8 Supplementary information: Detailed description of the construction of the Concourse Tunnel

The construction sequence for the Concourse Tunnel used a top heading, bench, top heading, bench, double-invert sequence. The invert was closed five rounds from the face. The construction sequence is schematically illustrated in Figure 1. The advance length varied from 0.8 m to 1.2 m depending on ground conditions and design requirements, including the proximity of sensitive structures. The primary support for the Concourse Tunnel consisted of 350 mm of sprayed concrete (shotcrete), reinforced with two layers of welded wire mesh (8 mm diameter at 150 mm centres) and full-section lattice girders ‘Type 110 ROM E3’. The exposed ground was supported by a 50–100 mm shotcrete sealing layer applied immediately after each advance. The 350 mm total thickness included the sealing layer.

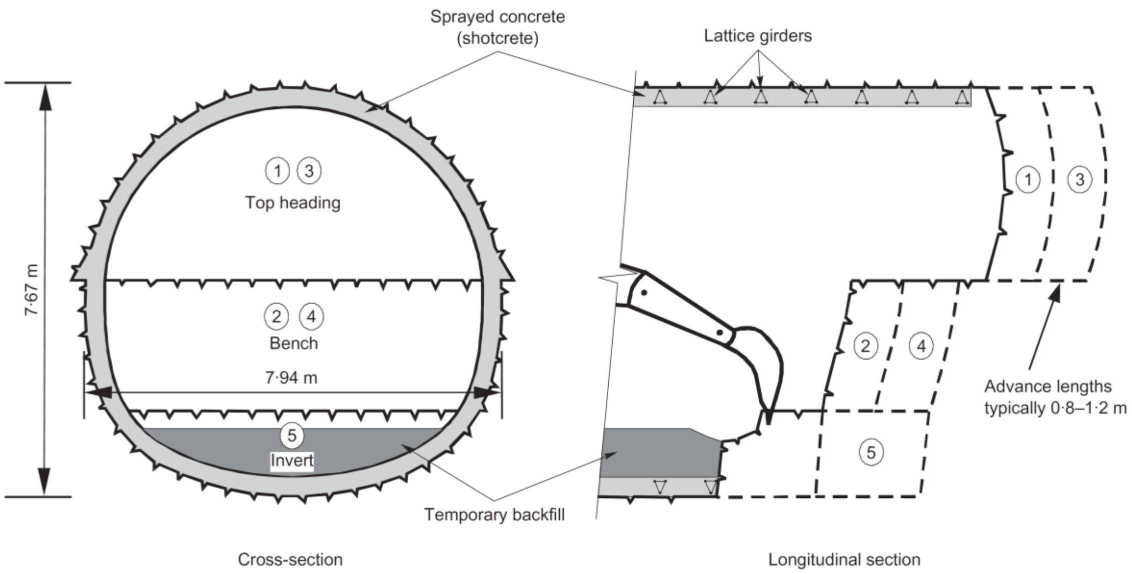

Figure 1: Concourse Tunnel construction sequence (from van der Berg et al., 2003)

The typical construction procedure was as follows. Excavation was carried out using a track-mounted excavator. With a skilled operator, the excavation could be carried out sufficiently accurately that only limited hand trimming was needed to bring the tunnel to the required shape. After the excavation had been trimmed with pneumatic clay spades, spacers comprising T-shaped pieces of mesh were driven into the London Clay. Areas where the radial pressure cells were to be placed were prepared and covered with timber (van der Berg et al., 1998a). The sprayer then applied a sealing layer of shotcrete, typically between 50 mm and 100 mm thick, on all the exposed London Clay surfaces, including the face. Following the application of the sealing layer, the radial pressure cells were installed against the ground. Then the lattice girder and first layer of mesh were installed. The mesh was secured tightly to the overlapping mesh and lattice girders to avoid vibration during shotcreting. The area was cleaned using compressed air, to remove all rebound from the sealing layer. The first layer of shotcrete was then applied. The tangential pressure cells were then secured in their positions in the centre of the lining thickness with their longest dimension (200 mm) in the longitudinal tunnel direction and 100 mm dimension in the radial orientation. A second layer of shotcrete was then applied. Then the second layer of mesh was fixed and finally, a third layer of shotcrete was applied. Some excavated material was used to fill the invert of the tunnel, which served as a working platform and access when excavating the top heading and bench.

Strain gauges were welded to approximately 500 mm long 8 mm diameter reinforcement bars and the bars were then fixed to either the outer or the inner layer of mesh in the tangential orientation.

This paper will focus on the pressure cells installed in Main Monitoring Section I (MMS I) and Main Monitoring Section VIII (MMS VIII) of the Concourse Tunnel. The locations of these sections are shown in Figure 2 and in the location plan (**Error! Reference source not found.**).

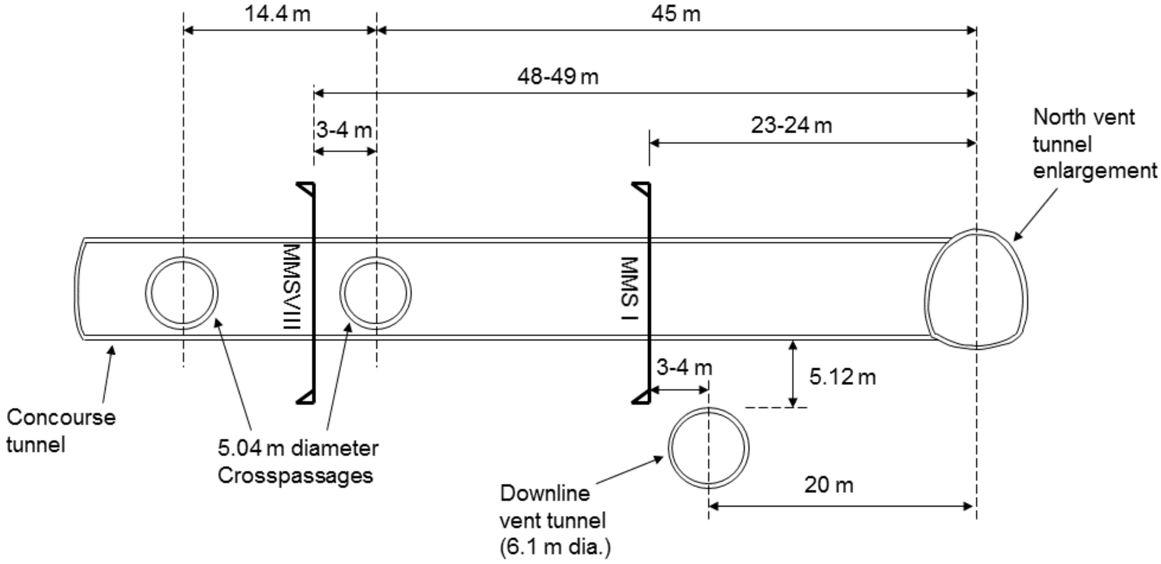

Figure 2: Long section of the Concourse Tunnel showing locations of MMS I and MMS VIII

At each section, 12 tangential pressure cells and 12 radial pressure cells were installed. The locations are shown in Figure 3. In MMS I there were no tangential pressure cells installed at positions 10 and 11, but positions 4 and 5 were equipped with two tangential pressure cells, one near the extrados and one near the intrados. In MMS VIII again no tangential pressure cells were installed at positions 10 and 11, but two were installed at positions 6 and 7 near the extrados and intrados. Where two tangential cells were installed at the same position, the 'OUT' one was centred 110 mm from the extrados and the 'IN' one was centred 230 mm from the extrados and 120 mm from the intrados. Therefore, the 'OUT' pressure cell had a cover of at least 60 mm, the 'IN' pressure cell had a cover of 70 mm to the theoretical spraying profile, and there was 20 mm between the 'OUT' and 'IN' pressure cells.

For 5 m either side of the centreline of the Downline Vent Tunnel, which encompasses MMS I, additional welded wire mesh with 7 mm bars at 100 mm spacing in the longitudinal direction and 7 mm bars at 200 mm spacing in the circumferential direction was placed at the intrados in the invert. The same type of additional mesh was placed in the crown intrados over a 22.5 m length encompassing both pairs of crosspassages, and hence including the location of MMS VIII.

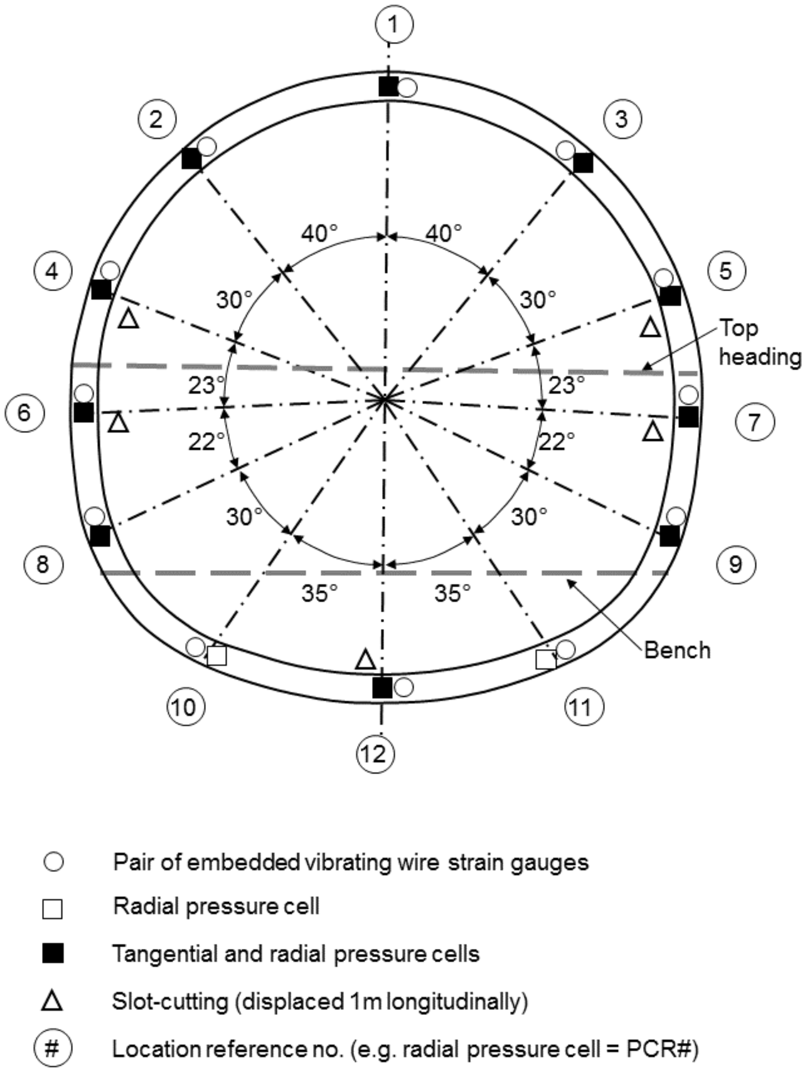

Figure 3: Main monitoring section schematically showing locations of pressure cells and strain gauges embedded in the sprayed concrete primary lining

The radial pressure cells installed in the Concourse Tunnel were Geokon model 4850-2 oil-filled vibrating wire cells, and the tangential pressure cells were Geokon model 4850-1 oil-filled vibrating wire cells. The technical specifications were given in Jones & Clayton (2021).

Table 1 lists construction events that may have affected stress measurements at MMS I and MMS VIII. The timings of excavation steps and pouring of the cast in situ secondary lining come from the construction records and the timings of spraying the primary lining are identified by a temperature rise measured in the thermistors attached to the tangential pressure cells. For the top heading and invert of MMS VIII, it is likely that the excavation was completed at least 30 minutes earlier than indicated in the construction records. Compensation grouting events were reported in Clayton et al. (2006). The timing of installation of the full round of the secondary lining is not known precisely but the construction programme indicates it would have begun approximately 6 weeks after waterproof membrane installation was complete and would have taken approximately 4 weeks to travel from the headwall to the North Vent Tunnel Enlargement. It therefore would have been completed around the middle of March 1997.

MMS I	
14th October 1996 02:00	Top heading excavated
14th October 1996 11:00	Top heading primary lining sprayed
15th October 1996 14:00	Bench excavated
15th October 1996 15:00	Bench primary lining sprayed
16th October 1996 16:00	Invert excavated
17th October 1996 03:00	Invert primary lining sprayed
18th November 1996	Compensation grouting
18th November 1996 11:30	Invert secondary lining cast
29th November 1996	Full round sheet waterproofing membrane installed
3rd December 1996 (approx.)	Underpassing of Downline Ventilation Tunnel (c.f. Figure 2)
MMS VIII	
26th October 1996 12:00	Top heading excavated
26th October 1996 12:00	Top heading primary lining sprayed at positions 1-3
27th October 1996 05:30	Top heading primary lining sprayed at positions 4 and 5
27th October 1996 17:00	Bench excavated
28th October 1996 19:00	Bench primary lining sprayed
28th October 1996 15:30	Invert excavated and primary lining sprayed
7th – 14th November 1996	Crosspassage construction (c.f. Figure 2)
18th November 1996	Compensation grouting
12th December 1996 (approx.)	Invert secondary lining cast
6th January 1997	Full round sheet waterproofing membrane installed

Table 1: Construction events that may affect stress measurements at MMS I and MMS VIII

9 Supplementary information: Detailed interpretation of pressure cell readings

9.1 MMS I radial pressure cells

At the time the secondary lining was cast approximately 1 month after installation, 10 out of 12 of the MMS I radial pressure cells were functioning well. This reduced to 7 out of 12 at 18.6 years.

PCR5 measured large negative pressures from the time it was sprayed in, therefore the results are not plotted from then on. It is unlikely that a pressure cell would have sufficient adherence to the ground and the lining to measure negative pressures, and in any case these negative pressures were higher than the cavitation pressure and therefore must have been due to a fault. PCR5 permanently ceased to respond sometime between 172 and 269 days. PCR4 began to give unstable readings from about the time the bench was sprayed, therefore the results are not plotted from then on. It ceased to respond after 7 days. PCR2 stopped working sometime between 50 and 56 days. PCR1 gave anomalous readings at 85 and 95 days, then stopped responding at 172 days, so from the 85 day reading onwards the results are not plotted. PCR8 stopped working sometime between 95 and 172 days. PCR9 stopped working between 8.4 years and 18.5 years.

9.2 MMS VIII radial pressure cells

Survivability of the MMS VIII radial pressure cells was much better than for MMS I. Although there were short periods when readings were not obtained from one or more radial pressure cells, all 12 were still measuring radial stresses at 8.3 years and all except PCR7 were giving readings at 18.6 years. At PCR2 and PCR12 the thermistors stopped working sometime between 1.1 and 2.0 years, and at PCR12 the thermistor stopped working sometime between 8.3 and 18.5 years. In order to apply the calibration correction for the vibrating wire transducer, the nearest tangential or radial pressure cell thermistor was used for the temperature at these locations.

9.3 Tangential pressure cells

The tangential pressure cell readings were interpreted according to the procedure set out in Jones & Clayton (2021). The temperature sensitivity of the vibrating wire transducer was removed. The cell action factor was assumed to be equal to unity. The mean 28 day compressive strength of sprayed concrete cores at Heathrow Terminal 4 was 35.8 MPa. The compressive strength development was assumed to be similar in shape to the relationship of Kuwajima (1999) based on a form of equation first proposed by Byfors (1980), given in Equation 1. The equation is bilinear in log-log space with the transition occurring at compressive strength $f_c = 10\ \mathrm{MPa}$.

$$f_c = \frac{a_1 t^{b_1}}{1 + \frac{a_1}{a_2} t^{(b_1 - b_2)}} \cdot \frac{f_{c,28d}}{100} \qquad \text{(Equation 1)}$$

where t is the age of the sprayed concrete in hours, a_1 is the strength ratio at 1 hour in percent (i.e. $f_{c,1h}/f_{c,28d}$), b_1 is the gradient of the first line ($f_c < 10\ \mathrm{MPa}$), b_2 is the gradient of the second line ($f_c > 10\ \mathrm{MPa}$), and a_2 is the remaining constant to give $f_c = f_{c,28d}$ at $t = 672\ \mathrm{h}\ (= 28\ \mathrm{d})$.

Kuwajima (1999) proposed the following values in Table 2 for the constants, for an alkaline accelerator used in Edmonton, Canada. For comparison, values for unaccelerated plain concrete by Byfors (1980), and values fitted by Jones (2005) to early age core tests for Heathrow Terminal 5 using an alkali-free accelerator are given. In particular, Kuwajima's value for the strength ratio at 1 h is much higher than for T5, because alkaline accelerators give a much higher strength at 1 h than modern alkali-free accelerators. Since the T4 concourse tunnel used alkaline accelerator, the Kuwajima values were used.

	a_1 (%)	a_2 (%)	b_1	b_2	f_{cc}^{28d} (Mpa)
Byfors (1980)	0.001-0.005	41.52	3.236	0.135	various
Kuwajima (1999)	0.300	29.446	2.676	0.188	29.022
T5 (Jones, 2005)	0.023258	36.9089	3.23525	0.1531	62.8
Used in this study	0.300	29.446	2.676	0.188	35.8

Table 2: Comparison of constants for Byfors' equation

The Young's modulus E was estimated from the compressive strength using the relationship proposed by Chang & Stille (1993), shown in Equation 2. The 28 day Young's modulus E_{28d} was therefore 33 GPa.

$$E = 3.86 f_c^{0.6} \quad \text{(Equation 2)}$$

No laboratory tests were available for shrinkage parameters so a value of 500 microstrain was used for the final shrinkage $\varepsilon_{sh,\infty}$ and shrinkage parameter B was assumed to be 55 days. Shrinkage was assumed to stop after installation of the sheet waterproofing membrane, thus the maximum shrinkage strain varied between 180 and 230 microstrain, depending on location. For the invert pressure cells (PCT10-12), this occurred just prior to pouring the invert secondary lining. For the rest of the pressure cells, this occurred at the time of membrane installation. Dates were given in Table 1. There were no laboratory tests for coefficient of thermal expansion of the shotcrete, so it was assumed to be 11.8 microstrain/°C.

9.4 MMS I tangential pressure cells

At the time the secondary lining invert was cast approximately 1 month after installation, all the tangential pressure cells were still functioning. However, at the time of the underpassing of the vent tunnel, about 50 days after installation, PCT2 and PCT3 stopped functioning. The reason for this is not known. At some point between readings at 95 and 171 days, PCT4-IN stopped functioning. Then between 3.1 and 7.7 years, PCT1, PCT5-OUT and PCT6 all stopped functioning. For the most recent readings at 18.5 and 18.6 years, only PCT7, PCT8, PCT9 and PCT12 were still working.

9.5 MMS VIII tangential pressure cells

Survivability of the MMS VIII tangential cells was marginally better than for MMS I, with 6 still functioning at 18.6 years. PCT4 stopped functioning at 25 days, just after being crimped. PCT8 stopped between 46 and 71 days. PCT1, PCT3, PCT6-OUT and PCT7-OUT stopped responding at some point between 8.3 and 18.5 years. In addition, results from 4 pressure cells have been curtailed because recorded pressures decreased below zero indicating they had lost contact. This occurred for PCT2 at 38 days, PCT3 at 44 days, PCT6-IN at 46 days and PCT6-OUT at 71 days.