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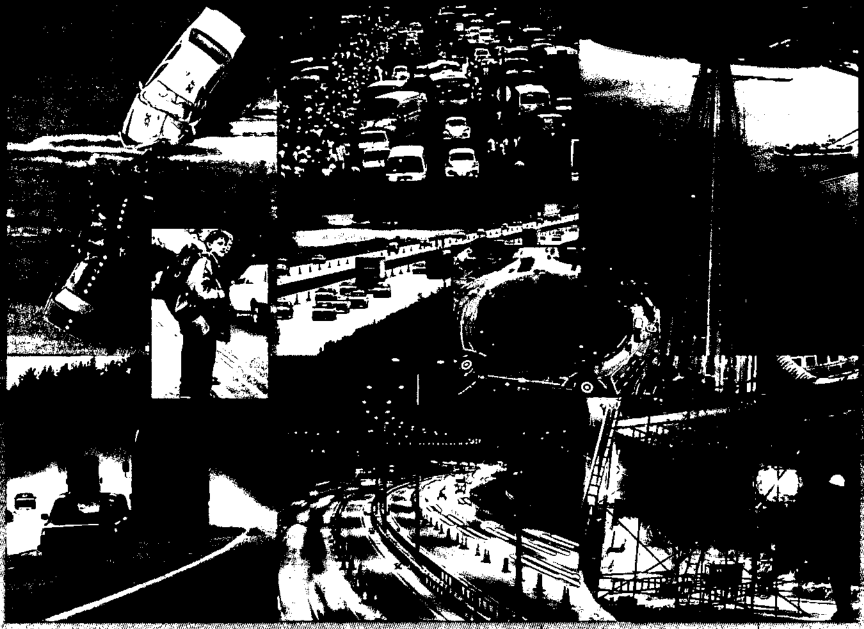

Measurement of thermal cyclic movements on two portal frame bridges on the M1

by P Darley and G H Alderman

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TRL Report 165

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TRL REPORT 165

MEASUREMENT OF THERMAL CYCLIC MOVEMENTS ON TWO PORTAL FRAME BRIDGES ON THE M1

by P Darley and G H Alderman

This report describes work commissioned by the Bridges Engineering Division of the Highways Agency under E465A/BG, Assessment of Integral Bridge Abutments.

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EXECUTIVE SUMMARY

Rigid frame bridges, where the abutments are structurally connected to a continuous deck to form an integral structure, have the advantage of reduced maintenance costs because of the absence of bridge bearings. However seasonal thermal movements of the bridge deck make it difficult to predict the magnitude and distribution of earth pressures acting on the abutments and movements within the backfill. These lead to uncertainties in the design of integral bridges. In order to confirm that longitudinal thermal movements of the deck were being transmitted to the abutments, two existing portal frame bridges spanning the M1 were instrumented and monitored over periods of up to 14 months. These bridges were constructed more than 30 years ago and have performed satisfactorily in service.

Both portal frame structures were instrumented to measure changes in length and level of the bridge deck and the temperature variations in the deck giving rise to the changes. Length measurements were made using a high precision electronic distance measuring system (Geomensor) and level measurements using precise levelling employing an invar staff and parallel plate micrometer. A reasonable estimate of temperature was obtained from two profiles of thermocouples installed at depths ranging from 25 to 500mm below the top surface of the concrete deck of each bridge.

Both bridge decks behaved in a reasonably predictable manner with an increase in length with temperature which correlated well with the coefficient of thermal expansion of 12 x 10^{-6} per °C commonly assumed for reinforced concrete. Measurements of bridge movement were taken when deck temperatures were between -1°C and +19°C. However the lower and upper limits of effective bridge temperatures in the Northampton area are expected to be outside this range over a 120 year period with overall changes of the order of 40°C. On this basis, a lateral movement of ±6.5mm is predicted at the top of each abutment. This is likely to be of sufficient amplitude to mobilise passive earth pressures in the granular backfill behind the abutments. More detailed studies measuring earth pressures developed behind the abutments of integral bridges will be needed to provide a comprehensive picture.

MEASUREMENT OF THERMAL CYCLIC MOVEMENTS ON TWO PORTAL FRAME BRIDGES ON THE M1

ABSTRACT

Rigid frame bridges, where the abutments are structurally connected to a continuous deck to form an integral structure, have the advantage of reduced maintenance costs because of the absence of bridge bearings. However seasonal expansion and contraction of the bridge deck causes cyclic movements of the abutments which lead to variations in the earth pressures acting on the abutment walls in service. In turn, these lead to considerable uncertainties in design. In this study the behaviour of two existing portal frame bridges spanning the M1 was studied over periods of up to 14 months. These bridges were instrumented to monitor the longitudinal thermal movements of the deck and the associated change in vertical level at various points along the deck.

1. INTRODUCTION

A major element of the repair and maintenance costs of conventional road bridges is caused by damage to the bearings from road deicing salts penetrating the deck joints (Wallbank, 1989). Integral bridges where the abutments and deck form a continuous unit with no bearings should therefore have much reduced maintenance costs. Integral bridges have been widely used in Europe and North America and are now being introduced into the UK. Their performance has been reviewed by Burke (1989) and more recently by Card and Carder (1993).

Seasonal thermal movements of the bridge deck make it difficult to predict the magnitude and distribution of earth pressures acting on the abutments and movements within the backfill. These lead to uncertainties in the design of integral bridges. In order to confirm that longitudinal thermal movements of the deck were being transmitted to the abutments, two existing portal frame bridges spanning the M1 were instrumented and monitored over periods of up to 14 months. These bridges were constructed more than 30 years ago and have performed satisfactorily. Measurements of change in length and vertical level were made at various points along the bridge deck using a high precision electronic distance measuring system and a precise level respectively. These movements were correlated to reasonable estimates of deck temperature derived from two arrays of thermocouples installed in the deck of each bridge.

The monitoring of these bridges forms part of a wider programme of research into the performance of integral bridges being undertaken on behalf of the Department of Transport. In addition to this study, more detailed studies are underway at other trial sites where measurements of the earth pressures acting on both shallow and full height integral abutments are being related to thermal movements of the abutment and deck.

2. LOCATION AND DESCRIPTION OF STRUCTURES

Bridge 1, DOT number M1/123.20, was designed by Sir Owen Williams and Partners and built in 1959. The bridge carries the Kilsby to Watford road over the M1 in Northamptonshire. Bridge 1 is a portal frame structure comprising reinforced concrete abutments 1.828m thick and a solid reinforced concrete deck 838mm thick and 9.75m wide. The abutments are cantilevers on spread footings which are founded on rock. A cross-section of the bridge is shown in Fig 1a. The bridge is approximately 56.7m long with a central pier at mid span. The available distance between the measurement points 3G and 1G is 49m (Fig 1a). The bridge was instrumented by TRL during October 1993.

Bridge 2, DOT number M1/121.40/1, is a similar portal frame structure with a central pier, a deck slab thickness of 762mm and width of 12.4m. The length of the bridge is 48m, with a distance of 41m between measurement points 3G and 1G as shown in Fig 1b. The bridge was built to a similar design as Bridge 1 except that the abutments are founded on stiff clay rather than rock. It is located some 2 miles south of Bridge 1 and carries the Welton to Watford road over the M1. The bridge was instrumented during February 1994.

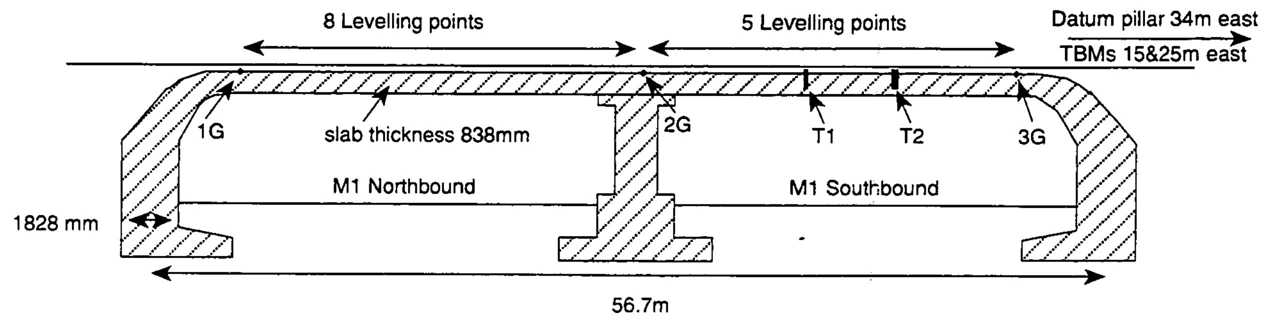
3. INSTRUMENTATION

Both portal frame structures were instrumented to measure changes in the length and level of the bridge deck and the temperature variations in the deck giving rise to the changes. The positions of the instruments for both bridges are summarised in Fig 1 and Table 1.

3.1 MONITORING OF LENGTH CHANGES

To measure changes in length of the deck, stainless steel sockets to accept a target reflector for the high precision electronic distance measuring system (Geomensor) were fixed with epoxy concrete into holes drilled in the top

(a) Bridge 1 [not to scale]



(b) Bridge 2 [not to scale]

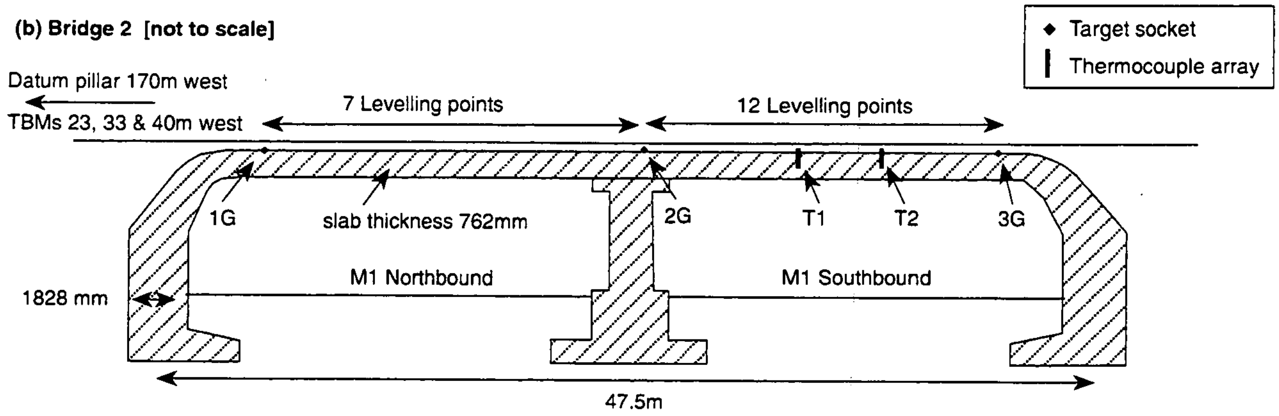


Fig.1 Instrument layout

surface of the concrete deck and the deck waterproofing reinstated. Sockets were installed at each end and in the centre of each bridge deck (Fig 1). At each bridge a fixed datum pillar with a tribach mounting for the Geomensor equipment was installed on the line of the bridge. At Bridge 1 the pillar was at a distance of 34m from the eastern end of the bridge and at Bridge 2 some 170 metres from the western end of the bridge. The precision of the Geomensor is such that it is capable of measuring changes in deck length to better than ±0.5mm over these ranges.

3.2 MONITORING OF LEVEL CHANGES

In order to measure any changes in level of the decks, levelling points were installed along the length of the decks at locations shown in Fig 1 and Table 1. The levelling points comprised the stainless steel sockets used for the Geomensor target reflector supplemented by stainless steel road nails installed in the blacktop of the footways. At locations T1 and T2 shown in Fig 1, stainless steel nails were fixed into the concrete deck. The levels of these points were determined relative to remote temporary benchmarks using precise levelling techniques employing an invar staff and parallel plate micrometer. The precision of these measurements was considered to be better than ±0.25mm.

3.3 MONITORING OF TEMPERATURE CHANGES

A reasonable estimate of the temperature of the deck was made using two thermocouple profiles, one of 6 and one of 4 "T type" thermocouples. These were installed at the locations T1 and T2 on each structure (Fig 1), at depths ranging from 25 to 500mm below the top surface of the concrete deck (Table 1). Care was taken when backfilling around the thermocouples to eliminate any air pockets around the thermocouple tips as such pockets can lead to erroneous temperature readings (Mortlock, 1974). A considerable amount of research into the measurement of temperature and movement in bridge decks has been carried out (Emerson 1968, 1973 and 1976a) but this research was carried out on bridges fitted with bearings and expansion joints. A method of calculating effective deck temperature is given by Emerson (1976b) but in the current limited study the mean of the ten thermocouples was considered to be sufficiently accurate.

TABLE 1

Locations of instrumentation

Bridge 1 Position	Type * C/B	Distance from 3G (m)	Bridge 2 Position	Type * C/B	Distance from 3G (m)
3G	C	0	3G	C	0
10L/T2	C	6	8L	B	1.45
9L/T1	C	12	7L	B	4.45
8L	B	18	T2	C	5.55
2G	C	24.3	6L	B	7.45
7L	B	27	5L	B	10.45
6L	B	30	T1	C	10.5
5L	B	33	4L	B	13.45
4L	B	36	3L	B	15.5
3L	B	39	2L	B	16.45
2L	B	42	1L	B	19.45
1L	B	45	2G	C	20.5
1G	C	48.82	14L	B	25
			13L	B	28
			12L	B	31
			11L	B	34
			10L	B	37
			9L	B	40
			1G	C	41

Bridge	Array	Depths below top surface of concrete deck (mm)
1	T1	25, 50, 100, 150, 300, 340
1	T2	50, 100, 150, 200
2	T1	25, 50, 100, 150, 300, 500
2	T2	50, 100, 150, 200

* Type C set in concrete deck, type B set in blacktop.
G is a Geomensor measuring station and levelling point,
T is a thermocouple array, L is a levelling point.

4. MEASUREMENTS

4.1 CHANGES IN LENGTH OF BRIDGE DECK

Figs 2a and 2b show the changes in length of Bridge 1 and Bridge 2 respectively together with the average temperatures measured by the thermocouples in the deck. The measurements indicate that the deck length changed in a broadly predictable manner with changes in temperature for both bridges, an increase in temperature giving rise to an increase in the length of the deck.

In Fig 3 the actual change in length of each bridge is plotted against the mean temperature recorded by the thermocouples. An overall temperature range from -1°C to +19°C. was recorded during the monitoring periods of 14 months at Bridge 1 and 12 months at Bridge 2. The best fit line

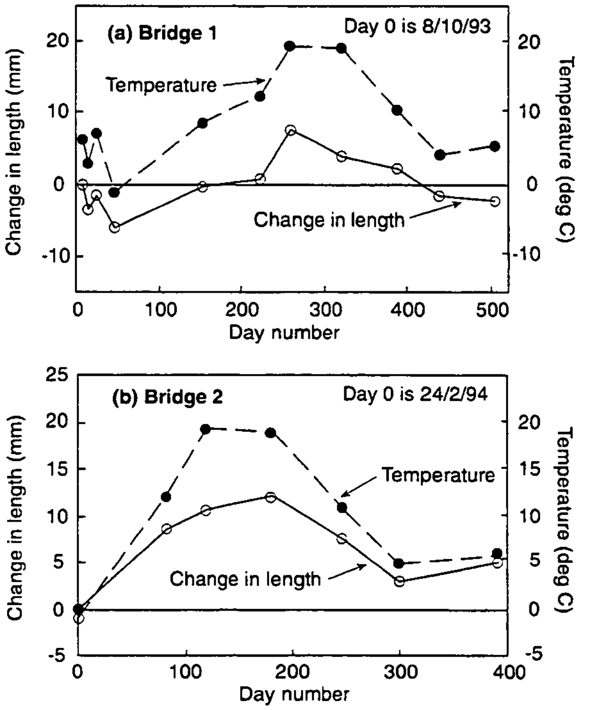


Fig 2. Change in deck length and temperature with time

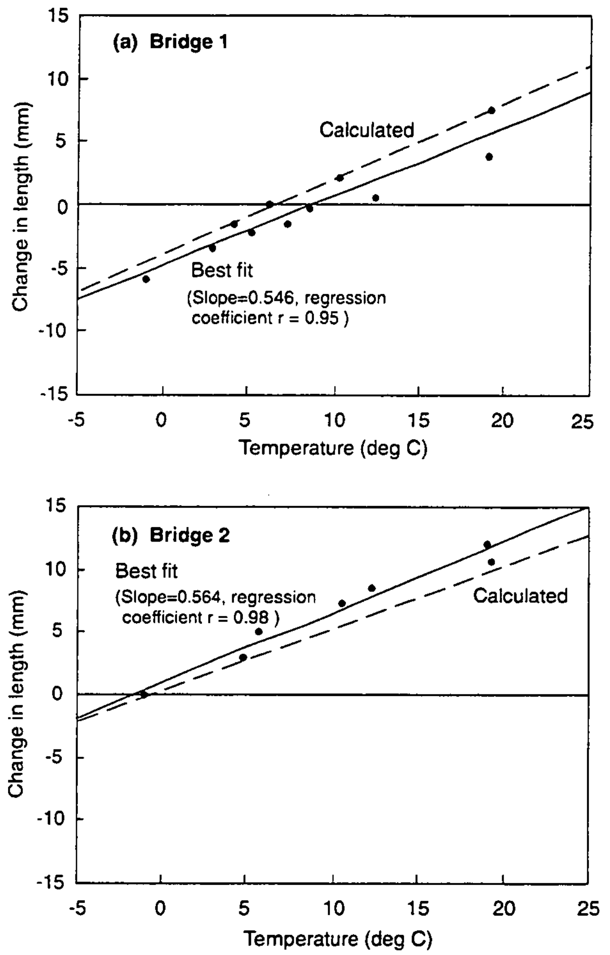


Fig 3. Change in length with temperature

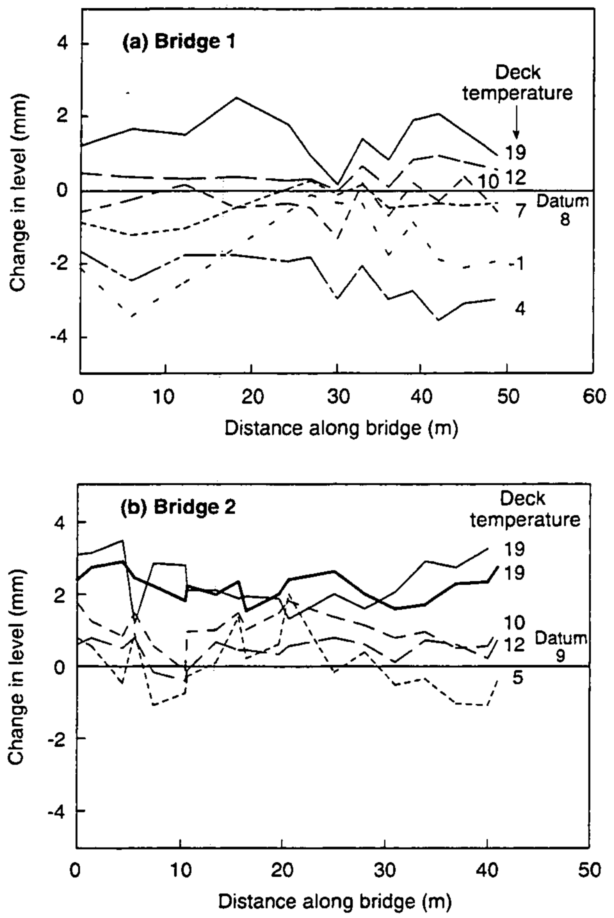


Fig 4. Change in level of bridge deck

through the results is compared in Fig 3 with the change in length calculated using a coefficient of expansion of 12 x 10^{-6} per °C as specified for steel and gravel aggregate concrete in BD37 (DMRB 1.3). On this basis the best fit line for Bridge 1 has a slope of 0.546mm/°C which on dividing by its span is equivalent to a coefficient of thermal expansion of 11.3 x 10^{-6} per °C. Similarly for Bridge 2 the slope is 0.564mm/°C with an equivalent expansion coefficient of 13.7 x 10^{-6} per °C. It must be noted that the average deck temperature was calculated from the results of ten thermocouples at each bridge and as such only represents a simple estimate of the true effective deck temperature. The largest variation of temperature within a single set of measurements from ten thermocouples on a bridge was at Bridge 2 and was from +3.0°C to +6.4°C with an average temperature of 4.8°C. More typically, the range for a set of ten thermocouples was ±1°C.

4.2 CHANGES IN LEVEL OF BRIDGE DECK

Fig 4a shows profiles of level changes measured along the deck of Bridge 1 at different mean deck temperatures. These changes are calculated from datum levels which were taken when the deck temperature was 8°C. The data indicate that changes in level of the deck of between +2.5mm and -3.5mm occurred during the period of measurement. Similar data for Bridge 2 are given in Fig 4b.

When the average change in level for the 13 points on Bridge 1 and the 19 points on Bridge 2 are plotted against the average temperature of the deck (Fig 5), the data show small increases in deck level with temperature of 0.21mm/°C and 0.15mm/°C for Bridge 1 and 2 respectively. Table 2 shows the slope and regression coefficients for the average change in level of all the levelling points and for those 5 points on each bridge (1G, 2G, 3G, T1 and T2) that were fixed directly into the concrete deck.

The results in this Table indicate that the levelling points set in concrete experienced smaller movements than those set in blacktop. This is probably due to the fact that points 1G, 2G and 3G on each bridge would experience greater vertical restraint than the other levelling points. This effect is quite marked for Bridge 1 in Fig 4a, where the maximum changes are at the quarter points. However the effect is not apparent in Fig 4b. Systematic differences between the levelling points set in concrete and those in blacktop are considered unlikely and there is not evidence to suggest such an effect in Fig 4. In addition it can be seen that the change in level with temperature for Bridge 1 is larger than that for Bridge 2. This implies that the lateral restraint at

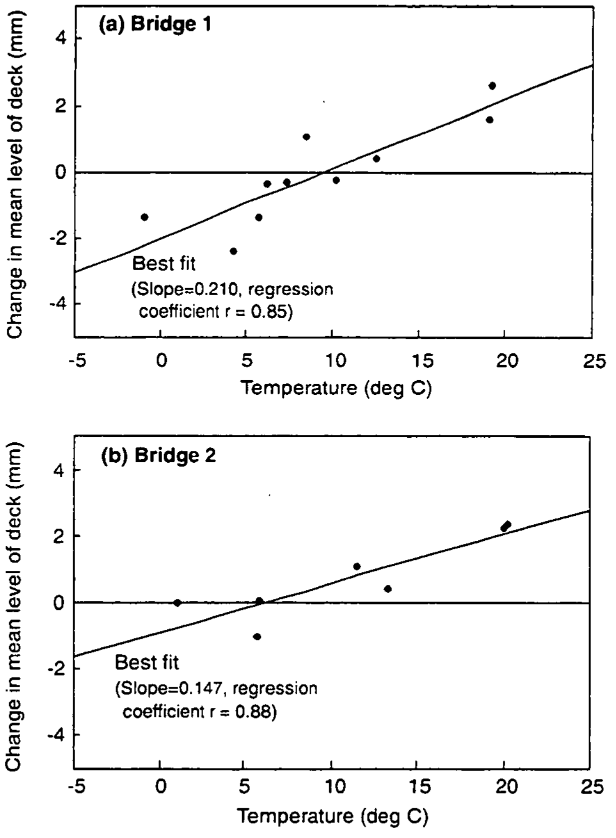


Fig 5. Change in mean level of deck with temperature

each end of the deck due to the abutments and backfill is greater for Bridge 1 than for Bridge 2.

5. DISCUSSION

Both portal frame structures being investigated were designed with relatively massive abutments (1.828m thick) and a central pier. For this reason it was by no means certain whether thermal movements of the bridge deck would be accommodated by lateral movement of the top of the abutments, by hogging/sagging of the deck itself, or by a combination of the two. The measurements of lateral and vertical thermal movements of the bridge deck indicated that lateral movements were close to those calculated from the appropriate coefficient of thermal expansion and that vertical movements were generally small.

Different foundation conditions existed for the abutments of the two bridges. At Bridge 1 the abutments are founded on rock and the M1 is in cutting so that the abutment backfill forms a wedge against the undisturbed ground. The abutments at Bridge 2 are founded on clay with the motorway at original ground level and approach embankments to the abutments. For these reasons it was considered that the lateral restraint of the abutments at Bridge 1 is slightly better than at Bridge 2: this is borne out by the marginally lower value of 0.546mm/°C as opposed to 0.564mm/°C for change in deck length and the marginally higher value of 0.21mm/°C as against 0.15mm/°C for average change in deck level for Bridges 1 and 2 respectively. The greater lateral restraint for Bridge 1 would appear to be consistent with the larger changes in deck levels. Thus, the quarter points on Bridge 1 show hogging as the temperature increases, with the hogging diminishing as the temperature decreases. The data in Fig 4b suggest that the deck moves up and down as a monolith for Bridge 2, indicating that the lateral restraint was insufficient to induce hogging as the temperature increased.

Measurements of bridge movement were taken when deck temperatures were between -1°C and +19°C. The lower and upper limits of effective bridge temperatures in the Northampton area are expected to be outside this range over a 120 year return period: values given in BD37/88 (DMRB 1.3) indicate that the temperature difference between the lower and upper limits is likely to be of the order of 40°C. On the basis of a 40°C variation, changes in overall length of about 26mm are calculated for both Bridge 1 and 2. This is equivalent to a lateral movement of ±6.5mm at the top of each abutment. Given that the mean abutment height (H) is 8.5m, the shear strain in the backfill can be calculated as 1.5×10^{-3} from $2\delta/H$ where δ is the lateral deformation at the top of the wall. Card and Carder (1993) report that according to the work of Ishihara (1982) on transient effects, this would be a sufficient amplitude of movement to mobilise passive earth pressures behind the abutments. England and Dunstan (1994) support the need to consider cyclic loading effects: they demonstrate that cyclic loading from daily and seasonal changes of temperature can cause 'strain ratcheting'

TABLE 2

Comparison of levelling data

	All levelling points		Levelling points set in concrete	
Structure	Slope of best fit line	Regression coefficient (r)	Slope of best fit line	Regression coefficient (r)
Bridge 1	0.210	0.85	0.201	0.86
Bridge 2	0.147	0.88	0.116	0.76

within granular material, thus leading to an escalation in the lateral stresses acting on an integral bridge abutment. The abutments on the M1 bridges under investigation are relatively massive (1.828m thick) to resist any increased earth pressures and the bridges have performed satisfactorily for more than 30 years.

6. CONCLUSIONS

The performance of two existing portal frame bridges spanning the M1 was studied over periods of up to 14 months. The bridges were instrumented to monitor the longitudinal thermal movements of the deck and the associated change in vertical level at various points along the deck. The following conclusions were reached.

1. Both bridge decks behaved in a reasonably predictable manner with an increase in length with temperature which correlated well with the coefficient of thermal expansion of 12×10^{-6} per °C commonly assumed for reinforced concrete.

2. Only small changes in level of the decks were measured with temperature and these were consistent in so far as hogging occurred with increased temperatures. Both the levelling and longitudinal movement data indicated that the lateral restraint of the abutments of Bridge 1 was marginally higher than at Bridge 2. This is consistent as Bridge 1 spans the M1 in cutting and has abutments founded on rock, whilst Bridge 2 has abutments founded on clay and approach embankments.

3. The range between the lower and upper limits of effective bridge temperatures in the Northampton area is expected to be of the order of 40°C over a 120 year return period (BD37/88, DMRB 1.3). On this basis, a lateral movement of ±6.5mm is predicted at the top of each abutment. This is likely to be of sufficient amplitude to mobilise passive earth pressures in the granular backfill behind the abutments. More detailed studies measuring earth pressures developed behind the abutments of integral bridges will be needed to provide a comprehensive picture.

7. ACKNOWLEDGEMENTS

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