maximum shade temperature in the calculations of the temperature of a south face would result in temperatures which are too high. (See also the comments in Section 4.2.)

The highest shade temperature recorded during the month of September at Edinburgh Airport between 1951 and 1980 is 25°C, (Meteorological Office, 1982). The 1 in 120 year maximum shade temperature for the Edinburgh area is 31°C. The maximum value of the shade temperature used in the calculation of '1 in 120 year' maximum temperatures for the

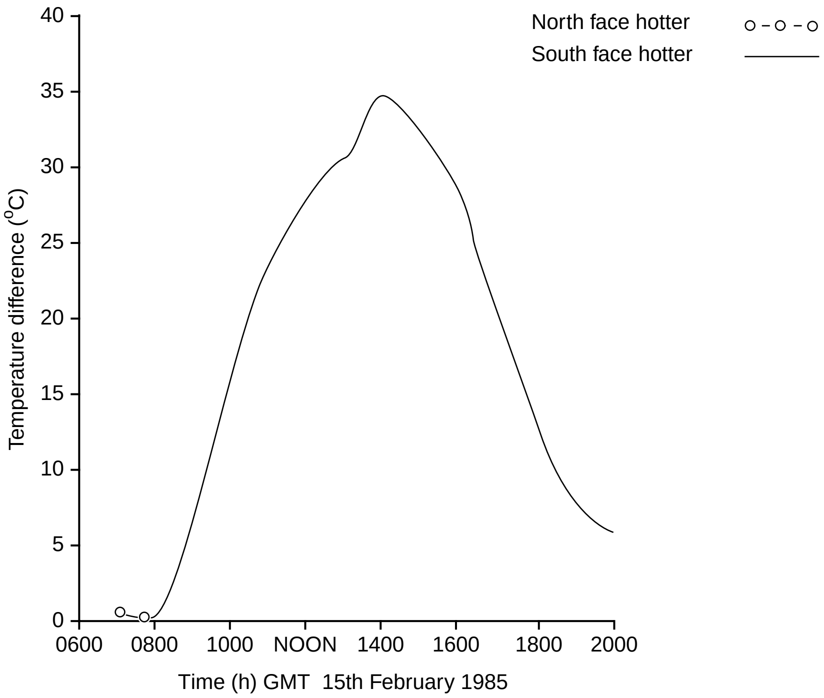


Figure 19 Measured temperature differences between north and south faces: SW tower leg

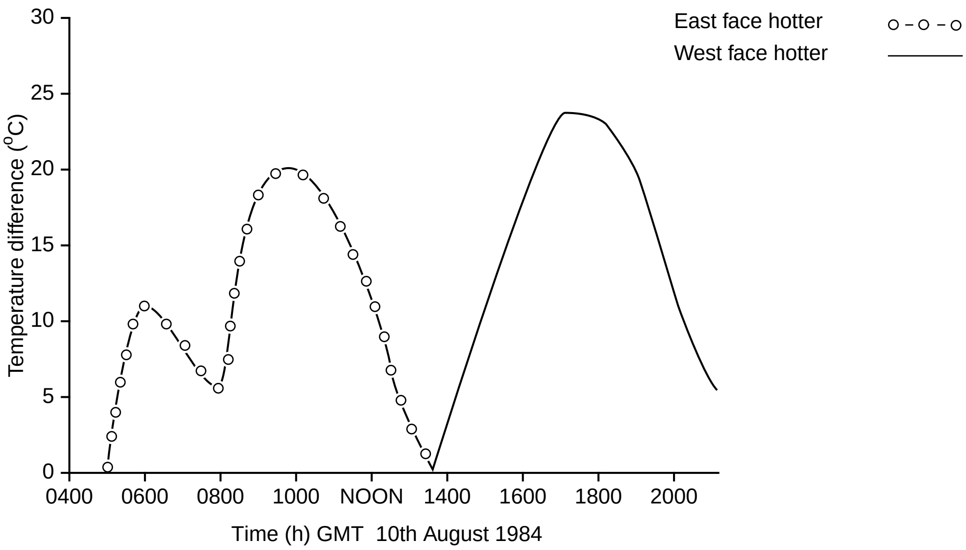


Figure 20 Measured temperature differences between east and west faces: SW tower leg, centre box

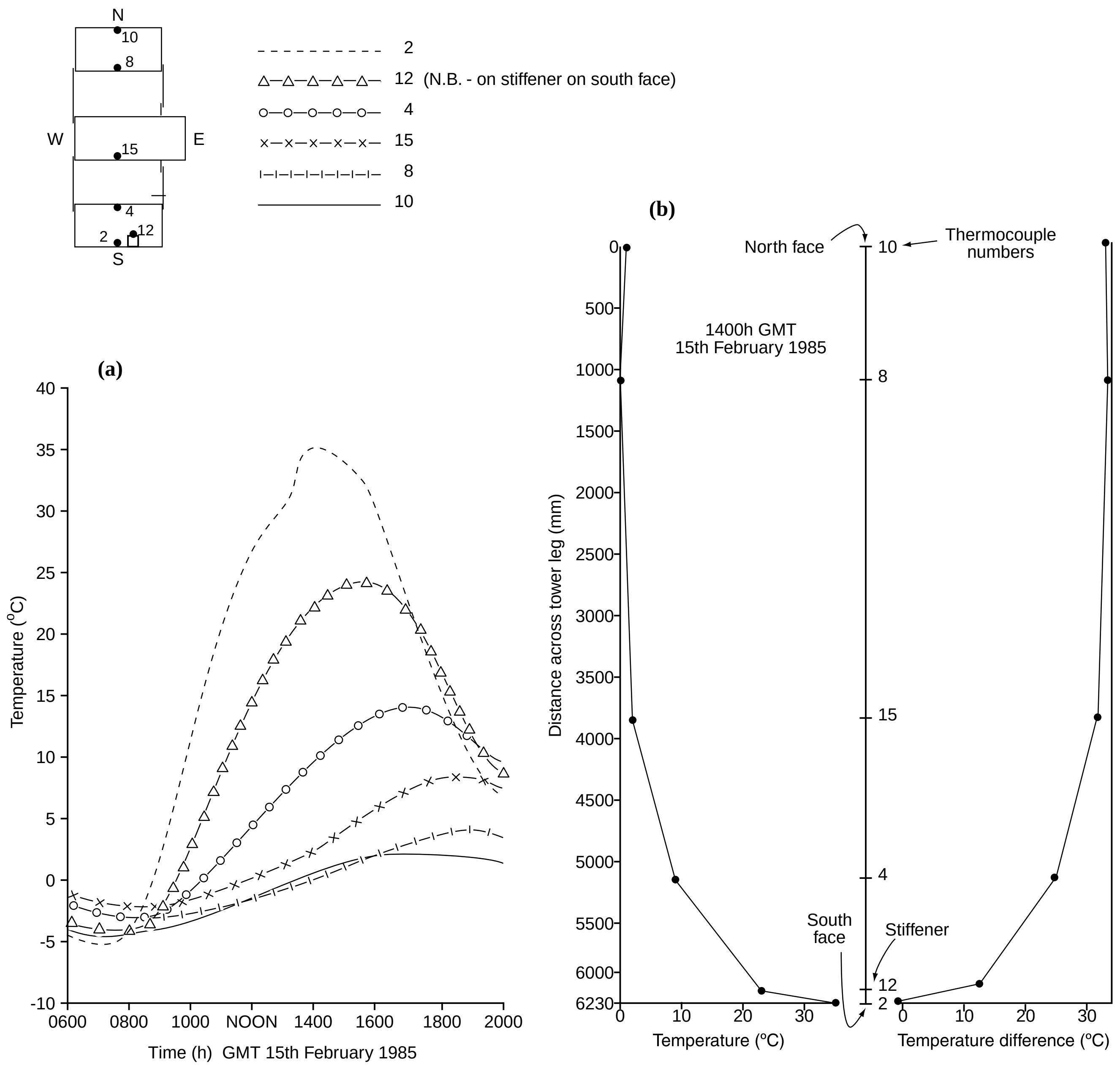


Figure 21 Temperature distributions and differences: north to south: SW tower leg

south face was taken as the average of these two temperatures, namely 28°C. It is thus neither a statistically based value, nor a true 1 in 120 year value.

For the north, east and west faces, the highest solar radiation values occur during May, June and July. There is more chance of a 1 in 120 year maximum shade temperature occurring during these months.

The calculated temperatures for combinations of environmental conditions which it is thought might result in 1 in 120 year maximum values are shown in Figure 22 for all four faces of the tower leg. It can be seen from Figure 22 that the highest temperatures are:

for a north face: 33°C;

for a south face: 62°C [5];

for an east face: 51°C;

for a west face: 59°C.

The reservations expressed in Section 4.2 regarding the values of the surface heat transfer coefficients should also be remembered.

The 1 in 120 year minimum shade temperature for the Edinburgh area is -18°C. Using the argument given in Section 4.2 about minimum temperatures for vertical surfaces, it could be expected that the minimum temperature experienced by the steel plates on all four faces of the tower leg would be in the region of -21°C. The observations of Section 4.1 about minimum shade temperatures should also be borne in mind.

The overall ranges of temperature resulting from these 1 in 120 year conditions are:

north face: 54°C, from -21°C to 33°C;

south face: 83°C, from -21°C to 62°C [5],

east face: 72°C, from -21°C to 51°C;

west face: 80°C, from -21°C to 59°C.

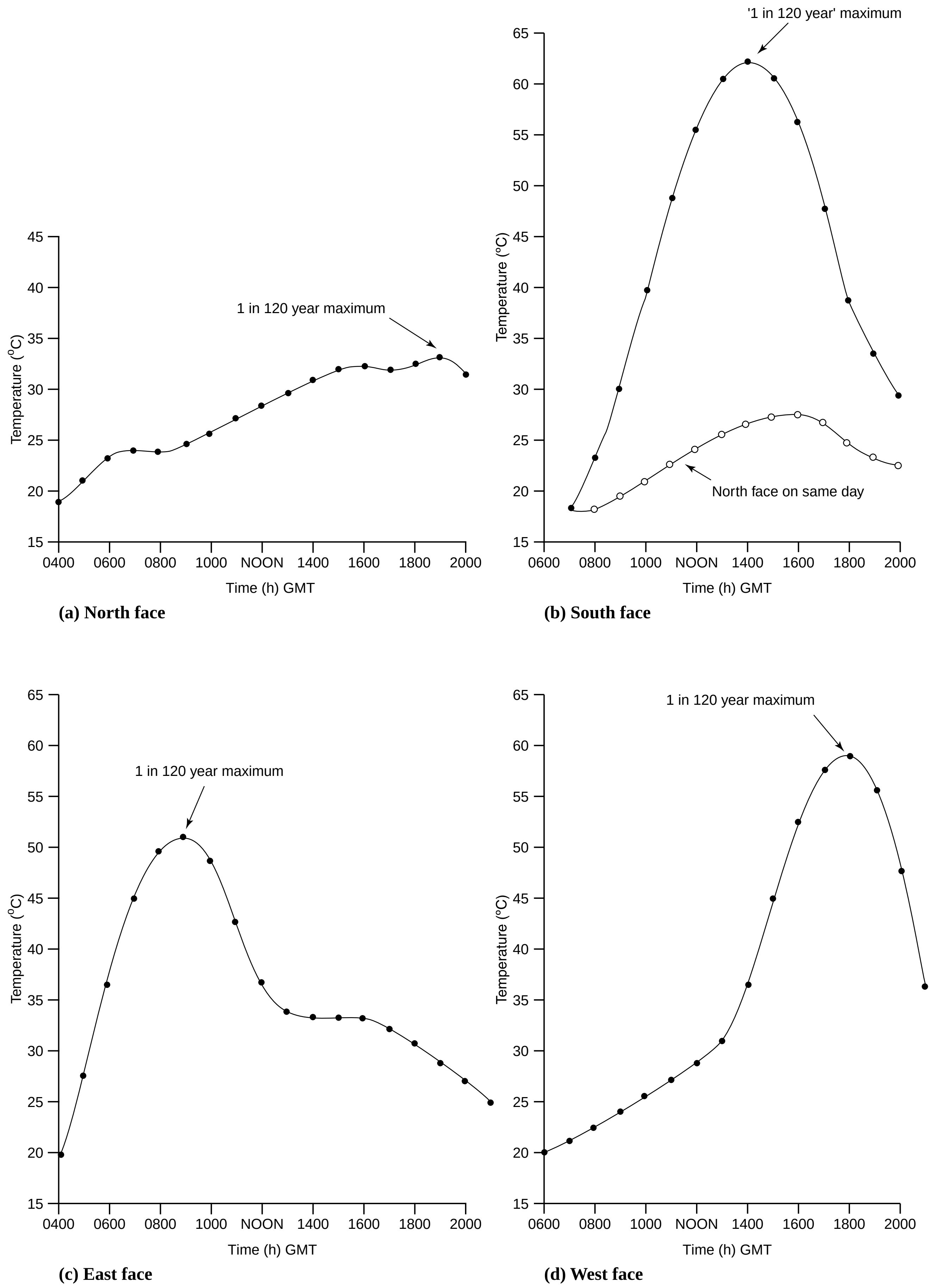


Figure 22 Calculated temperatures: 1 in 120 year maximum conditions: SW tower leg

4.5 The main suspension cables and the hangers

4.5.1 The east side main suspension cable

It can be seen from Figure 4(a) that the interior of the cables is complex, and it is mentioned in Section 2.4 that about 20 per cent of each main suspension cable is made up of voids. In addition, the cables have a longitudinal curve as well as a circular cross-section. This means that the orientation of the cables to the sun varies both along their lengths and around their circumferences. The temperature of the cables will thus vary along their lengths as well as around their circumferences.

Because of the above factors no attempt was made to calculate any temperatures of the cable, or to predict 1 in 120 year temperatures. Measured temperatures only are presented below.

4.5.1.1 Measured temperatures and temperature differences

The two locations at which the temperature of the main suspension cable on the east side of the bridge was measured are shown in Figure 5(a). The positions of the four thermocouples at each location are also shown.

Examples of the variation in the temperature of the outer surface of the cable are shown in Figures 23(a), (b) and (c) for two days during which high temperatures occurred. Figure 23(a) relates to 10 August 1984, and shows the

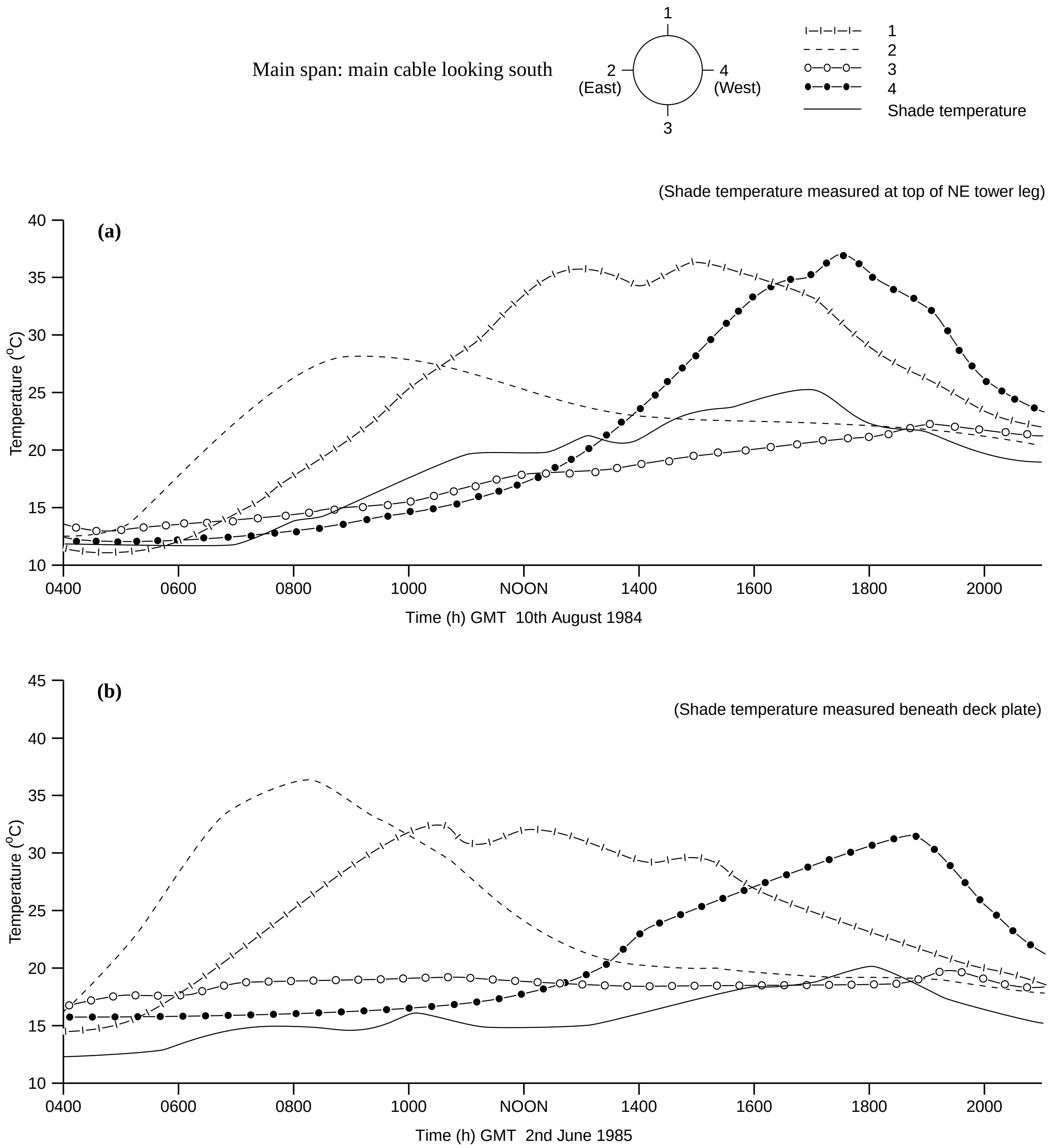


Figure 23 (a and b) Main cable temperatures

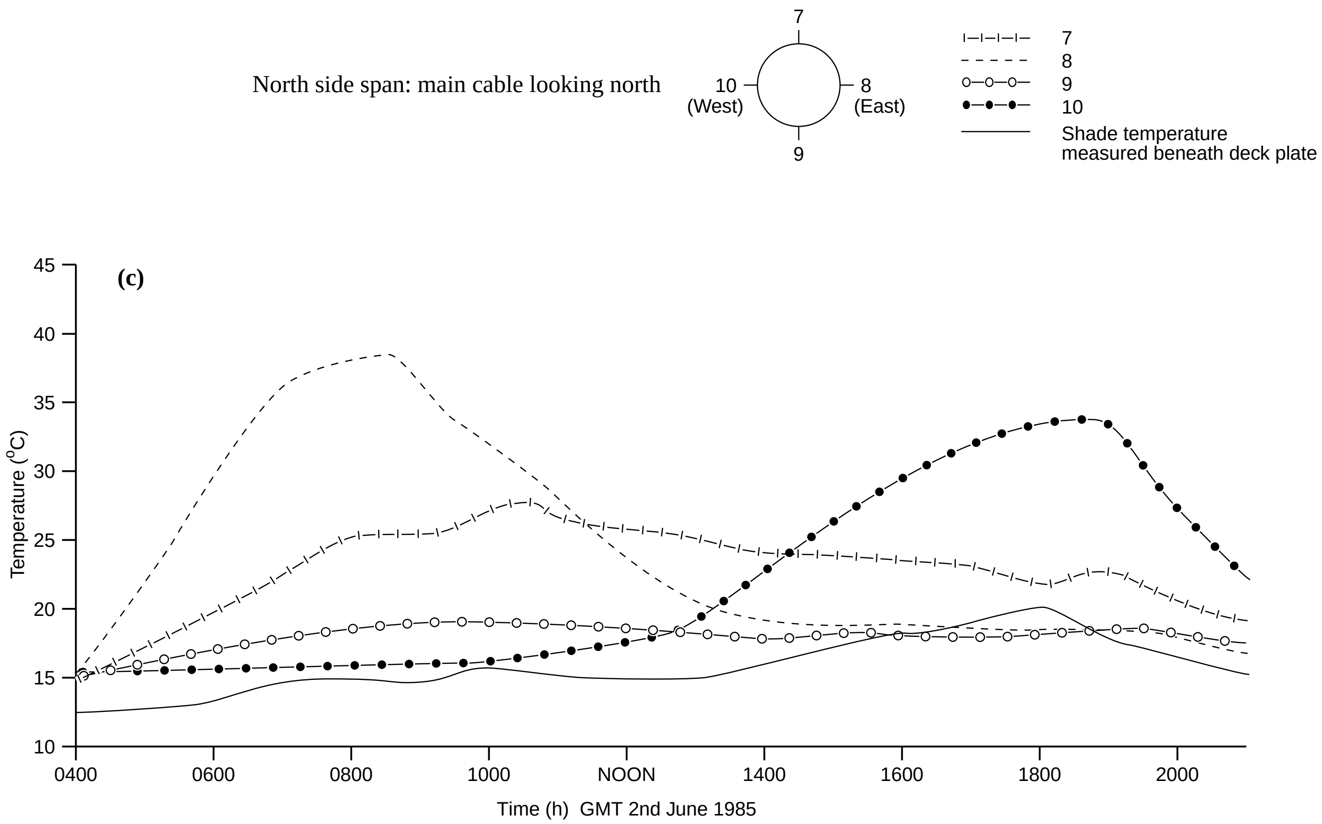


Figure 23 (c) Main cable temperatures

temperatures of the main span section of the cable only. Figures 23(b) and (c) both relate to 2 June 1985, and show the temperatures of the main span and north side span sections of the cable respectively.

A point to note is the difference in the mid-day temperatures measured at the two locations on the upper surface of the cable. In the side span the upper surface is oriented towards the north, and so achieves a lower maximum temperature than the upper surface of the main span cable, which is oriented towards the south.

The temperatures shown in Figures 23(a), (b) and (c) do not include all the highest that were measured. The highest measured temperatures were:

main span:

upper surface, 38°C (oriented towards the south);

lower surface, 23°C;

east surface, 39°C;

west surface, 37°C.

north side span:

upper surface, 29°C (oriented towards the north);

lower surface, 21°C;

east surface, 40°C;

west surface, 34°C.

It should be remembered that because of the variability of the orientation of the cable to the sun, it is likely that temperatures higher than those listed above occurred at other locations on the cable.

The variations in the differences in temperature between the upper/lower and east/west surfaces at each of the two locations on the cable are shown in Figures 24(a) and (b) for the same two days. They are not necessarily the largest measured differences.

The largest measured differences were:

main span:

19°C between the upper and lower surfaces, with the upper surface the hotter;

22°C between the east and west surfaces, with the east surface the hotter;

15°C between the east and west surfaces, with the west surface the hotter.

north side span:

9°C between the upper and lower surfaces, with the upper surface the hotter;

24°C between the east and west surfaces, with the east surface the hotter;

16°C between the east and west surfaces, with the west surface the hotter.

The average temperatures at each of the two locations on the cable were calculated by adding up the four temperatures measured at each location, and dividing each total by four. The temperatures so derived are shown in Figures 25(a) and (b) for the two days illustrated in Figures 23 and 24. The average temperature of 28°C which occurred at 1600h on 10 August 1984 was the highest recorded.

It can also be seen that the average cable temperature in

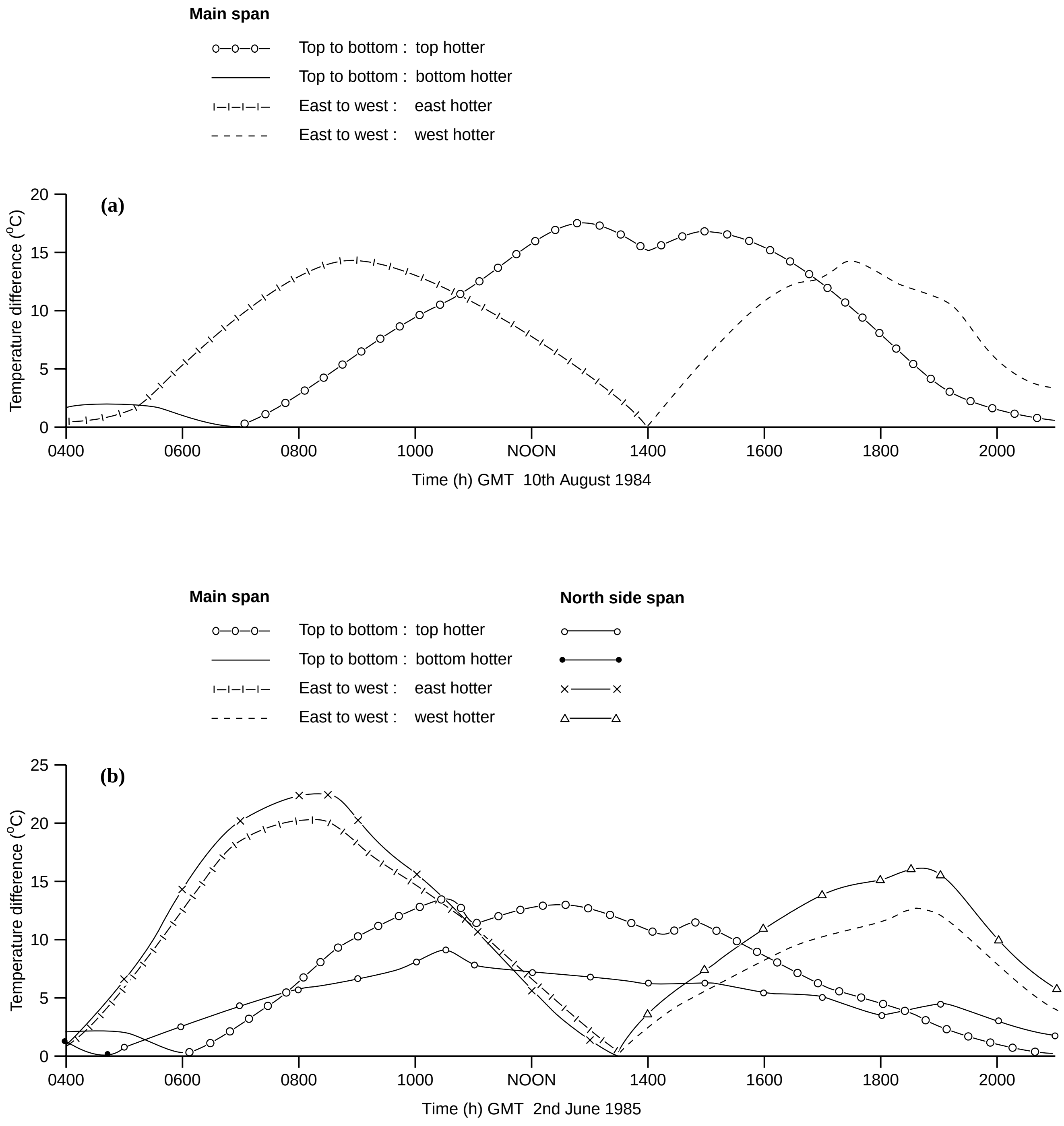


Figure 24 Temperature differences across main cable

both spans was consistently higher than the shade temperature. A further example of this is shown in Figure 26. The temperature difference of approximately 10°C between the average cable temperature and the shade temperature was one of the largest recorded.

The lowest minimum temperature recorded at all eight of the thermocouple positions was -4°C, occurring in the early morning of 27 January 1985. The corresponding minimum shade temperatures were -4°C at the top of the NE tower leg, and -3°C beneath the deck plates.

The overall range of the average temperature of the main span cable was 32°C (from -4°C to 28°C). The overall ranges of temperature experienced by the surface of the cable were:

main span:

upper surface, 42°C, from -4°C to 38°C;

lower surface, 27°C, from -4°C to 23°C;

east surface, 43°C, from -4°C to 39°C;

west surface, 41°C, from -4°C to 37°C.

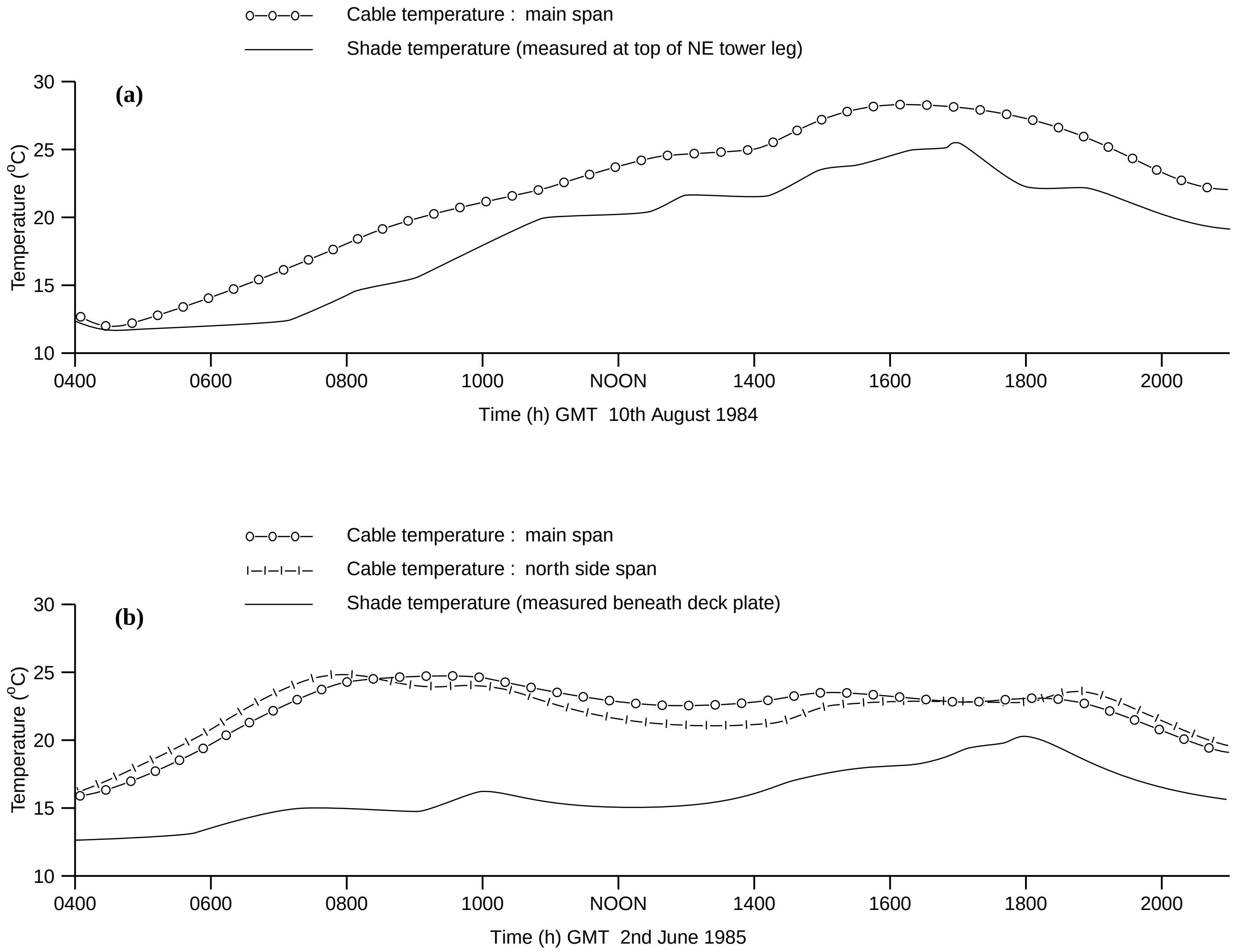


Figure 25 Average temperature of main cable

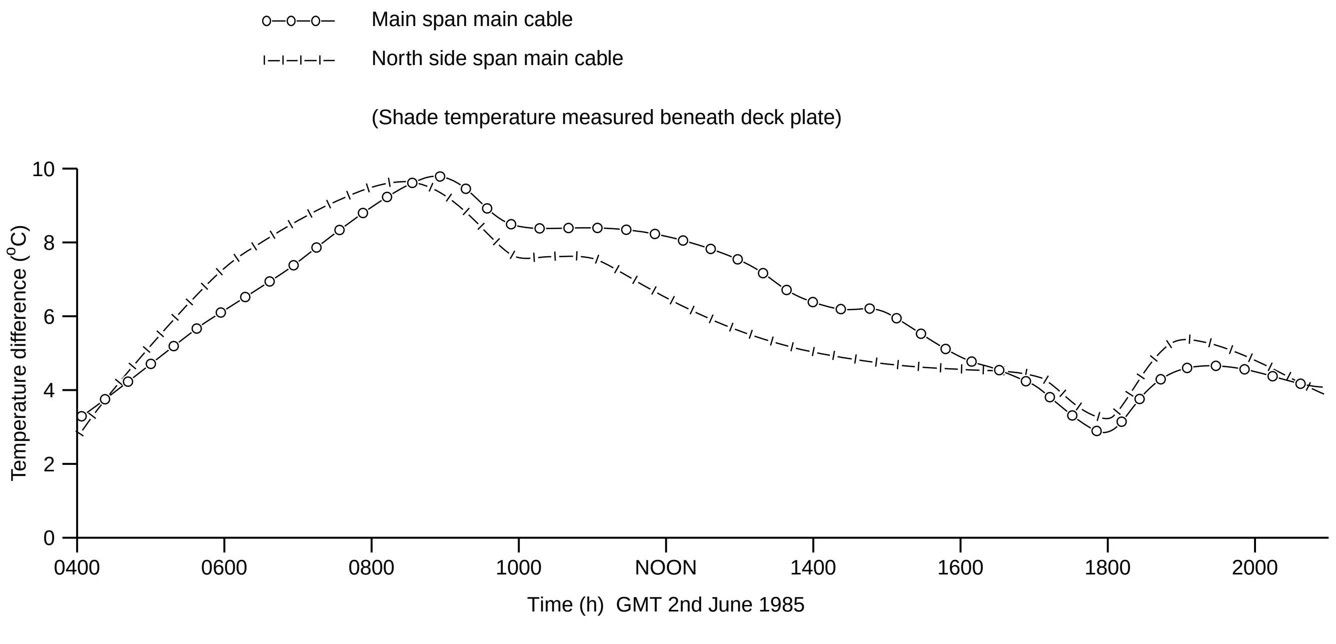


Figure 26 Difference between mean main cable temperature and shade temperature

north side span:

upper surface, 33°C, from -4°C to 29°C;

lower surface, 25°C, from -4°C to 21°C;

east surface, 44°C, from -4°C to 40°C;

west surface, 38°C, from -4°C to 34°C.

4.5.2 The hangers

Details of the cable band and hanger assembly are shown in Figure 4(b).

The positions of the thermocouples on two of the hangers are illustrated in Figure 5(b), and examples of the temperatures recorded are shown in Figures 27(a) and (b) for two summer days when the highest temperatures were measured. The average hanger temperatures (i.e. the average values of each pair of thermocouple readings) for the same two days are shown in Figures 28(a) and (b). The differences between these temperatures and the shade temperature are illustrated in Figures 29(a) and (b).

It can be seen from Figures 27, 28 and 29 that:

a the highest individual temperatures recorded by the thermocouples were 30°C occurring during the morning, and 32°C occurring during the afternoon, (Figures 27(b) and 27(a) respectively);

b the highest average temperatures of a hanger were 27°C occurring during the morning and 30°C occurring during the afternoon, (Figures 28(b) and 28(a) respectively);

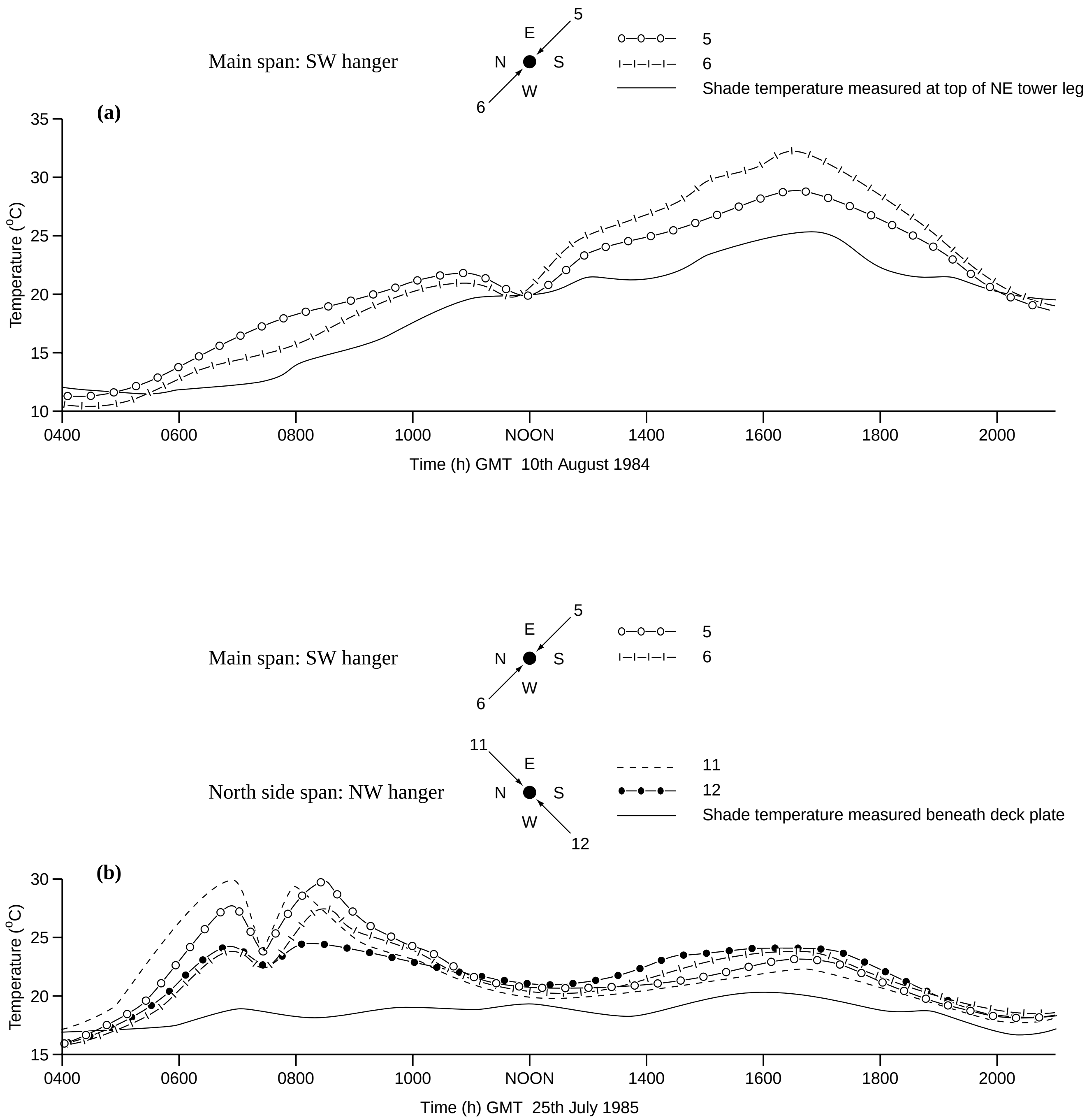


Figure 27 Hanger temperatures

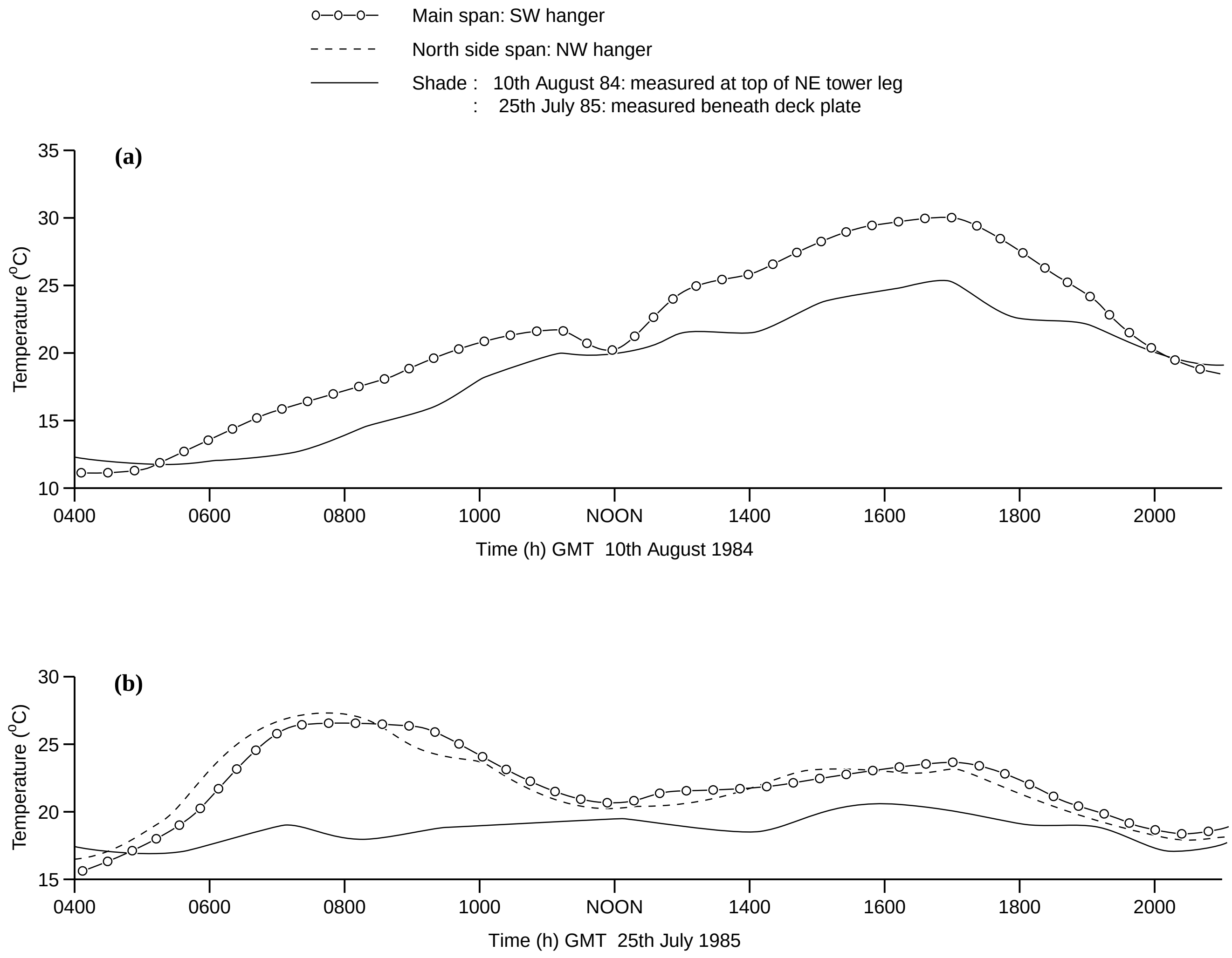


Figure 28 Average hanger temperatures

c one of the largest differences between the average hanger temperature and the shade temperature was 9°C, (Figure 29(b)). The largest recorded difference was 11°C, occurring on 30 May 1985. When the small thermal mass of a hanger rope is considered, these temperature differences are quite large.

The lowest temperature recorded by all four thermocouples on the hangers was -4°C, occurring during the early morning of 27 January 1985. The corresponding minimum shade temperature was -4°C measured at the top of the NE tower leg, and -3°C measured beneath the deck plates.

The overall range of average hanger temperature was 36°C, from -4°C to 32°C.

Calculation of hanger temperatures has not been attempted. The theoretical 1 in 120 year maximum temperature will probably be a few degrees above the corresponding maximum shade temperature. The theoretical 1 in 120 year minimum temperature is not likely to be very different from the corresponding minimum shade temperature.

5 Summary and concluding remarks

The lowest and highest temperatures measured at the various locations on the bridge, together with the associated ranges of temperature, are summarised in Table 1. Theoretical 1 in 120 year temperatures for the suspended superstructure of the main span and the SW tower leg are also included in Table 1.

With regard to Eurocodes (CEN, 1997), where bridges have a 100 year design life, theoretical 1 in 100 year minimum temperatures for the Forth Road Bridge will be approximately 0.5°C higher than the 1 in 120 year values shown in Table 1. Theoretical 1 in 100 year maximum values will be less than 0.5°C lower than the 1 in 120 year values. These estimations are based on the differences between 1 in 100 year and 1 in 120 year minimum and maximum shade temperatures.

It should be remembered that the temperatures shown in Table 1 are minimum and maximum temperatures of different *components* of the bridge. For the Forth Road Bridge, the difference between a 1 in 100 year and a 1 in 120 year minimum *effective* bridge temperature will be less than 0.5°C. The difference between a 1 in 100 year and a 1 in 120 year maximum *effective* bridge temperature will also be less than 0.5°C. The definition of an effective bridge temperature can be found elsewhere (Emerson, 1973, 1976a, 1976b, 1977).

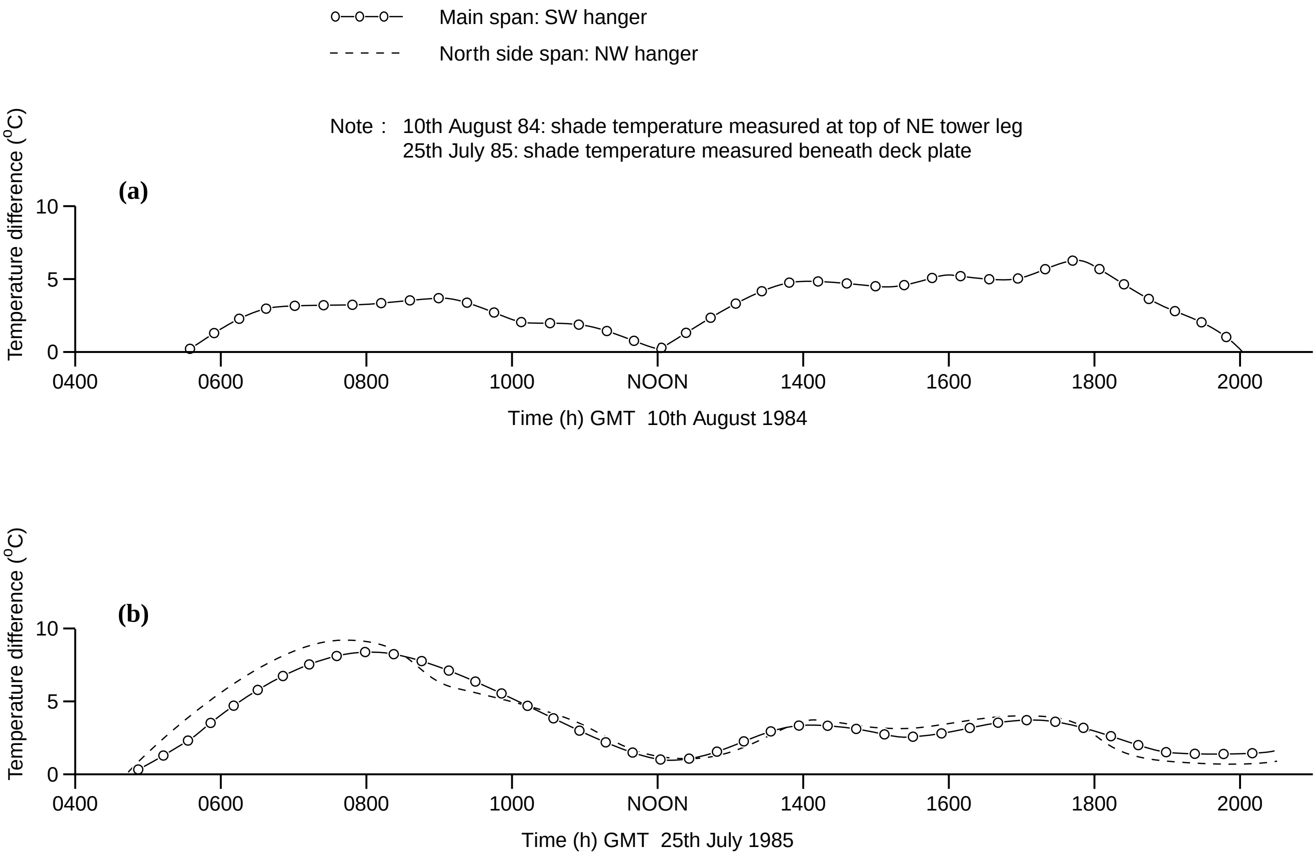


Figure 29 Difference between average hanger temperature and shade temperature

Other comments of relevance to Table 1 are:

a All the measured minimum temperatures were recorded during the early morning of 27 January 1985. The minimum shade temperature measured beneath the deck plates on this date was -3°C.

b The days on which the measured maximum temperatures were recorded occurred between the months of May and September, depending on the orientation of the surface, and the occurrence of high solar radiation. The maximum recorded shade temperature measured beneath the deck plates was 26°C, and it occurred on 19 August 1984.

c The measured maximum temperatures are not necessarily illustrated in the Figures. Where relevant, this has been noted in the text.

Some of the largest measured temperature differences are listed in Table 2. It should be remembered that these are not the largest differences which can occur. This is mainly because of the effect of shadow on some of the measured temperatures, and, in the case of the main cable, the effect of its varying orientation to the sun.

Other points of particular interest which were mentioned in the text are:

1 It may be that, because of differences in exposure, the 1 in 120 year minimum shade temperature of -18°C is too low for the environs of the bridge.

2 The highest temperatures achieved by south facing vertical surfaces do not occur during the summer months. Published 1 in 120 year maximum shade temperatures (which are most likely to occur between June and August) are therefore not relevant to temperature calculations for a south facing surface.

3 The description of temperature differences as either positive or reversed, which is used in current Standards, needs further consideration. It was designed to describe the temperature differences between the top surface and the soffit of a bridge deck, and is not well suited to describing temperature differences between vertical surfaces. See also Note 2 on page 33.

4 Adjustments to the theoretical approach adopted for previous work resulted in calculated temperatures which usually showed good agreement with measured values when the surface under consideration was not affected by shadow. The adjustments were necessary to accommodate:

a the intensity of solar radiation on vertical surfaces of different orientations;

b the heat loss to the sky from a vertical surface;

c the heat exchange at both upper and lower surfaces of an orthotropic deck plate;

d the heat exchange at both the inside and the outside vertical surfaces of the tower legs.

Some of the adjustments required amendments to the surface heat transfer coefficients which quantify the heat losses/gains from radiation and convection at a surface.

Table 1 Measured temperatures and predicted 1 in 120 year temperatures

Location		*Measured temperatures (°C)*			*Predicted 1 in 120 year temperatures (°C)*		
		Min.	*Max.*	*Range*	*Min.*	*Max.*	*Range*
Deck plate		-5	39	44	-24	52	76
Steel beneath deck plate		-5	29	34	-18	37	55
West upper chord	Top face	-5	36[1]	41	-24	57	81
	Bottom face	-3	28	31	-18	37	55
West lower chord	East face	-4	33[1]	37	-21	57	78
	West face	-4	52	56	-21	65	86
SW tower leg	North face	-6	28	34	-21	33	54
	South face	-6	45	51	-21	62[2]	83
	East face	-6	39[1]	45	-21	51	72
	West face	-6	51	57	-21	59	80
Main span main cable	Upper surface	-4	38[3]	42			
	Lower surface	-4	23	27			
	East surface	-4	39	43			
	West surface	-4	37	41			
North side span main cable	Upper surface	-4	29[4]	33			
	Lower surface	-4	21	25			
	East surface	-4	40	44			
	West surface	-4	34	38			
Hanger		-4	32	36			

[1] *Affected by shadow*
[2] *September shade maximum used*
[3] *Oriented south*
[4] *Oriented north*

While the adjusted coefficients lay within the range of published values, they did not always match the pattern. Further work might help to clarify this situation.

5 The use of 'theoretical' solar radiation values (i.e. values which had not been measured on site) inevitably introduced some errors into the temperature calculations.

6 All the measurements were carried out before the strengthening works were started.

7 Although the data in the report apply to a specific bridge in a specific location in the UK, there is no reason why, provided that adequate meteorological data are available, the temperatures of decks, towers and cables of bridges in other areas of the world cannot be estimated.

8 Some of the data contained in the report are to be used as the basis for expanding the information given in the temperature clauses of BD 37/88 and Part 2 of BS 5400. Some information has already been used to assist with the preparation of data for Eurocodes (CEN, 1997).

6 Acknowledgements

The work described in this report was carried out while TRRL (now TRL) was in the Department of Transport. It was instigated by a request from the Forth Road Bridge Joint Board, channelled to TRRL via the Scottish Development Department (now the Scottish Executive Development Department). At the time, the Head of TRRL Scottish Branch was Dr G D Matheson, and thanks are extended to him for his critical appraisal of the three unpublished reports which were written some years ago, and upon which this present report is based. Thanks are also extended to the Highways Agency, not only for providing the funds for the work since the privatisation of TRL, but also for their support and interest. Mr B W Smith of Flint & Neill Partnership (Consultants to the Highways

Table 2 Measured temperature differences

Bridge components	*Temperature difference (°C)*	*Comments*
Deck plate to base of trapezoidal stiffener	9	Deck plate hotter
West upper chord: top face to bottom face	13[1]	Top face hotter
West lower chord: east face to west face	21[1]	East face hotter
West lower chord: east face to west face	29	West face hotter
SW tower leg: north face to south face	35	South face hotter
SW tower leg: east face to west face	24[1]	East face hotter
SW tower leg: east face to west face	24	West face hotter
Main span main cable: upper surface to lower surface	19[2]	Upper surface hotter
Main span main cable: east surface to west surface	22	East surface hotter
Main span main cable: east surface to west surface	15	West surface hotter
North side span main cable: upper surface to lower surface	9[3]	Upper surface hotter
North side span main cable: east surface to west surface	24	East surface hotter
North side span main cable: east surface to west surface	16	West surface hotter

[1] *Affected by shadow*
[2] *Oriented south*
[3] *Oriented north*

Agency for the related Eurocode work) is also to be thanked for supporting the publication of the report.

The work would not have been possible without the helpful co-operation of the Forth Road Bridge Joint Board via the General Manager and Bridgemaster (at that time, Mr Bruce Grewar) and his staff, continued more recently by the present General Manager and Bridgemaster, Mr Alastair Andrew. Staff from the bridge maintenance crew, together with staff of W A Fairhurst & Partners, carried out all the instrumentation of the bridge, and were involved with the monitoring of the data which were collected. In particular, Messrs Alan Simpson and Bob Ward of W A Fairhurst & Partners are to be thanked for their invaluable help and interest.

The permission of W A Fairhurst & Partners to use Figures 2, 3 and 5 is gratefully acknowledged. Figures 1 and 4 are reproduced from the Proceedings of the Institution of Civil Engineers, and Figure 6 is reproduced from the IHVE Guide, Book A.

Thanks are extended again to Mr Alastair Andrew for his permission to publish the report.

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Notes

[1] Exposed steel (and/or concrete) losing heat by radiation to a clear night sky will fall to a lower temperature than it would if it was losing heat by convection (i.e. in windy conditions) and/or evaporation of surface moisture. This is because the 'radiation temperature' of a clear sky is many degrees lower than the temperature of the air surrounding the steel (and/or concrete).

[2] In previous work, where heat gain/loss was associated with horizontal surfaces only, a positive temperature difference related to heating conditions, i.e. the top surface of the deck was hotter than internal areas and/or the soffit. A reversed temperature difference related to cooling conditions, i.e. the top surface of the deck was colder than internal areas and/or the soffit. In this current work, where vertical surfaces are involved, the distinction is not so clear-cut, and further consideration needs to be given to any changes in nomenclature which may be necessary. Such consideration is beyond the scope of this report.

[3] It should be noted that for the purposes of this report 'north', 'south', 'east' and 'west faces' are vertical surfaces facing N, S, E and W respectively.

[4] In Eurocodes (CEN, 1997), bridges have a 100 year design life. Comment on the differences between 1 in 100 year and 1 in 120 year minimum and maximum temperatures for the Forth Road Bridge is given at the beginning of Section 5.

[5] This temperature is not based on a statistically derived 1 in 120 year maximum shade temperature.

Abstract

During the course of a load assessment of the Forth Road Bridge, temperatures were measured on: (a) the suspended superstructure, (b) one of the main tower legs, (c) one of the main suspension cables, and (d) two of the hangers. The data collected were used to determine the highest and lowest temperatures experienced by these areas of the bridge, and the magnitudes of associated temperature differences. These results are reported. In addition, temperatures of some of the components were calculated and, where agreement between measured and calculated temperatures was satisfactory, the calculation method was used to determine 1 in 120 year extreme temperatures. These results are also reported. The data associated with vertical surfaces and with the main suspension cable are of particular interest, for published information on such temperatures is scarce.

Related publications

TRL344 *Seasonal thermal effects over three years on the shallow abutment of an integral bridge in Glasgow* by P Darley, D R Carder and K J Barker. 1998 (price £25, code E)

TRL165 *Measurement of thermal cyclic movements on two portal frame bridges on the M1* by P Darley and G H Alderman. 1995 (price £25, code E)

LR765 *Temperature differences in bridges: basis of design requirements* by M Emerson. 1977 (price £20)

LR760 *Calculated deck plate temperatures for a steel box bridge* by M R Jones. 1977 (price £20)

LR744 *Extreme values of bridge temperatures for design purposes* by M Emerson. 1976 (price £20)

LR696 *Bridge temperatures estimated from the shade temperature* by M Emerson. 1976 (price £20)

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