International Conference on Smart Infrastructure and Construction 2019 (ICSIC):
Driving data-informed decision-making

DeJong, Schooling and Viggiani
ISBN 978-0-7277-6466-9
https://doi.org/10.1680/icsic.64669.743

STRUCTURAL HEALTH MONITORING OF AN INTEGRAL BRIDGE

S.A. Skorpen[1], E.P. Kearsley[1] and C.R.I. Clayton[2]

[1] *Department of Civil Engineering, University of Pretoria, Pretoria, South Africa*
[2] *Department of Civil Engineering, University of Southampton, Southampton, United Kingdom*

ABSTRACT This paper gives an overview of almost three years of monitoring data obtained from instrumentation installed in a 90m long reinforced concrete integral bridge in South Africa. The main objective of this structural health monitoring project was to assess the effect of environmental factors on integral bridge abutment movement, with specific focus on thermal effects. The data obtained from the instrumentation enables designers to compare real and assumed effective bridge deck temperature, earth pressure and abutment movement. Analysis of the data seems to indicate that the deck cross section shape (defined as the ratio of surface area to cross sectional area) has a significant effect on the effective bridge temperature, abutment movement and earth pressure. This hypothesis was tested using the preliminary SHM data, and conclusions were drawn as to whether an increase in deck thermal inertia might be used to mitigate the effects of increased deck length.

Notation

L = Bridge deck length; R = Horizontal reaction force on integral bridge footing; T = Deck temperature; α = coefficient of thermal expansion

1. Introduction

Integral bridges are favoured by bridge authorities and road agencies because they eliminate the use of bearings, providing a simpler form of construction, with reduced maintenance costs. Most existing integral abutment bridge (IAB) research focused on the behaviour of IAB substructures, and as a result, the design limit states considered by many road authorities are largely based on substructure considerations, usually as a function of soil properties at the abutment and pile foundation. This focus has been motivated by the significant increase in substructure demands for integral construction. Integral bridge behaviour during construction and service life however remains poorly understood. As integral bridge decks become ever longer, and working environmental conditions become harsher, there is a need for monitoring and the development of design tools to support the use of this type of bridge.

Recent research indicates that a better understanding of the bridge deck behaviour can benefit integral bridge designers. LaFave et al., (2016) has shown that integral abutment construction also affects superstructure behaviour and demands, and that superstructure properties can directly influence on substructure behaviour. Parametric studies by Kim et al., (2010) indicate that the bridge deck factors with the most significant influence the structure are the deck length and coefficient of thermal expansion of the deck material. England et al., (2000) shows that smaller bridge deck thermal movements results in lower lateral earth pressures and reduced settlement of the fill behind the abutment.

Understanding the effect of changes in deck temperature is thus crucial to the efficient design of durable integral bridges. While temperature effects in conventional jointed bridge structures are often negligible (as the thermal movement is accommodated at the expansion joints), integral bridges cannot be designed without taking thermal movement into account. Work done by Elbadry et al. (1983), Emerson (1976) and Black et al. (1976) on reinforced concrete decks shows that the changes in effective bridge deck temperature are dependent on the ratio of the deck cross sectional area to deck width. Thus the response of any structure to environmental climatic variation is dependent on the structure geometry and material.

2. Bridge Deck Temperatures

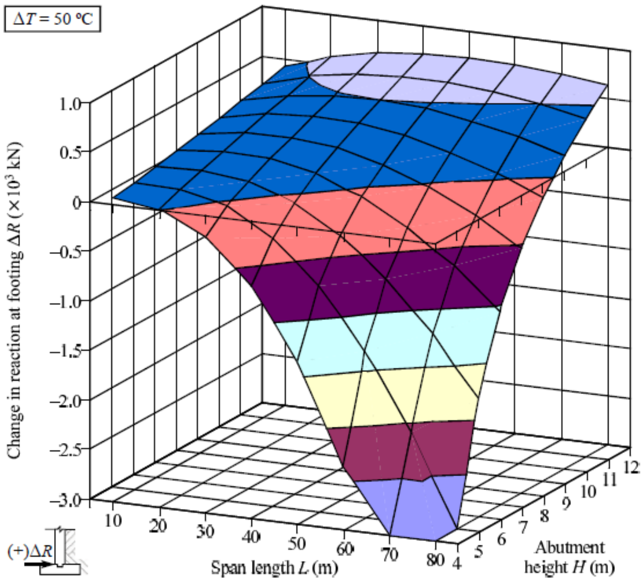
Changes in the ambient shade temperature and solar radiation result in changes to the bridge deck temperature. In reinforced concrete decks, the low thermal conductivity of concrete and a variation in the depth of the deck across its width has a significant effect on the temperature variation in the deck. The temperature variation in the deck affects the effective deck temperature, which governs the change in length of the deck due to temperature variation. The effective bridge temperature is defined by Emerson (1973) and Roeder (2003) as the weighted average bridge temperature.

The change in length of the deck of an integral bridge results in both a reaction force applied to the top of the abutment and in the movement of the abutment. The movement of the abutment causes changes in the earth pressure behind the abutment.

Robberts (2003) used work and energy principals to solve for the horizontal reaction forces (ΔR) on single span portal framed structures with hinged supports. The portal frames were subjected to cyclic thermal changes where material properties and loads (i.e. earth pressure) varied with time and change in seasonal temperature (ΔT). This study identified span length and abutment height as having the biggest influence on the abutment reaction, while the stiffness properties of the members had a lesser influence. Temperature variations were identified as the parameter with the most uncertainty as design values in codes are usually limiting values based on the maximum possible temperatures that can occur. It is noted that the influence of the beam (i.e. deck) cross section on the thermal inertia of the deck was not discussed, and the ΔT values used in the analyses were assumed. Solar radiation was also discussed, but does not seem to be included in the models.

Using an assumed seasonal temperature change of ΔT = 50°C the largest values for ΔR occurred when the span length L becomes large and abutment height H becomes shallow (see Figure 1). The 50°C temperature change was not based on measured values. It would thus be valuable to know what real deck temperature changes are.

Figure 1 Influence of span length and abutment height on the change in reaction ΔR at the footing (Robberts, 2003)



3. Experimental set up

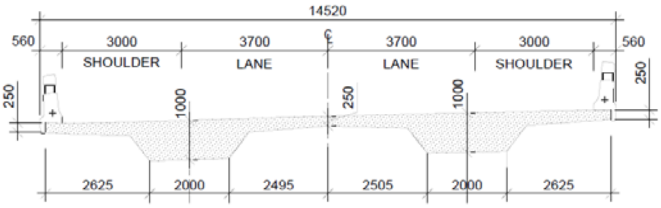
The Van Zylspruit bridge is located on the South African National Roads Agency SOC Limited (SANRAL) National Route N1 in central South Africa, about 600 km South of Pretoria, near the town of Trompsburg (see Figure 2). This is an area known for its dry harsh climate with both high and low temperatures.

The bridge is a 90m long, reinforced concrete, fully integral bridge has been extensively instrumented to measure the environmental effects on the structure. Instrumentation was installed during construction, and the data from this instrumentation has been logged continually from the construction phase onwards. This instrumentation includes 41 thermistors, 110 vibrating wire strain gauges (which each have a built in thermistor), 20 earth pressure cells, a shape-accel-arrays (string of approximately 21 tilt meters) at each abutment and 8 tilt meters, one on each pier.

The deck section varies significantly in depth with the flange thickness being a quarter of the beam thickness (1000mm). The deck comprises two 2000mm wide outside flanges which vary in depth from 250mm to 350mm, two 2000mm wide and 1000mm deep beams, and a 250mm thick, 4000mm wide central flange that connects the beams (see Figure 3).

Figure 2 Van Zylspruit Bridge (Photo - Rikus Kock)

Figure 3: Typical section through deck showing variation in deck thickness.



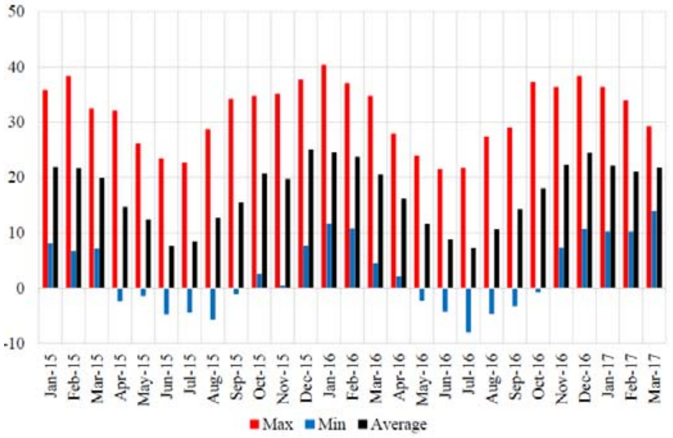
4. Measured temperatures

4.1 Ambient temperature and solar radiation

In summer, the shade temperature at the bridge varies between about 20°C and 40°C, and the solar radiation reaches a maximum of 1000W/m^2 at midday. The length of solar day in peak summer is approximately 13 hours. In winter, the shade temperature varies from about -6°C to 18°C, and the solar radiation peaks at 600W/m^2 at midday, which is almost one third less than the maximum radiation measured in summer. The length of solar day in mid-winter is 11 hours. The solar radiation on a hot summer's day is significantly higher than the solar radiation on a cold day; however the range in ambient shade temperature is higher in winter.

Measured maximum, minimum and average shade air temperatures at the bridge site from January 2015 to March 2017 are shown in Figure 3. The shade temperature range is approximately 48.2°C, varying from a maximum of 40.3°C in summer and -7.9°C in winter. The average shade temperature in summer is 23.9°C and 10.9°C in winter.

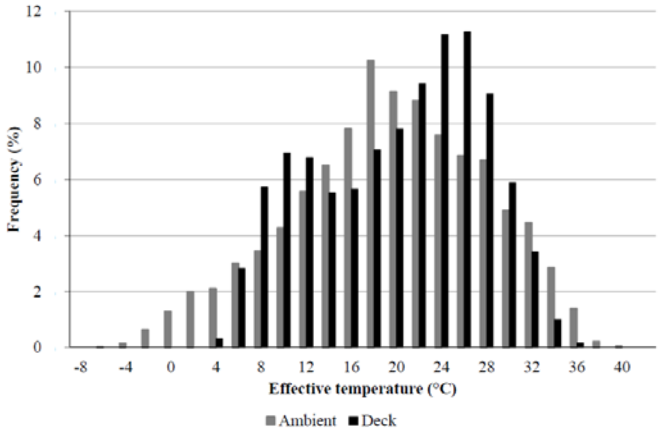
Figure 4 Maximum, minimum and average shade temperatures on site from January 2015 to March 2017



4.2 Effective bridge temperature

The thermistor data was used to calculate the weighted average temperature of the bridge deck (i.e. the effective bridge temperature). This temperature governs the thermal deck movement. Figure 5 shows a normal distribution of this calculated effective bridge temperature compared to the ambient temperature. The deck temperatures were on average higher than the ambient temperature. The effective deck temperature over a two-year period ranged between 35°C in summer and 3°C in winter, a range of 32°C which is a lot lower than the ambient temperature range, and also lower than the assumed seasonal temperature range of 50°C used by Robberts (2003).

Figure 5 Normal distribution of effective bridge temperatures and the ambient temperature

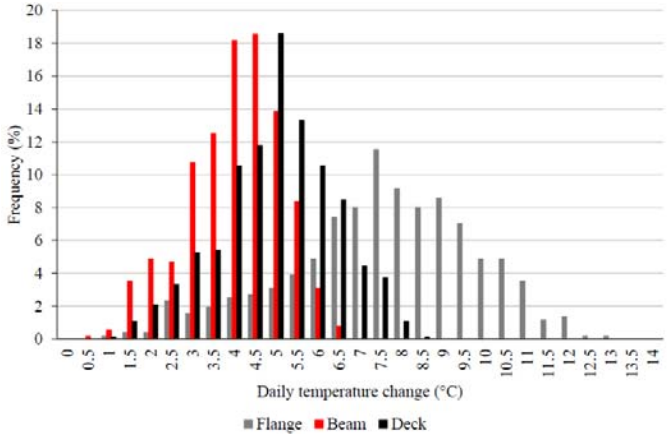


4.3 Change in effective bridge temperature

The most important aspect of bridge temperature with regards to integral bridges is the change in effective bridge temperature (daily and seasonally) which causes the deck to move, and with that the abutment and fill behind it.

Figure 6 shows a normal distribution of the measured daily change in effective deck temperature, with a maximum daily temperature change of 8.5°C. Included with this is the daily change in the effective flange temperature (250mm thick) as well as the effective beam temperature (1m thick). This graph shows a much larger daily temperature range for the thin flanges (up to 13.0°C) compared to the thick beams (a maximum of 6.5°C). It also shows that the mean daily change in effective temperature is definitely dependant on the thickness of the section. The difference in the mean effective temperature of the beam is at least 3°C lower than the thin flanges.

Figure 6 Normal distribution of the daily change in effective bridge, flange and beam temperatures

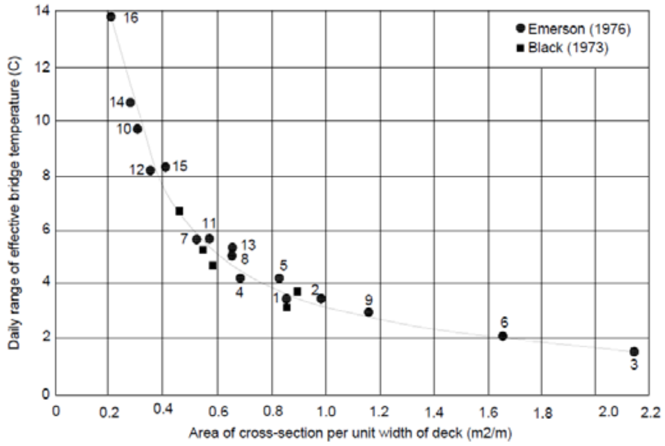


The trend observed in the measured daily change in effective bridge temperature is consistent with work done by Black et al., (1976) and Emerson (1796) who compared the daily change in effective bridge temperature for bridge decks of various thicknesses. Black et al., (1976) suggested that the daily range of effective bridge temperature can be related to the area of cross section of deck per unit width of the deck. This work was continued by Emerson (1976) who selected various concrete bridge cross sections, and for each cross section calculated the temperature distribution and maximum effective temperature using the same theoretical input data of solar radiation and shade temperature, and the same starting temperature.

Figure 7 shows the effect of area of cross section per unit width of deck on daily range of effective bridge temperature, and compares them to the original calculations done by Black et al., (1976). A summer ambient temperature change from 18°C to 38°C was used as well as a maximum midday solar radiation of 900W/m^2 and a 14 hour solar day, which is similar to weather conditions on a typical summer's day at the Van Zylspruit bridge. The deck marked as number 3 was a 2.15m thick section and deck marked as number 16 was a 0.15m thick section.

The correlation between the daily change in effective bridge temperature and area of cross section of deck per unit width of the deck can be clearly seen. It is clear that increasing the deck cross section per unit width ratio increases the thermal inertia of the section and this reduces thermal movement. On a 90m long bridge with a coefficient of thermal expansion of 9.5x10^{-6}/°C (concrete with dolerite aggregate) the difference in daily deck movement in summer for Deck 3 (2.15m thick) and Deck 16 (0.15m thick) could be as much as 5mm.

Figure 7 Effect of deck cross sectional area per unit width on daily range of effective bridge temperature (Emerson, 1976)



5. Abutment movement

In an integral bridge, once the deck has been cast monolithically with the abutment, the abutment movement is governed by the deck. The thermal action of the deck on the abutment causes the abutment to move outwards, as the deck expands, and inwards, as the deck contracts. To verify the deck action onto the abutment the relative movement of the top of the shape-accel array (located 1m down from the centroid of the deck) was plotted with respect to the base of the instrument, which is at the bottom of the central abutment pile. A sketch of the abutment showing the relative positions of the shape-accel-array as well as the lateral earth pressure cells is shown in Figure 8.

Figure 9 shows the thermal movement of the top of the shape-acccel-array (SAA) from October 2016, up until August 2018. As October 2016 is almost 10 months after the completion of the deck, the shrinkage movement can assumed to be negligible for this graph. The seasonal cyclic nature of movement of the abutment can be clearly seen. The average seasonal thermal movement is from +5.5mm to – 5.5mm at each abutment (i.e. a total of 11.0mm movement at each abutment).

Using the maximum measured seasonal effective deck temperature change (33°C) the predicted movement at each end of a 90m long deck is slightly higher than the measured movement at Van Zylspruit (See Table 1). A better match is obtained using the change in effective temperature of the beam portion of the deck. One of the reasons for this could be attributed to cracking in the flanges over the piers which would mean that the thermal movement of the deck would be governed be the un-cracked 1m thick beam section, which varied in temperature seasonally by a maximum of 30°C.

Table 1 Predicted abutment movement

	ΔT °C	α /°C	ΔL mm
Deck	33	9.5×10^{-6}	14.0
Beam	30	9.5×10^{-6}	12.8

Figure 8 Section through the southern abutment wall showing the pressure cell and SAA positions

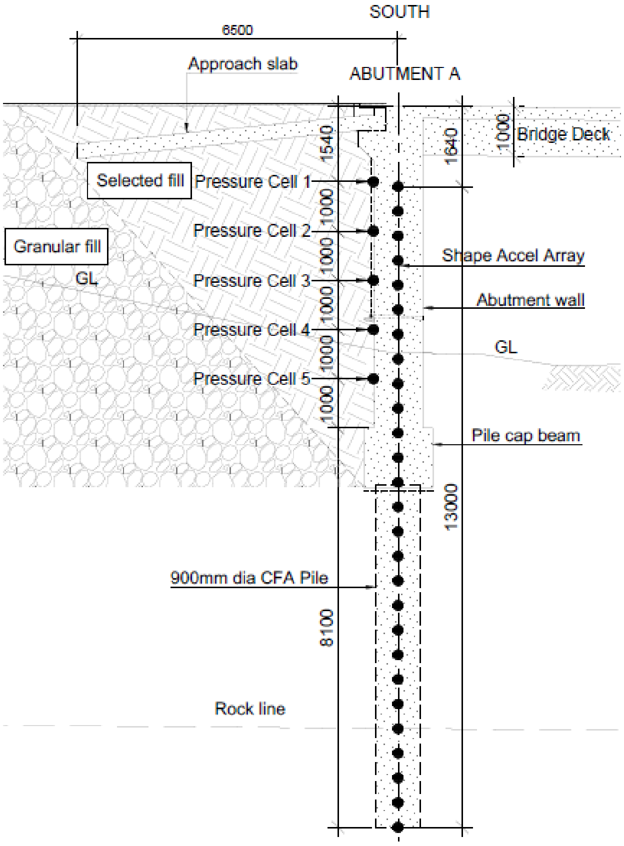
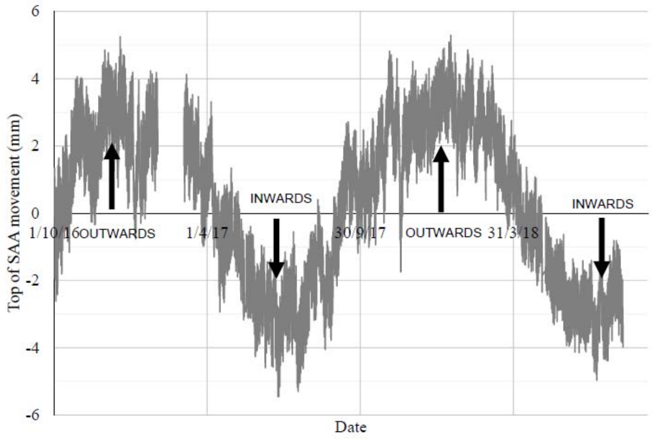


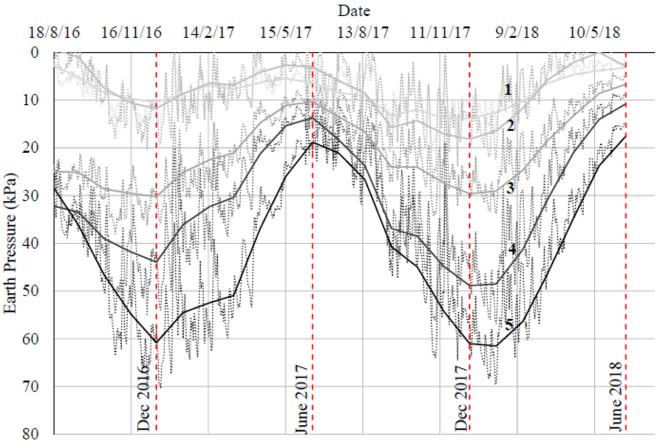
Figure 9 Relative top of SAA movement from October 2016 to August 2018



6. Lateral Earth Pressure

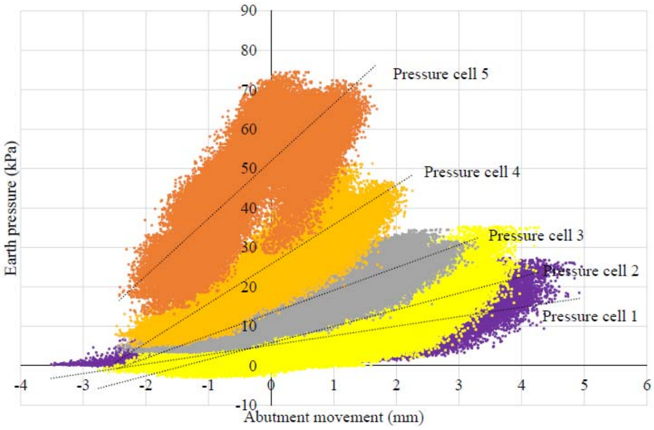
The seasonal change in temperature causing the deck and abutment to extend outwards in the hotter summer months and inwards in the colder winter months is reflected in the earth pressures measured from August 2016 (just after the backfill was completed) to June 2018 (see Figure 10). The readings from the earth pressure cells were zeroed in April 2016 before the backfilling began and temperature compensated, so that the readings from the backfill surcharge are taken into account. Earth pressure in summer increases linearly towards the base of the abutment wall, however in winter the earth pressure is significantly reduced. This seasonal change in earth pressure has been observed in other integral bridges where earth pressures have been monitored (Darley et al., 1998).

Figure 10 Earth Pressure measured Aug 2016 to June 2018



A linear relationship between the effective bridge temperature and the lateral earth pressure can be observed in Figure 11 where the earth pressure and corresponding deck effective temperature are plotted against each other. An increase in effective deck temperature results in an increase in earth pressure as the deck pushes out into the earth fill.

Figure 11 Effective deck temperature plotted against the average North and South abutment earth pressure



The earth pressure variation from season to season seems to have increased between December 2016 and December 2017, which could be caused by the ratcheting effect and this will continue to be monitored.

When the earth pressure variation along the height of the wall is plotted, pressures higher than soil at rest were observed in summer months, and lower than active pressure in winter months.

7. Heat flow modelling

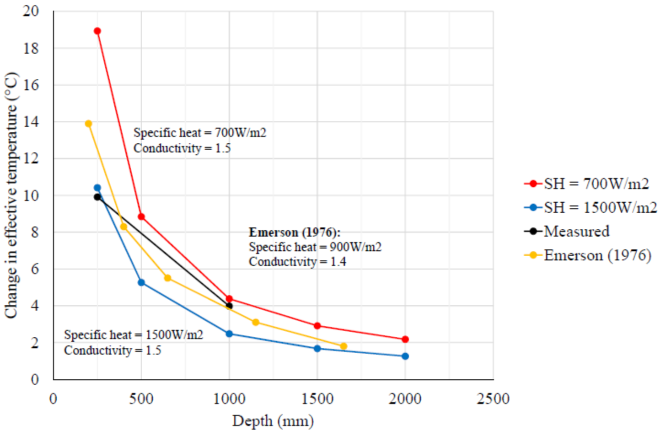
Beside solar radiation and ambient temperature, the other important parameters to consider when studying the heat flow and temperature change of a concrete bridge decks is the concrete conductivity and specific heat. To assess the importance of the heat flow parameters of the deck material on change in effective temperature of a cross section, a number of heat flow finite element models were performed in Abaqus (2018) for a range of concrete conductivity and specific heat values and typical summers and winters day conditions. Different deck cross sections, ranging from 0.25m to 2m thick were modelled and the change in effective temperature calculated.

A range of conductivity and specific heat values typically used in research were assess (Emerson (1973); Priestly (1978); Branco and Mendes (1993); Larson et al., (2013)). Conductivity was varied from 1.5 to 2.5 W/m/°C and specific heat values varied from 700 to 1500 J/(kg°C). Higher specific heat is linked to concrete with a higher moisture content.

The heat flow models show that conductivity has a smaller influence on the change in effective temperature than specific heat. Figure 12 shows the influence of specific heat on the change in effective temperature in summer when the ambient temperature changes by 20°C (thermal loading as per Emerson (1973) example) when the conductivity is assumed to be 1.5 W/m/°C. It is clear that the lower the specific heat, the higher the change in temperature on any given day (i.e. less energy required to heat the deck). The measured results from Van Zylspruit on a day similar to this fall within the range of calculated values.

The trend of small effective temperature changes observed in decks with a higher thermal inertia (i.e. higher area of cross section per unit width of deck) is still evident. The biggest daily temperature changes were calculated for a thin section with low moisture content, and the smallest temperature changes in a thick section with a higher moisture content. The difference in the change in effective temperature was as much as 16°C, indicating that the thermal inertia of a deck cross section should be carefully considered when selecting a deck cross section for an integral bridge.

Figure 12 Daily change in effective deck temperature compared to the area of cross section per unit width of deck for different specific heat values



8. Conclusion

Measured temperature, movement and lateral earth pressure data from the Van Zylspruit Bridge have been presented and discussed in this paper. The measured data has proved valuable as it shows the real temperatures, movement and loads on an integral bridge structure.

The effect of deck cross section thermal inertia on the expansion of integral bridges has been shown. An increase in the cross sectional area per unit width of deck results in a lower change in effective deck temperature, and therefore smaller movement of the integral abutments. This trend is clearly seen with the measured data and confirms research done by Emerson (1976) and Black et al., (1976).

Measured top of abutment movement was comparable with the measured change in effective deck temperatures. In reinforced concrete decks it appears that the abutment movement is governed by the change in temperature of the un-cracked deck section.

Seasonal earth pressure variation was observed as the abutment moved into the fill in summer and away from the fill in winter. Earth pressures higher than soil at rest were observed in summer months, and lower than active pressure in winter months.

Heat flow modelling confirmed the importance of the thermal inertia of the deck cross section on the daily (and hence seasonal) movement of the bridge. The trend of smaller effective temperature changes observed in decks with a higher thermal inertia (area of cross section per unit width of deck) was evident.

Both measured and modelled temperature data confirm that at for a given set of bridge environmental conditions, longer integral bridges could be constructed if careful consideration is given to the selection of a deck cross section with a high thermal inertia.

9. Acknowledgements

The following organizations are gratefully acknowledged for their assistance during the course of the study:

The South African National Roads Agency SOC Ltd;

Mott Macdonald PDNA;

Aveng Grinaker-LTA

10. References

Journal articles

Branco, F.A., Mendes, P.A., 1993, *Thermal Actions for Concrete Bridge Design*, Journal of Structural Engineering, Vol. 119, No. 8, August 1993

Kim, W., Laman, J.A., 2010, *Integral abutment bridge response under thermal loading. Engineering Structures*, Vol 32, No. 6, Pages 1495-1508.

LaFave, J.M., Riddle, J.K., Jarret, M.W., Wright, B.A., Svatora, J.S., An, H., Fahnestock, L.A., 2016, *Numerical Simulations of Steel Integral Abutment Bridges under Thermal Loading,* ASCE Journal of Bridge Engineering, Vol 21, No. 10, Pages 1 – 17

Larsson, C., Svensson, G., 2013, *Realistic modelling of thermal effects in concrete bridges*, Report TVBK-5223, Lund University.

Priestley, M., 1978, *Design of concrete bridges for temperature gradient*, American Concrete Institute, Vol 75 Number 5, Pages 209–217

Roeder C.W., 2003, *Proposed design method for thermal bridge movement,* ASCE Journal of Bridge Engineering, Vol 8 No. 1, Pages 12-19

Books

England, G.L., Tsang, C.M., Bush, D.I., 2000, *Integral bridges: A fundamental approach to the time-temperature loading problem*, Thomas Telford

Reports

Black, W., Moss, D.S., and Emerson, M., (1976), *Bridge Temperatures Derived from measurement of movement*, TRRL Report LR 748, Transport and Road Research Laboratory, Crowthorne, Berk-shire

Darley, P, Carder, D.R., and Baker, K.J., 1998, *Seasonal Thermal Effects Over Three Years on the Shallow Abutment of an Integral Bridge in Glasgow*, TRL Report 344, Transport Research Laboratory, Crowthorne, Berkshire

Emerson, M., 1973, *The Calculation of the Distribution of Temperature in Bridges*, TRRL Report LR 561, Transport and Road Research Laboratory, Crowthorne, Berkshire

Emerson, M., 1976, *Bridge Temperatures Estimated from the Shade Temperature*, TRRL Re-port LR 696, Transport and Road Research Laboratory, Crowthorne, Berkshire

Theses

Robberts J.M. (2003) *Behaviour of Integral Bridges subject to nonuniform temperature creep and soil structure interaction loading*. PhD thesis, Imperial College of Science Technology and Medicine, London, UK.