

Fire Protection of Tunnel Joints for the A55 Conwy Immersed Tube Tunnel

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ABSTRACT

This paper presents the design of a passive fire protection system for the joints in the Conwy immersed tube tunnel in Wales. The design presented a number of challenges, including seasonal movements of the elements with respect to each other, and significant misalignments between the element edges. The final design was developed following a series of fire tests and simulations carried out using CFD models of the passive fire protection system. The CFD models generally showed a good correspondence with measured data, with deviations being on the conservative side. A final set of CFD simulations were then carried out to predict the performance of the protection systems proposed for the six primary joint types within the tunnel. The designed solution has subsequently been successfully installed in the Conwy Tunnel.

KEYWORD: tunnel passive fire protection, joint protection, CFD, immersed tube

INTRODUCTION

Conwy Tunnel is a twin-bore immersed tube tunnel that forms part of the A55 under the estuary of the River Conwy near the town of Conwy on the north coast of Wales. The A55 Chester to Holyhead Trunk Road forms part of the Trans-European Road Network (TERN) route E22. Conwy Tunnel is part of this TERN and as such is subject to the Road Tunnel Safety Regulations 2007. The tunnel is also subject to the requirements of the Regulatory Reform (Fire Safety) Order 2005.

The tunnel is 1090m long, with cut and cover sections of the east and west of 260m and 120m lengths respectively with six immersed tube tunnel sections forming the central 710m section beneath the estuary. Figure 1 shows a typical as-built tunnel cross-section.

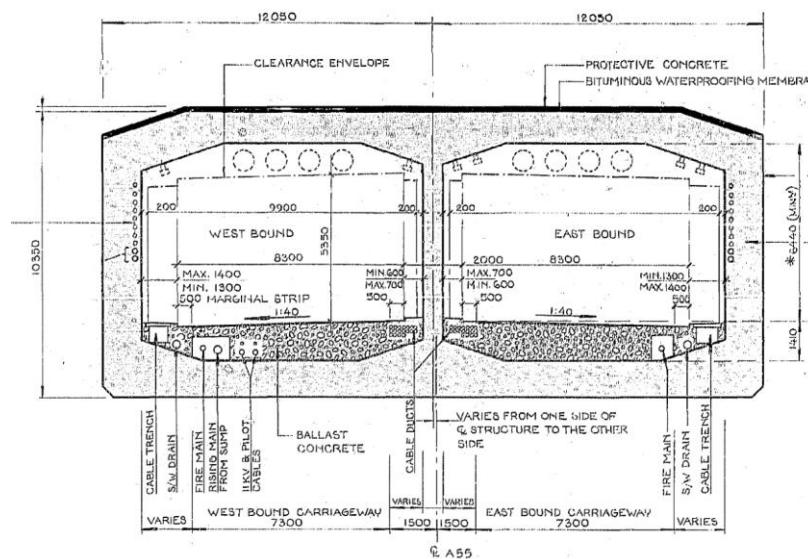


Figure 1 Typical As-Built Tunnel Cross-Section

When opened in 1991, the Conwy Tunnel had no passive fire protection installed to protect its structure. Subsequent studies identified that the element and dilation joints in Conwy Tunnel were vulnerable to fire, with a potential risk of inundation in case of fire-induced damage of the joints. Fire protection to the joints was therefore recommended as a high priority, and the design and installation of a fire protection system to the joints was subsequently commissioned.

CONWY TUNNEL JOINT TYPES

The locations of the tunnel joints are shown in Figure 1. The joints between the immersed elements and the interface between the cut and cover and immersed elements are known as the element joints and are numbered from TEJ1 to TEJ6. The joints between cut and cover sections are known as dilation joints and are numbered from EDJ2 to EDJ5 on the east side and WDJ1 to WDJ3 on the west side.

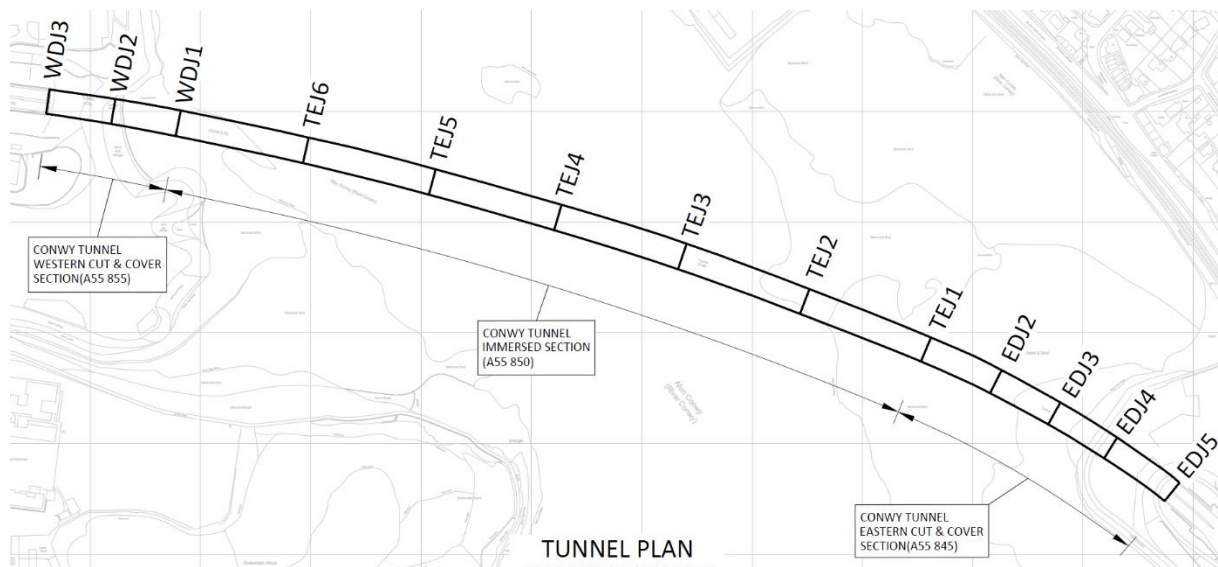


Figure 2: Locations of Tunnel Joints

For both types of joint the areas requiring passive fire protection (walls and soffit) are divided into three discrete regions; external walls, soffit (including the haunches) and internal walls that separate the two bores. Figure 3 shows a typical original element soffit joint, and Figure 4 shows a typical original element internal wall joint.

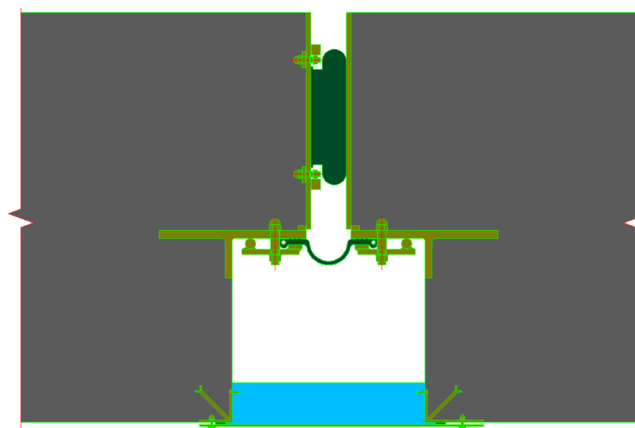


Figure 3: Original Element Soffit Joint

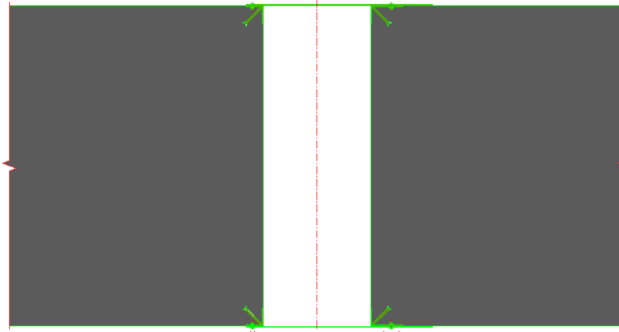


Figure 4: Original Element Internal Wall Joint

Figure 3 and Figure 4 suggests that the two sides of the element joints are completely aligned with one another. In practice this is not the case. Joints can be misaligned vertically (up to 65mm) or rotationally. The passive fire protection must accommodate these misalignments in addition to the seasonal variations in the joint width as the tunnel elements expand and contract. The measured seasonal variations indicated a total range of movement of 9.5mm. For conservatism, a total seasonal movement of 15mm was allowed for.

PASSIVE FIRE PROTECTION CRITERIA

The concrete joints were to be protected against exposure to a 2-hour RWS fire curve. The protection system was deemed satisfactory if all requirements noted below are satisfied.

1. For the primary protection of the joint (up to 335mm from the joint) a maximum average concrete interface temperature of 350°C after 2 hours' fire exposure and an average temperature of 120°C or less at the gasket material (Omega seal). The 335mm length was selected on the basis of experience and the widths of commercially available fire protection boards.
2. The fixing system should not fail during 2 hours of fire exposure. Failure is defined as either partial dislodgement or complete collapse of the fire protection board.
3. No spalling of the concrete in the primary protected area of the joint (up to 335mm from the joint) should occur during 2 hours of fire exposure under the conditions defined above.

The dilation joints were filled with Korkpak. This is a bitumen impregnated cork board material used to prevent the ingress of moisture through a construction joint. If the Korkpak were to be ignited then the fire could potentially propagate through the joint sufficiently to damage the Omega seals. To prevent this occurring it is necessary to limit the temperature of the Korkpak to less than spontaneous ignition temperature. Further it is possible that when warmed, the bituminous element of the Korkpak may flow under gravity to warmer locations where it may spontaneously ignite or come in direct contact with flames. To better determine if bitumen will flow from the Korkpak under fire conditions, physical tests on material removed from the dilation joints were carried out. The results of these tests showed that bitumen did not melt or leak from samples of Korkpak removed from the tunnel at temperatures of up to 120°C. This was adopted as the fire protection criterion for the dilation joints.

PASSIVE FIRE PROTECTION SCHEME

The selected passive fire protection scheme comprises passive fire protection calcium silicate fibre boards (trade name "Promatect-T") spanning across the face of the joint to a sufficient distance beyond the joint to prevent the temperature at the Omega seal reaching its limiting value and to ensure that concrete spalling will not occur within 335mm of the joint. The boards were coated with a special paint (trade name "Ceramiccoat C") to protect them from water ingress and to ensure sufficient reflectivity in the tunnel.

Longitudinal movement is allowed for at the connections between the boards and the walls through slotted holes. Misalignments between the tunnel elements were addressed through usage of packing

boards and the boards' inherent flexibility.

Composite steel/cement impact protection sheets (trade name 'Durasteel') was applied immediately across the face of the joints in order to minimise damage to the joints should any impact occur with vehicles or equipment. Allowance for movement was the connections of these sheets to the boards and walls. Stainless steel edge protection strips was applied in potential impact zones below a nominal level of 3.75m above verge level. All stainless steel used for the edge protection strips was grade 316L.

Individual layers of insulation inserted into the element voids were bagged in aluminium bags which act as vapour barriers against the movement of superheated steam generated from the boards in case of a fire. Figure 5 depicts the protected element soffit joint.

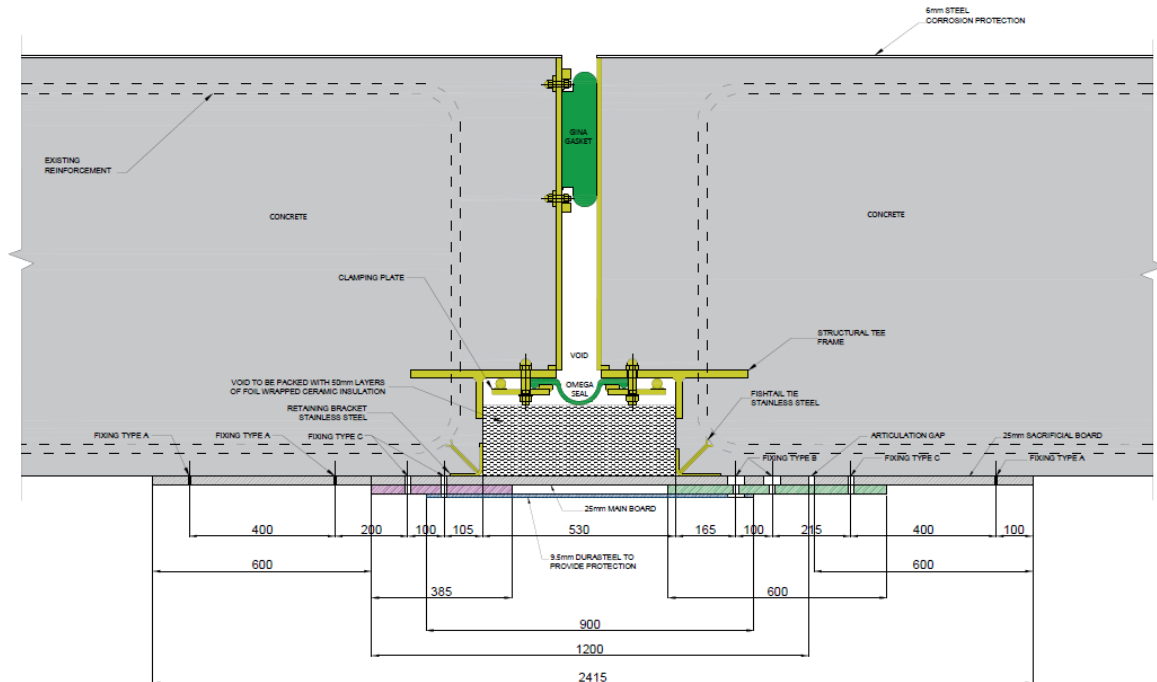


Figure 5: Protected Element Soffit Joint

FIRE TESTING

The following full-scale fire tests were conducted at CSTB in France to verify that the fire protection designs for the element joints would comply with the fire protection requirements:

1. Vertical (wall) element joint (Figure 6)
2. Horizontal (soffit) element joint (Figure 8)
3. Vertical (wall) dilation joint (Figure 10)

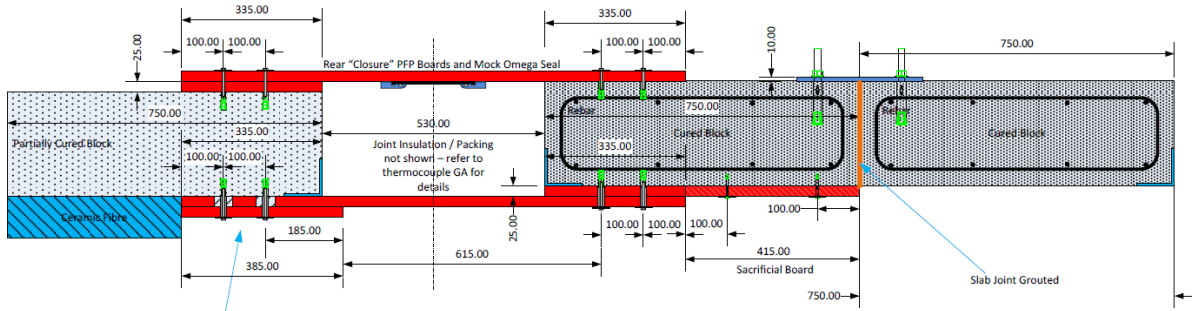


Figure 6: Sectional View of Vertical (Wall) Element Fire Test



Figure 7: Vertical (Wall) Element Fire Test: Preparation of the insulation material and thermocouples positioned on the joint ('cold' side)

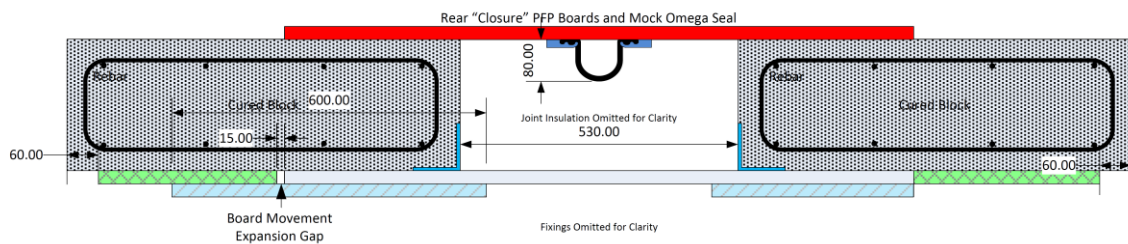


Figure 8: Sectional View of Horizontal (Soffit) Element Joint Fire Test

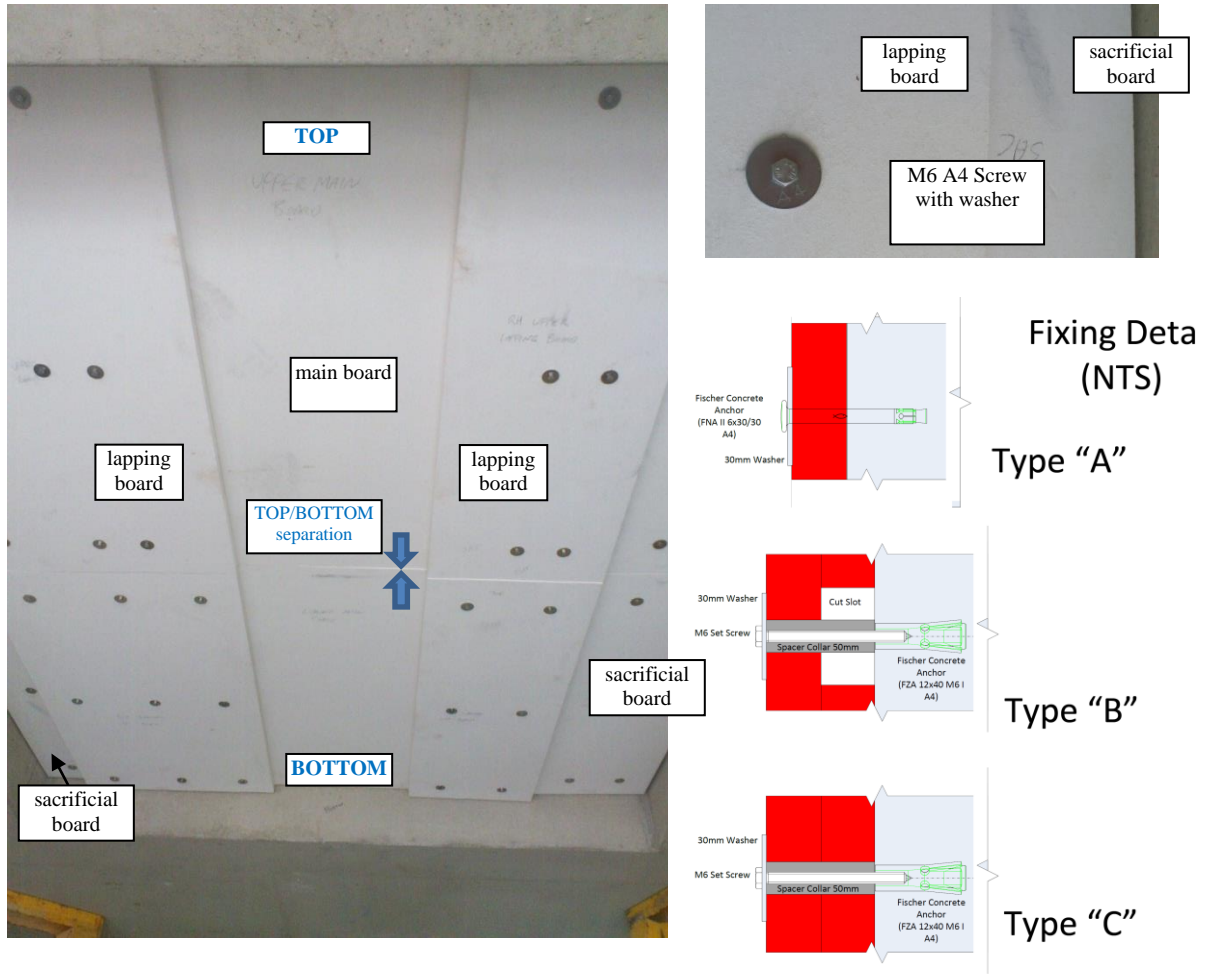


Figure 9 : Horizontal (Soffit) Element Joint Fire Test: Promatect-T (25mm) protection boards positioned on the exposed surface before the test ('hot' side)

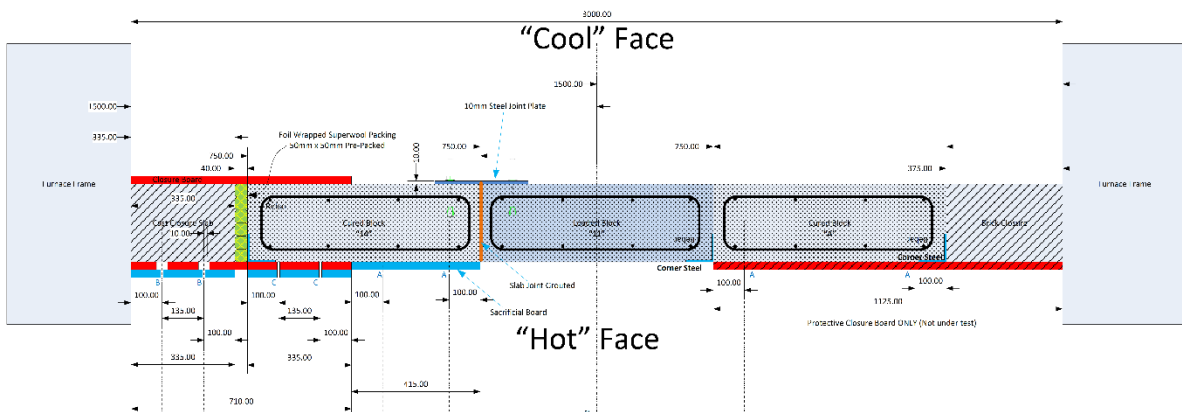


Figure 10: Sectional View of Vertical (Wall) Dilation Joint Fire Test

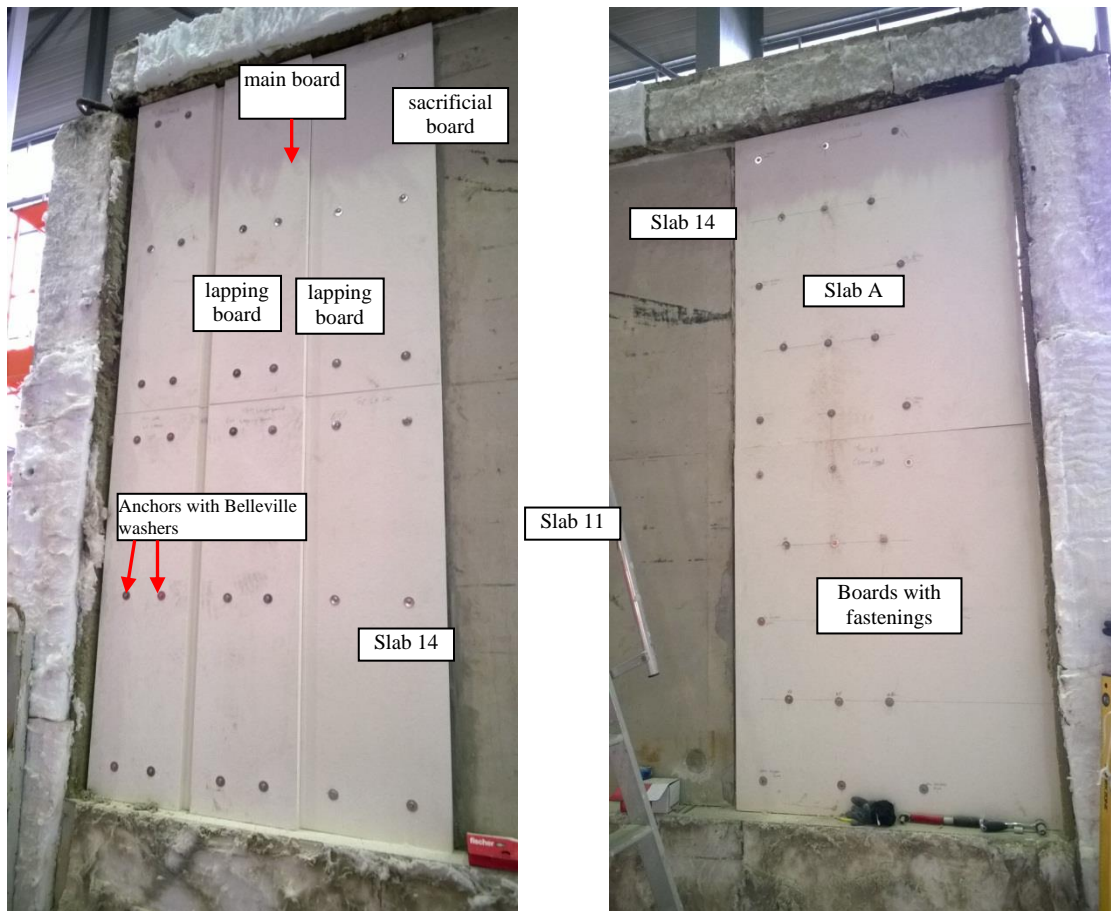


Figure 11 : Vertical (Wall) Dilation Joint Fire Test: Promatect-T (25mm) protection boards positioned on the exposed surface before the test

The fire tests were undertaken using cured concrete blocks with the same material specification as the tunnel (cube strength of 37.5 N/mm^2 and 20mm aggregates). The measured water content of the test blocks was around 5%, which was consistent with core samples taken from the tunnel.

The unprotected slabs in the first and third tests were to be subjected to a compressive stress of 12.5 N/mm^2 , which was the maximum design compressive stress of the tunnel concrete. The extent of concrete spalling is linked to the compressive stress in the concrete, so the concrete in the test slab would then be representative of the maximum compressive stress likely to occur in the tunnel.

An axial load of 2343kN (239 tonnes) would be required to produce a stress of 12.5 N/mm^2 . The loading frame at CSTB was limited to 1765kN (180 Tonnes). A load of 1750kN applied centrally to the slab provided a uniform compressive stress of 9.3 N/mm^2 across the section. The load was displaced to give an eccentricity of 14mm, which gave a combined (axial + bending) compressive stress of 12.5 N/mm^2 on the front face of the unprotected test slabs.

A 10mm steel plate was used to connect the protected and unprotected slabs on the back (cool side), in order to minimise the relative displacement at the front face, and to minimise the appearance of any joint gap between the slabs during fire tests 1 and 3.

The three fire tests confirmed that all the passive fire protection criteria had been satisfied. The measured temperatures are presented in the section below.

CFD MODELLING OF JOINT HEAT TRANSFER

Since there were differences between the test geometries and the actual tunnel construction, it was decided to use 3D CFD modelling to predict the conditions in the vicinity of the joints in the presence of an RWS fire located in the traffic space. Comparisons were also undertaken between the measured test temperatures and 3D CFD predictions of the experimental rigs.

It was recognised early on in the modelling process that the water content of the fire protection boards had to be accounted for. This was due to two reasons: firstly, it became clear that the boards were “held” at around 100°C for a substantial length of time during the tests due to the conversion of water into vapour, implying that reliance upon conduction as the only heat exchange mechanism through the boards would not be appropriate. Secondly, there were concerns that any super-heated steam could penetrate into the insulation and damage the Omega seals.

The three-dimensional (3D) simulations have been undertaken using the three-dimensional finite volume CFD code ANSYS-CFX version 16.1. This mature software is designed for the solution of fluid flow and heat transfer problems and includes options relating to the modelling of radiative heat transfer and multi-phase physics modules.

The solid elements of the joint (fire protection boards, concrete, insulation) are represented as conducting solids through which the computer software can calculate thermal conduction. However, in addition, the software allows the solid to be treated as porous and separate fluid transport equations are solved across the volume representing the flow of water and vapour. The two sets of equations for the solid (conduction only) and fluid (fluid flow and heat transfer) are then interconnected by heat transfer equations to allow for appropriate heat exchange between the solid and the fluids within.

Water embedded in the fire protection board and other porous materials has a significant impact on the rate of temperature rise and the transfer of heat through the materials. As the board (or other material) heats up, liquid water embedded in the material evaporates and forms vapour within the pores of the material, which slightly cools the solid. As the evaporation continues the pressure in the pores will increase and start to drive water vapour and air through the material into cooler regions. At this point, vapour will condense back into water and release heat into the solid.

As fire protection boards and concrete have very small pores and very high resistances to flow, the pressures generated by the water vapour will be high and as a result the local boiling temperature of water will be significantly higher than at atmospheric pressure. If vapour exits the material into a lower pressure environment then it will condense very rapidly back into water until an equilibrium condition is reached. This will tend to occur in the gaps between boards and between boards and adjacent surfaces (concrete and insulation).

Within the CFD code, liquid water is represented using a scalar representing the mass of water per unit volume. Source terms are used to add and subtract water in each computational cell as evaporation and condensation occur. It is assumed that the liquid water is at the same temperature as the solid it is contained within.

In this representation the water itself has no thermal properties; instead the heat capacity of the water and the transfer of thermal energy associated with evaporation and condensation are associated with the solid. This is valid as water and solid are assumed to be at the same temperature.

Water vapour is represented as a mass fraction of a mixture of water vapour and air that exists within the porous medium of the board. The CFD software automatically calculates the thermodynamic and transport properties of the mixture based on this mass fraction.

Source terms are used to add and subtract vapour and thermal energy to the vapour/air mixture in each computational cell as evaporation and condensation occur. Unlike the liquid water, the vapour/air

mixture has thermal properties and a transport equation for the mixture temperature is solved so the mixture and solid can be at differing temperatures. However, in practice there is little or no difference in the dry bulb temperatures of the vapour/air mixture and the solid, due to the very small dimensions of the pores.

At conditions other than boiling (described below), the rate of evaporation or condensation of water is calculated on the basis of:

$$q = uA[m_{surf} - m_v] \quad (\text{Equation 1})$$

where:

q – rate of vapour transfer (kg/s)
u – mass transfer coefficient (kg/(m² s))
A – mass transfer area (m²)
m_{surf} – saturation vapour mass fraction at water ‘surface’
m_v – vapour mass fraction

And mass fractions m_{surf} and m_v are defined so that

$$m = \frac{M_v}{M_v + M_a} \quad (\text{Equation 2})$$

where:

M_v – specific mass of vapour (kg/m³)
M_a – specific mass of air (kg/m³)

The mass fraction of vapour and air is calculated by the CFD code. The saturation mass fraction at the water surface is calculated on the following basis:

It is assumed that the liquid water is at the temperature of the adjacent solid. The saturation vapour pressure at the solid temperature (P_{vs}) is made by reference to steam tables. The concentration of water vapour at the surface (m_{surf}) can then be calculated from the saturation pressure using:

$$m_{surf} = \frac{\omega}{1 + \omega} \quad (\text{Equation 3})$$

$$\omega = \frac{0.622 \cdot P_{vs}}{P_{as}} \quad (\text{Equation 4})$$

$$P_{as} = P_{tot} - P_{vs} \quad (\text{Equation 5})$$

where:

P_{tot} – absolute local pressure (Pa)
P_{as} – partial pressure of air (Pa)

The equations above have been implemented in the computer model and used to calculate the mass transfer between the liquid water equation and the water vapour mass fraction. The heat transfer between the phases is then calculated from the latent heat of vaporisation for water and energy source terms set appropriately.

Experimental or other empirical data for the rates of condensation and evaporation of water within fire protection boards have not been located at the time of writing. Instead the base transfer rate term (uA) has been determined by tuning the model to obtain the best fit possible for the ‘Test 2’ results. The results discussed here assume a base transfer rate (uA) of 0.005 kg/m³.

When the saturation pressure at the solid temperature is greater than the total pressure in the pores within the material then boiling heat transfer will occur.

Heat transfer rates in the boiling regime are dependent upon the difference between the temperature of the surface driving the boiling (for instance the element of a kettle or in this case the temperature of the solid) and the saturation temperature of the air/vapour mixture. This varies as shown in Figure 12.

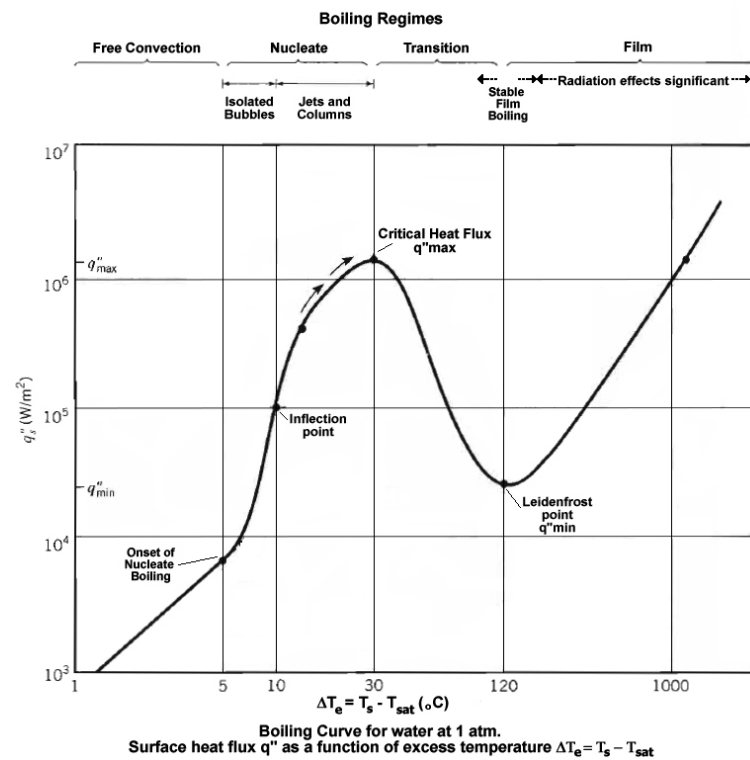


Figure 12: Boiling Heat Transfer Rates (Ref. 1)

This basic boiling behaviour has been implemented in the computer model. It is assumed that with a temperature difference of 1°C that boiling occurs at a rate of 1.23kg/m³s. The rate varies at rates proportional to those shown in Figure 12 .

Although the fire protection board is a solid, it is porous and is filled with many extremely small pores. These pores allow both liquid water and water vapour to pass through the solid albeit at a low rate. There are two mechanisms for the transport of fluid through the solids: diffusion and pressure driven convection. Diffusive transport is calculated by the CFD code using fluid properties and local concentration gradients. The pressure driven transport is calculated by the CFD code from local pressure gradients and pressure loss coefficients for the material.

The velocity of vapour through the material can be calculated from Darcy's law [Ref. 2].

$$v_G = \frac{KK_G}{\mu_G} \nabla P_G \quad (\text{Equation 6})$$

where

- V_G – velocity of vapour/air mixture (m/s)
- P_G – pressure difference (Pa/m)
- μ_G – dynamic viscosity of vapour/air mixture (m²/s)
- K – intrinsic permeability of board (m²)
- K_G – relative permeability of vapour/air mixture

The intrinsic permeability of the board has been measured as 0.0246mdarcy or 2.42x10⁻¹⁷m². The relative permeability of the air/vapour mixture was assumed to be 0.5.

Where possible specific manufacturer's data are used to define material properties backed up by measured data. Where this is not possible generic material data have been used. Concrete properties are taken from BS EN 1992-1-2:2004.

The properties of the passive fire protection boards and the ceramic insulation were based on the manufacturer's literature. The moisture content of the boards at room temperature was measured as 5.3%. The porosity of the boards was measured as 57.9%, and the mean pore diameter was measured as 0.1421 μ m.

A contact resistance equivalent to a heat transfer coefficient of 25W/(m²K) was used at all the interfaces.

Figure 13 depicts the calculated and measured board interface temperatures for one of the tests. The CFD calculations were in reasonable agreement with the measured results, and that provided confidence with for the designed arrangement.

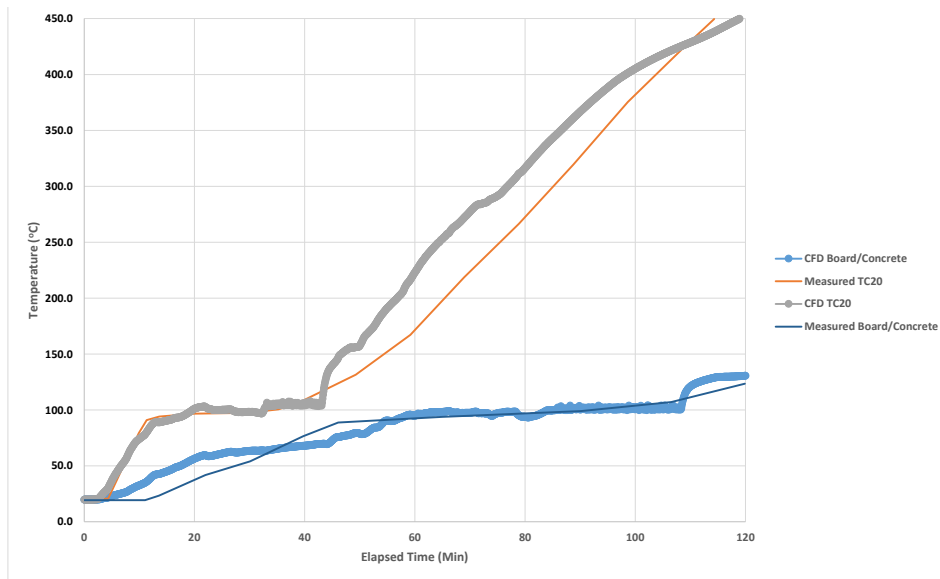


Figure 13: Board Interface Temperatures (Calculated versus Measured)

The CFD calculations were subsequently repeated for all tunnel joint types for the proposed construction, to confirm that the passive fire protection requirements were met.

PASSIVE FIRE PROTECTION INSTALLATION

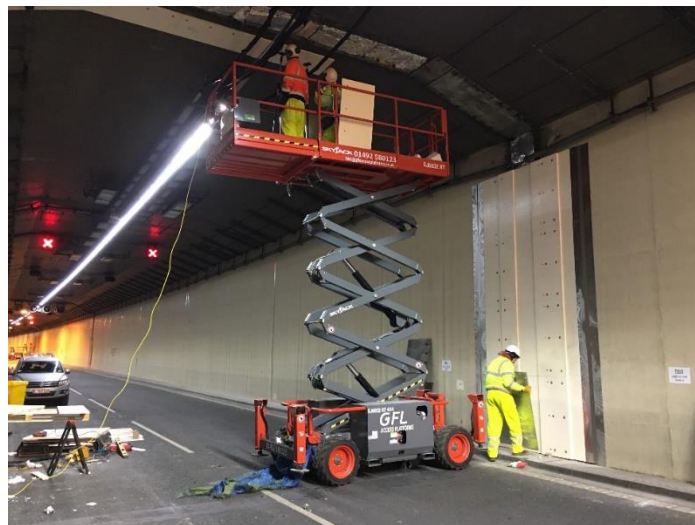


Figure 14: Installation of fire protection boards on tunnel wall



Figure 15: Passive fire protection boards installed on tunnel soffit

CONCLUSIONS

A passive fire protection system for the joints in the Conwy immersed tube tunnel has been designed, tested and installed. The design was arrived at following a series of physical tests and simulations carried out using CFD models of the passive fire protection system. Following the completion of the physical tests, the predictions of the computer models were tested and compared with measured data. A final set of simulations were then carried out to predict the performance of the protection systems proposed for the six primary joint types within the tunnel. The design has received technical approval and has been successfully installed in the Conwy tunnel.

ACKNOWLEDGEMENTS

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REFERENCES

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