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Special Issue: Women in STEM

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Foreword

Welcome to the latest edition of our AtkinsRéalis Technical Journal. In this issue, we proudly feature papers with women as lead-author, highlighting the significant contributions from women in Science, Technology, Engineering, and Mathematics (STEM). Behind these exceptional papers, reflecting the expertise, creativity, and commitment to excellence of our female engineers and consultants, is our own organizational commitment to championing equality, diversity and inclusion and all of the benefits this brings for the wider profession.

This edition features some of the work we have been doing in civil and structural engineering, nuclear engineering, transport planning and asset management, water and environment, and mining. It highlights our efforts to reduce the carbon in new infrastructure, extend the safe life of existing assets, and help safeguard the environment from a variety of threats.

To drive carbon reduction in new infrastructure, we have highlighted best practice during early-stage optioneering in transport schemes at the time when the greatest influence on carbon reduction can be achieved. We have carried out research into reducing thermal bridging in buildings using multicellular clay bricks to improve energy efficiency whilst maintaining sustainable and efficient construction practices. And we have made recommendations for reducing embodied carbon in the design of precast concrete, sprayed concrete, and spheroidal graphite iron tunnel linings, through innovative optioneering, design efficiency, material selection, and specification choices.

In extending the safe life of existing assets, we have undertaken an evidence review for the UK Department for Transport demonstrating the benefit-cost ratio and value for money of investing in local highway maintenance, helping highway authorities make the case for investment at local, regional, and national levels. And we have used digital twinning technology developed and validated by AtkinsRéalis to support the continued operation of UK nuclear power stations, ensuring energy security and supporting Net Zero objectives.

In helping safeguard the environment, we have conducted research to address the pressing challenges posed by trace contaminants in wastewater treatment works and provided essential evidence for optimizing investments, informing regulatory decision-making, and enhancing treatment strategies across England and Wales. We have set out the case for constructing buttresses to stabilize existing tailings dams, preventing failure and harmful release of tailings into the natural environment, and provided guidance on how to design buttresses. And we have undertaken predictive simulations to help derisk first-of-a kind nuclear facilities at Hanford, USA, through the provision of critical insights into the expected performance of the complex preparation, treatment, vitrification and immobilization of low activity waste.

The above examples provide only a small insight into the wealth of innovation that AtkinsRéalis creates day to day and we hope you find this collection of papers as enjoyable, inspiring and informative as we do. Thank you for joining us in celebrating the remarkable contributions of women in STEM and in helping us encourage more women to pursue careers in this dynamic and rewarding field.

CHRIS HENDY

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Avant-propos

Bienvenue dans la toute dernière édition de la Revue technique d'AtkinsRéalis. Dans ce numéro, nous présentons fièrement des articles avec des femmes en tant qu'auteures principales, soulignant les contributions importantes des femmes en science, technologie, ingénierie et mathématiques (STIM). Derrière ces articles exceptionnels, qui témoignent de l'expertise, de la créativité et de l'engagement envers l'excellence de nos ingénieures et consultantes, se trouve notre propre engagement organisationnel à promouvoir l'égalité, la diversité et l'inclusion et tous les avantages que cela apporte à l'ensemble de la profession.

Cette édition présente une partie du travail que nous avons accompli dans les domaines de l'ingénierie civile et structurale, de l'ingénierie nucléaire, de la planification des transports et de la gestion des actifs, de l'eau et de l'environnement, et des minéraux. Elle met en avant les efforts que nous déployons pour réduire les émissions de carbone dans les nouvelles infrastructures, prolonger la durée de vie des actifs existants et contribuer à protéger l'environnement contre diverses menaces.

Afin de favoriser la réduction des émissions de carbone dans les nouvelles infrastructures, nous avons mis en lumière les meilleures pratiques à adopter lors du choix d'options à un stade précoce dans les programmes de transport au moment où il est possible d'avoir la plus grande influence sur la réduction des émissions de carbone. Nous avons mené des recherches sur la réduction des ponts thermiques dans les bâtiments en utilisant des briques d'argile multicellulaires pour améliorer l'efficacité énergétique tout en maintenant des pratiques de construction durables et efficaces. Nous avons aussi fait des recommandations pour réduire le carbone intrinsèque dans la conception des revêtements de tunnel en béton préfabriqué, béton projeté et fonte à graphite sphéroïdal, grâce à des options novatrices, à l'efficacité de la conception, au choix des matériaux et aux choix de spécifications.

En prolongeant la durée de vie des actifs existants, nous avons entrepris un examen des données probantes pour le ministère des Transports du Royaume-Uni, démontrant le ratio avantages-coûts d'un investissement dans l'entretien des routes locales et l'optimisation des ressources réalisable dans le cadre de cet investissement, aidant ainsi les autorités routières à plaider en faveur d'investissements aux niveaux local, régional et national. Nous avons également utilisé la technologie de jumelage numérique développée et validée par AtkinsRéalis pour soutenir l'exploitation continue des centrales nucléaires du Royaume-Uni, garantir la sécurité énergétique et soutenir les objectifs nets zéro.

En participant à la protection de l'environnement, nous avons mené des recherches pour relever les défis pressants posés par les contaminants à l'état de traces dans les installations de traitement des eaux usées et nous avons fourni des preuves essentielles pour optimiser les investissements, éclairer la prise de décisions réglementaires et améliorer les stratégies de traitement en Angleterre et au pays de Galles. Nous avons exposé les arguments en faveur de la construction de contreforts pour stabiliser les digues à résidus miniers existantes, prévenir les défaillances et les rejets nocifs de résidus dans le milieu naturel, et fourni des directives sur la façon de concevoir des contreforts. Nous avons également entrepris des simulations prédictives pour aider à éliminer le risque lié à l'exploitation d'installations nucléaires uniques en leur genre à Hanford, aux États-Unis, en fournissant des renseignements essentiels sur le rendement attendu de la préparation, du traitement, de la vitrification et de l'immobilisation complexes des déchets de faible activité.

Les exemples ci-dessus ne donnent qu'une petite idée de la richesse de l'innovation que crée quotidiennement AtkinsRéalis et nous espérons que vous trouverez cette série d'articles aussi agréable, inspirante et informative que nous. Merci de vous joindre à nous pour célébrer les contributions remarquables des femmes en STIM et pour nous aider à encourager davantage de femmes à poursuivre une carrière dans ce domaine dynamique et enrichissant.

Editor-in-chief

Production Team

2024 Editorial Board Members

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01: Evaluating the Impact of Multicellular Clay Bricks in Mitigating Thermal Bridging in Light Gauge Steel Frame UK Housing Envelopes

Significance Statement

Nearly 30% of heat loss in UK homes happens through conductive materials at key points like walls and windows. Known as thermal bridging, this issue causes cold spots, mould, and affects overall building performance. As Light Gauge Steel Frame (LGSF) construction becomes more popular, managing thermal bridging is essential. This research explores how multicellular bricks can significantly reduce thermal bridging and boost thermal performance while supporting sustainable construction practices. With building regulations raising the bar for thermal standards, this innovative solution has broad applications - from high-end residential to social housing and low-rise buildings like schools. By integrating these findings, we can design smarter, more sustainable structures that meet today's demands for energy efficiency and comfort.

Énoncé d'importance

Près de 30 % des pertes de chaleur dans les foyers britanniques sont causées par des matériaux conducteurs à des endroits clés comme les murs et les fenêtres. Connu sous le nom de pont thermique, ce problème cause des points froids, de la moisissure et affecte le rendement global du bâtiment. La construction de charpentes d'acier de faible épaisseur gagnant en popularité, il est essentiel de gérer le pontage thermique. Cette recherche explore comment les briques multicellulaires peuvent réduire considérablement les ponts thermiques et améliorer la performance thermique tout en soutenant des pratiques de construction durables. Avec la réglementation du bâtiment qui relève la barre en matière de normes thermiques, cette solution novatrice peut s'appliquer à de vastes domaines, depuis les résidences haut de gamme jusqu'aux logements sociaux et aux immeubles de faible hauteur comme les écoles. En intégrant ces résultats, nous pouvons concevoir des structures plus intelligentes et plus durables qui répondent aux exigences actuelles en matière d'efficacité énergétique et de confort.

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Abstract

Thermal bridging refers to the transfer of heat through a material that is more conductive than the surrounding materials, creating a pathway for heat to flow across a building envelope. In the context of UK housing, thermal bridging is a significant concern due to its impact on energy efficiency, building performance, and occupant's comfort. Around 30% of the total heat loss through a building's fabric can be caused by thermal bridging. With the increasing use of Light Gauge Steel Frame (LGSF) construction to meet the growing demand for housing in the UK, thermal bridging frequently occurs at junctions between different building elements such as walls, floors, roofs and windows. Common examples include wall-to-floor junctions, wall-to-roof junctions, window and door reveals, and corners and intersections. Thermal bridging can lead to several issues such as reduced energy efficiency, cold spots, and risk of moisture and mould. To address thermal bridging in UK housing, Building Regulations such as Part L set standards for thermal performance and require the mitigation of thermal bridging in new construction and major renovations. This often involves using insulation materials, improving building design and employing thermal break technologies to minimize heat loss at junctions and improve overall energy efficiency. This research aims to analyze how multicellular bricks can help mitigate thermal bridging when used in LGSF construction.

KEYWORDS
Thermal Bridging; UK Housing; Light Gauge Steel Framing; Multicellular Clay Bricks

1. Introduction

1.1 WHAT IS THERMAL BRIDGING

The building envelope contains certain areas with low thermal resistance, allowing heat to transfer more easily. Examples include windows, doors, skylights, and thermal bridges. Thermal bridges are specific spots in the building envelope with significantly reduced thermal resistance, typically caused by interruptions in the insulation layers as shown in Figure 1 (Zero Carbon Hub. 2016). The rate of heat flow through a thermal bridge depends on several factors:

- The temperature difference across the thermal bridge.
- The thermal conductivity of the materials that penetrate the insulation layer.
- The cross-sectional area of the thermal bridge.

FIGURE 1

Thermal Bridging

Source: H2x Engineering 2024

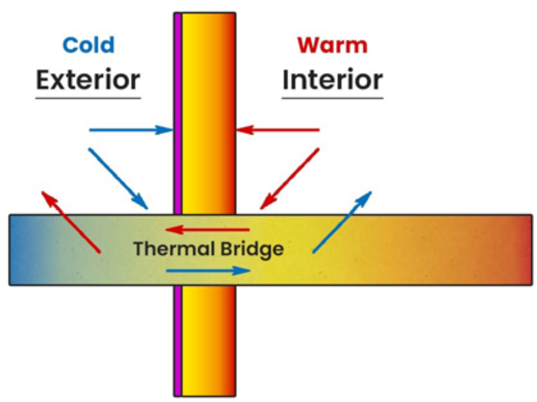
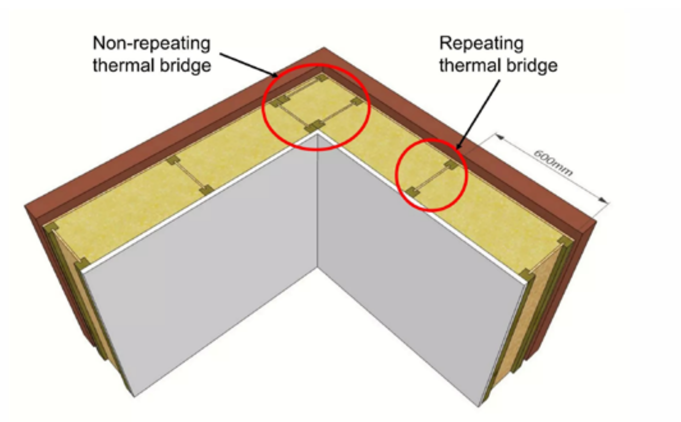


FIGURE 2

Repeating and Non-repeating Thermal Bridge

Source: Mathew Brook, Peat. 2015



1.2 TYPES OF THERMAL BRIDGING

The general categories of thermal bridge are:

Repeating Thermal Bridges – These occur when there are regular interruptions in the building fabric such as studs or wall ties. A repeating thermal bridge occurs at regular intervals within the building structure. These are typically seen in situations like a steel frame wall where the steel members bridge the layer of insulation (see Figure 2). As we know that this is a regular occurrence, we can account for the thermal bridge when we calculate our U-values.

Linear (non-repeating) thermal bridges – occur where there are gaps in the insulation layer around openings such as windows or doors or where a more conductive material penetrates or bridges through the insulation layer. A non-repeating thermal bridge refers to a thermal bridge that occurs sporadically and is not part of a regular pattern of the building (see Figure 2). Examples include junctions where walls intersect with roofs or floors, external wall corners, openings like windows and doors. (Detail Library. 2024).

1.3 CONSEQUENCES OF THERMAL BRIDGING IN UK HOUSING

Thermal bridges should be minimized due to their adverse effects on both the building and its occupants. Here are some key consequences:

- **Higher Heating Needs and Energy Use:** Increased heat loss results in lower internal surface temperatures, which reduces thermal comfort and drives up energy consumption.
- **Indoor air quality:** When warm, moist air meets cold surfaces, condensation forms. Combined with dust, wallpaper paste or paint, this creates a perfect environment for mould growth, which can pose health risks.
- **Risk of structural damage:** Consistent condensation can lead to a damp building with moisture infiltration potentially causing long-term structural damage. Permanently damp building components also cause increased thermal conductivity, which reinforces the thermal bridge

1.4 BUILDING REGULATIONS AND HOW TO CALCULATE THERMAL BRIDGING

To meet Building Control requirements in England and Wales, it is must to comply with Building Regulations. According to the latest Building Regulations Part L (2013) and the associated guidance document for residential construction, Approved Document L1 2021 with 2023 amendments, thermal bridging must be considered into fabric heat loss calculations. The Government Standard Assessment Procedure (SAP 10) is the straightforward model used to demonstrate compliance with carbon emissions targets. The SAP calculation incorporates HTB (heat loss due to thermal bridging), which is calculated or estimated as follows (ShockIsoKorb, 2015):

The sum of all linear thermal transmittances (Ψ) x length of detail (L)

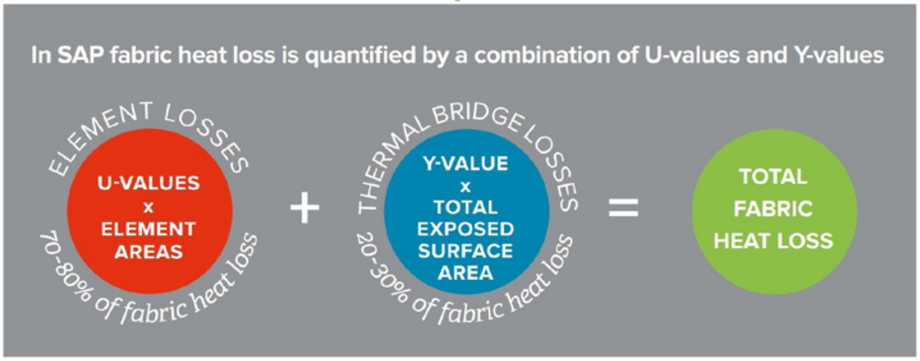
$$HTB = \Sigma(L \times \Psi)$$

The heat loss along a linear thermal bridge is represented by its psi value (Ψ), which is determined through complex thermal modeling as outlined in BR 497 and IP 1/06. Once the psi value is established, the SAP assessor calculates the heat loss for the entire junction by multiplying the psi value by the length of the relevant construction junction (such as the length of a lintel or the junction where the wall meets the floor). The total heat loss from all junctions is then divided by the area of all exposed surfaces (including floors, roofs, walls, windows, doors, and roof lights) to determine the overall *y*-value for the home (see Figure 3).

FIGURE 3

Fabric Heat Loss Calculation Formula

Source: Zero Carbon Hub. 2016



1.4.1 What is PSI Value?

As per BRE 497, The Ψ value represents the extra heat flow through the linear thermal bridge over and above that through the adjoining plane elements. From the numerical modelling of a 2D junction, L^{2D}, is the thermal coupling coefficient between the internal and external environments and is calculated from:

$$L^{2D} = \frac{Q}{T_i - T_e} \ (W/m \cdot K)$$

where:
Q = total heat flow in W/m from the internal to the external environment
T_i = temperature of the internal environment
T_e = temperature of the external environment

Hence the linear thermal transmittance, Ψ, of the 2D junction is the residual heat flow from the internal to external environment after subtracting the 1D heat flow through all flanking elements, expressed in W/m·K and is determined from:

$$\varphi = L^{2D} - \sum (U \times l) \ (W/m \cdot K)$$

where:
L^{2D}= thermal coupling coefficient
U = U-value (W/m·K) of the flanking element
l = length (m) over which U applies

FIGURE 4

Cross-section of a Corner Junction
Source: BRE 497. 2016

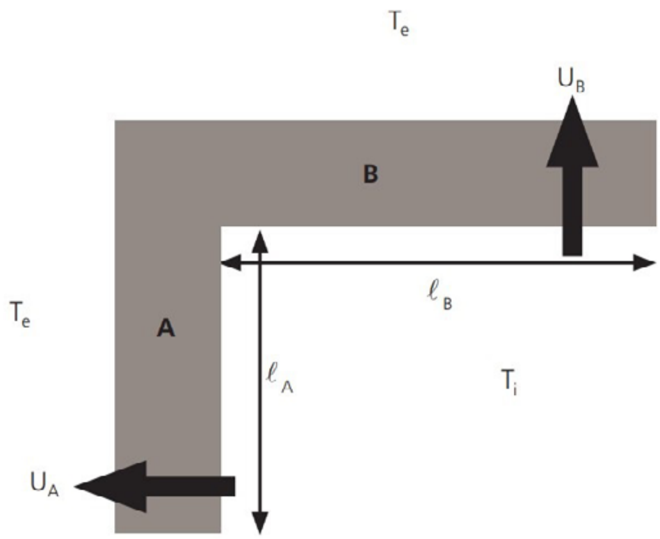


Figure 4 shows a 2D horizontal cross-section of the normal corner junction of a simple masonry wall with flanking elements A and B, whence the Ψ value is calculated from:

$$\varphi = L^{2D} - (U_A \times l_A) - (U_B \times l_B) \ (W/m \cdot K)$$

where:
L^{2D} = thermal coupling coefficient
U_A and U_B = U-values (W/m·K) of the flanking elements A and B
l_A and l_B = lengths (m) over which U_A and U_B apply. (BRE 497, 2016)

2. Methodology

This research aims to explore ways to enhance the exterior skin of Light Gauge Steel Framing (LGSF) construction in UK housing projects to mitigate thermal bridging. The methodology involves several key steps:

- **Analyzing Typical Construction Details:** Review standard LGSF construction details with various materials.
- **Exploring Alternatives:** Identify and assess alternative materials that could be used.
- **Developing Improved Details:** Create updated construction details incorporating the proposed materials.
- **Modeling and Simulation:** Use analysis software to model both standard and improved details for selected thermal bridging junctions and run simulations to evaluate their performance.

2.1 LIGHT GAUGE STEEL FRAMING IN UK HOUSING

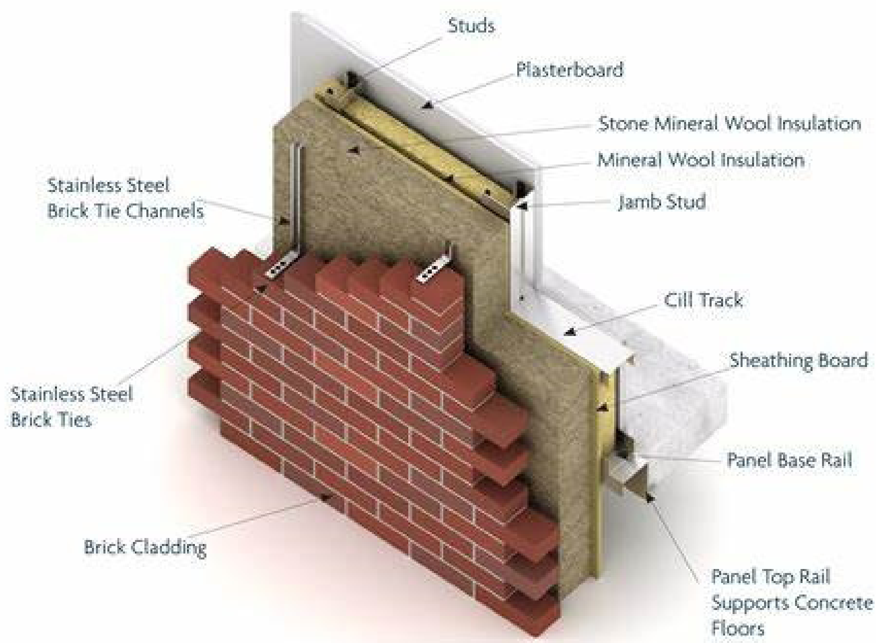
Light Gauge Steel Framing (LGSF) as shown in Figure 5 is increasingly popular in UK housing due to its efficiency, sustainability, and cost-effectiveness. Light gauge steel is a thin sheet (commonly range between 1-3 mm) of steel which has been bent into shape to form C-sections or Z-sections. LGSF offers a lightweight yet robust structural solution that simplifies construction and accelerates project timelines. Its use in residential projects is valued for its flexibility, allowing for versatile design options and ease of integration with various building systems. LGSF is also recognized for its environmental benefits; it often incorporates recycled steel and can contribute to sustainable building practices. However, challenges such as thermal bridging and insulation must be addressed to optimize performance and energy efficiency. Innovations in detailing and material use are critical to overcoming these challenges and enhancing the overall effectiveness of LGSF in residential applications. As the UK construction industry continues to prioritize sustainability and energy efficiency, LGSF remains a prominent choice for modern housing solutions.

FIGURE 5

LGSF Housing Construction in UK

FIGURE 6

Components of LGSF Construction
Source: Sigmat 2024



In a Light Gauge Steel Framing (LGSF) wall used in housing projects, the primary components include (Sigmat, 2024):

- **Studs:** Vertical steel members that form the main framework of the wall.
- **Sheeting:** Panels or sheets, like gypsum plasterboard, attached to the interior side of the studs, providing support and a surface for interior finishes.
- **Insulation:** Material placed between the studs to improve thermal and acoustic performance. This is typically noncombustible material such as mineral wool.
- **Vapour Barrier:** A layer installed to prevent moisture from entering the wall cavity, helping to avoid condensation and mould.
- **Cavity:** An air space between the sheeting and the facing bricks that helps with insulation and moisture control.
- **Brick Ties:** Metal connectors that attach the steel frame to the brickwork, ensuring stability and integration between the LGSF frame and the brick cladding.
- **Facing Bricks:** The exterior layer of the wall, providing a durable, weather-resistant finish and aesthetic appeal as shown in Figure 6.

2.2 EXPLORING MATERIAL ALTERNATIVES

In the UK, it is common practice to use solid facing bricks for the external leaf of a typical two-storey light gauge steel framing house. Recently, concrete facing bricks have become increasingly popular among housebuilders and are now the fastest-growing segment in the UK brick industry. The appeal of concrete facing bricks lies in their availability, with average lead times often under four weeks and many manufacturers maintaining substantial stockpiles. However, the type of brick used can impact the thermal insulation of a building's wall. Bricks differ in thermal conductivity, which measures how easily heat passes through them. For example, solid bricks made from dense materials like concrete have higher thermal conductivity, meaning they transfer more heat and can lead to higher energy costs for heating and cooling. Solid concrete bricks typically have a thermal conductivity of around 1.33 W/mK (Marshalls,. 2024). In contrast, hollow bricks with air pockets offer better insulation. These air pockets reduce heat transfer, helping to keep buildings cooler in the summer and warmer in the winter. Clay bricks, in particular, have low thermal conductivity due to clay's low thermal coefficient, making them effective insulators.

2.2.1 Multicellular Clay Blocks

The multi-cellular clay block walling system is highly regarded across Europe for its exceptional thermal and acoustic performance. Crafted from fired clay, these blocks incorporate multiple internal voids that trap air, enhancing their insulation capabilities. This design effectively reduces heat transfer, leading to lower energy costs and increased comfort in buildings. One notable example is Porotherm by Wienerberger, a multi-cellular clay block system designed to deliver superior thermal insulation and boost energy efficiency as shown in Figures 7 and 8. While Porotherm is a prominent brand, several other manufacturers in Europe offer similar high-performance multi-cellular clay blocks. These bricks are now gaining traction in the UK due to their broad range of benefits, from economic advantages to environmental and lifestyle improvements.

FIGURE 7

PorothermPLS100
Multicellular Clay Brick
by Wienerberger
Source: Wienerberger. 2024

FIGURE 8

Figure 8: Porotherm
Multicellular Clay Brick Wall
Source: Wienerberger. 2024

Fast - Porotherm, with its precision design and lighter weight, offers faster construction compared to traditional masonry. Builders can achieve 25-30 m² per man per day with Porotherm, versus 12-15 m² with conventional methods. Its design allows for quicker watertight completion, enabling finishing trades to start sooner. Porotherm is more stable and rigid, allowing for single-story construction in a day and additionally, the ZeroPlus mortar allows construction down to 0°C, extending the working season in winter (Wienerberger, 2024).

Dry - Porotherm construction uses about 95% less water than traditional methods. For a typical 212 m² building, Porotherm's thin joint mortar requires only 72 liters of water, compared to 1060 liters for traditional mortar. This significantly reduces dependence on local water supplies and speeds up achieving a watertight shell. Additionally, Porotherm blocks are nearly dry, unlike concrete blocks, which can contain up to 30% moisture and require an extra 1000 liters of water in the mortar (Wienerberger, 2024).

Safe - Porotherm blocks are lighter than concrete, reducing strain injuries and maintaining production rates. Their design avoids sharp edges, minimizing cuts, and the use of ZeroPlus mortar with a specialized roller reduces skin risks. Certified to BS EN 771-1, CE marked, and recognized by NHBC and insurance providers, Porotherm is also A1 non-combustible, offering fire resistance throughout construction. The system's reduced mortar handling improves site safety and eliminates repetitive strain injuries common with traditional methods (Wienerberger, 2024).

Sustainable - Porotherm blocks meet all sustainable homes code levels, featuring 30% materials from alternative, recycled, or secondary sources (MARSS). They have an embodied carbon footprint of 17 kg CO_2 e/m² (cradle to gate A1-A3), which is 40% lower than that of concrete blocks. According to Morgan Sindall, a leading UK construction company, using Porotherm blocks in the construction of Addenbrooke Care Home in Gosport, Hampshire, resulted in a saving of 324.5 tonnes of embodied carbon. With a life expectancy of over 150 years, these blocks are also recyclable at end-of-life, such as being repurposed into hardcore. Additionally, they boast an A+ rating in the BRE Green Guide for external walls (Wienerberger, 2024).

Efficient - Porotherm blocks are thermally efficient, helping to stabilize temperature fluctuations, and achieve maximum airtightness. The thermal conductivity of PorothermPLS 100 is 0.029 $\mathrm{W/mK}$. They offer excellent acoustic performance. The blocks are breathable, aiding in humidity regulation when used with other breathable materials. They do not experience moisture shrinkage, which minimizes disruption to finishes, reduces the need for movement joints (to 1:20 linear meters), and lowers the risk of cracking. Porotherm also ensures minimal wastage, with an average of just 2%, enhancing site waste management, reducing costs, and maintaining cleaner sites. Additionally, there is no need for bed joint reinforcement during installation (Wienerberger, 2024).

2.2.2 Insulating External Render

Porotherm blocks require external protection and should not be left exposed to the elements because they are fired at a lower temperature than facing bricks, resulting in lower frost resistance. ProofTherm is one of the insulating external render products widely used across Europe to enhance the insulation of external walls while maintaining high levels of vapor permeability. This render is formulated with expanded Perlite and a lime binder and is applied as an insulating basecoat with a minimum thickness of 20 mm on external walls. The product contains insulating aggregates with microscopic air bubbles arranged in a honeycomb structure. This design minimizes heat transfer, similar to how cavity walls and down-filled jackets provide insulation. Applying a continuous layer of this highly aerated render creates millions of tiny air pockets that significantly resist heat transfer. With an exceptional thermal conductivity value of 0.06 W/mK (ProofShield, 2018), ProofTherm offers substantial insulation, improved thermal comfort, and lower heating costs.

2.2.3 Fixing Detail

Figure 9 shows how the Porotherm Bricks are integrated with the LGSF framework. Specifically, the connection between the Porotherm Bricks and the LGSF is facilitated using Ancon 25/14 Channels and Ancon CCB-SMJ 200. Figure 10 shows how the Ancon Channels and Ties are used to achieve a stable and effective connection between the Porotherm Bricks and the LGSF framework, ensuring structural integrity and proper insulation (Wienerberger, 2023).

FIGURE 9

LGSF Wall Construction Detail with Porotherm Bricks

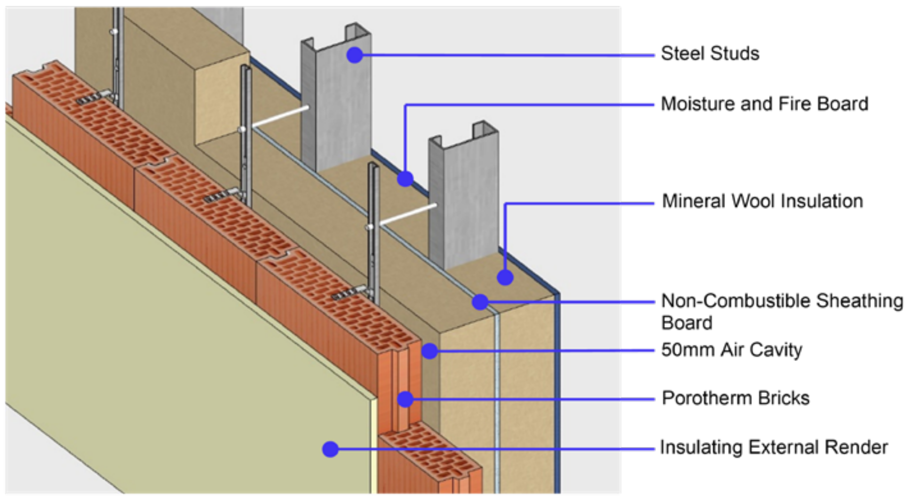
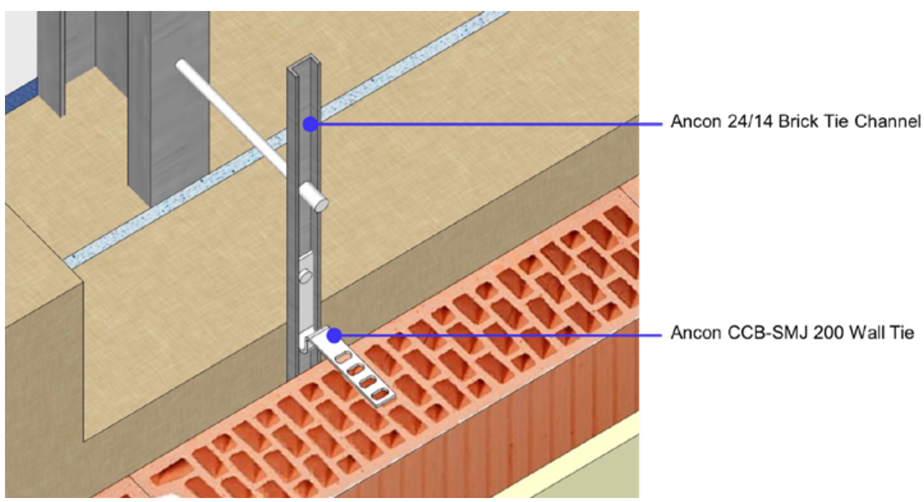


FIGURE 10

Wall ties connecting Porotherm Bricks to Channel



2.3 U VALUE ANALYSIS

A BuildDesk analysis was performed to assess the U-value of a standard light gauge steel framing (LGSF) wall with both concrete facing bricks and multi-cellular bricks, as illustrated in Figures 11 and 12. BuildDesk is a specialized software capable of calculating precise U-values for various building constructions. The analysis indicates a 13% improvement in U-value when using multi-cellular bricks compared to concrete facing bricks, with the U-value decreasing from 0.15 W/(m²K) to 0.13 W/(m²K).

FIGURE 11

U Value Calculation in BuildDesk for LGSF Wall with Concrete Facing Bricks

BuildDesk U 3.4

Documentation of the component
Thermal transmittance (U-value) according to Digest 465
Source: **own catalogue - Technical Journal Paper**
Component: **LGSF Wall - Concrete Facing Bricks**

OUTSIDE INSIDE

This illustration of inhomogeneous layers is provided only to assist in visualising the arrangement.

Assignment: External wall

		Manufacturer	Name	Thickness [m], number	Lambda [W/(mK)]	Q	R [m²K/W]
		Rse					0.0400
☑	1	Marshalls	concrete facing brick & Mortar outer leaf (f = 0.000 / automatic disregard acc. BRE 443)	0.1000	1.330	E	0.0752
☑	2	Unventilated Airspace BR 443	Normal cavity - 50 mm, unventilated	0.0500	0.278	D	0.1799
☑	3	Rockwool Ltd	High Performance Partial Fill Cavity Slab (>80mm)	0.1500	0.035	B	4.2857
		Fixings	Ancon ST1 50-125mm cavity No./m²:	2.5/m²	17.000	C	-
		Fixings	equivalent diameter: 4.982787E-03 m				
		Air gaps	Level 1: dU" = 0.01 W/(m²K)				
☑	4	Siniat Limited	GTEC Weather Defence 12.5mm	0.0125	0.250	B	0.0500
☑	5	Light steel-frame	consisting of:	0.1500	ø 0.205		0.7307
	5a	Rockwool Ltd	Steel Frame Slab 034	99.66 %	0.034	B	-
		Air gaps	Level 1: dU" = 0.01 W/(m²K)				
	5b	BS EN 12524	Steel	00.34 %	50.000	D	-
☑	6	BS EN 12524	Polyethylene 0.15 mm (600 Gauge)	0.0002	0.170	D	0.0009
☑	7	British Gypsum Limited	Gyproc FireLine	0.0150	0.240	D	0.0625
☑	8	British Gypsum Limited	Gyproc FireLine	0.0150	0.240	D	0.0625
		Rsi					0.1300
				0.4927			

$R_T = p^*R_T' + (1-p)^*R_T'' = 7.09$ m²K/W

Correction to U-value for	according to	delta U [W/(m²K)]
Mechanical fasteners	Digest 465	0.0032
Air gaps	BS EN ISO 6946 Annex F	0.0038
		0.0070

$U = 1/R_T + \Sigma\Delta U = 0.15$ W/(m²K)

Q .. The physical values of the building materials has been graded by their level of quality. These 5 levels are the following
A .. A: Data is entered and validated by the manufacturer or supplier. Data is continuously tested by 3rd party.
B .. B: Data is entered and validated by the manufacturer or supplier. Data is certified by 3rd party
C .. C: Data is entered and validated by the manufacturer or supplier.
D .. D: Information is entered by BuildDesk without special agreement with the manufacturer, supplier or others.
E .. E: Information is entered by the user of the BuildDesk software without special agreement with the manufacturer, supplier or others.

Calculated with BuildDesk 3.4.6

FIGURE 12

U Value Calculation in BuildDesk for LGSF Wall with Porotherm Bricks

BuildDesk U 3.4

Documentation of the component
Thermal transmittance (U-value) according to Digest 465
Source: **own catalogue - Technical Journal Paper**
Component: **LGSF Wall - Porotherm Bricks**

30. August 2024
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OUTSIDE INSIDE

This illustration of inhomogeneous layers is provided only to assist in visualising the arrangement.

Assignment: External wall

		Manufacturer	Name	Thickness [m], number	Lambda [W/(mK)]	Q	R [m²K/W]
		Rse					0.0400
☑	1	TBC	external EWICS	0.0200	0.060	E	0.3333
		Air gaps	Level 0: dU" = 0.00 W/(m²K)				
☑	2	Wiienerberger	Porotherm	0.1000	0.290	E	0.3448
☑	3	Unventilated Airspace BR 443	Normal cavity - 50 mm, unventilated	0.0500	0.278	D	0.1799
☑	4	Rockwool Ltd	High Performance Partial Fill Cavity Slab (>80mm)	0.1500	0.035	B	4.2857
		Fixings	Ancon CCB3 for Cellular Clay Blocks No./m²:	2.5/m²	17.000	C	-
		Fixings	equivalent diameter: 3.309057E-03 m				
		Air gaps	Level 1: dU" = 0.01 W/(m²K)				
☑	5	Siniat Limited	GTEC Weather Defence 12.5mm	0.0125	0.250	B	0.0500
☑	6	Light steel-frame	consisting of:	0.1500	ø 0.205		0.7307
	6a	Rockwool Ltd	Steel Frame Slab 034	99.66 %	0.034	B	-
		Air gaps	Level 1: dU" = 0.01 W/(m²K)				
	6b	BS EN 12524	Steel	00.34 %	50.000	D	-
☑	7	BS EN 12524	Polyethylene 0.15 mm (600 Gauge)	0.0002	0.170	D	0.0009
☑	8	British Gypsum Limited	Gyproc FireLine	0.0150	0.240	D	0.0625
		Rsi					0.1300
				0.4977			

$R_T = p^*R_T' + (1-p)^*R_T'' = 7.69\ m^2K/W$

Correction to U-value for	according to	delta U [W/(m²K)]
Mechanical fasteners	Digest 465	0.0012
Air gaps	BS EN ISO 6946 Annex F	0.0032
		0.0044

$U = 1/R_T + \Sigma\Delta U = 0.13\ W/(m^2K)$

Q .. The physical values of the building materials has been graded by their level of quality. These 5 levels are the following
A .. A: Data is entered and validated by the manufacturer or supplier. Data is continuously tested by 3rd party.
B .. B: Data is entered and validated by the manufacturer or supplier. Data is certified by 3rd party
C .. C: Data is entered and validated by the manufacturer or supplier.
D .. D: Information is entered by BuildDesk without special agreement with the manufacturer, supplier or others.
E .. E: Information is entered by the user of the BuildDesk software without special agreement with the manufacturer, supplier or others.

Calculated with BuildDesk 3.4.6

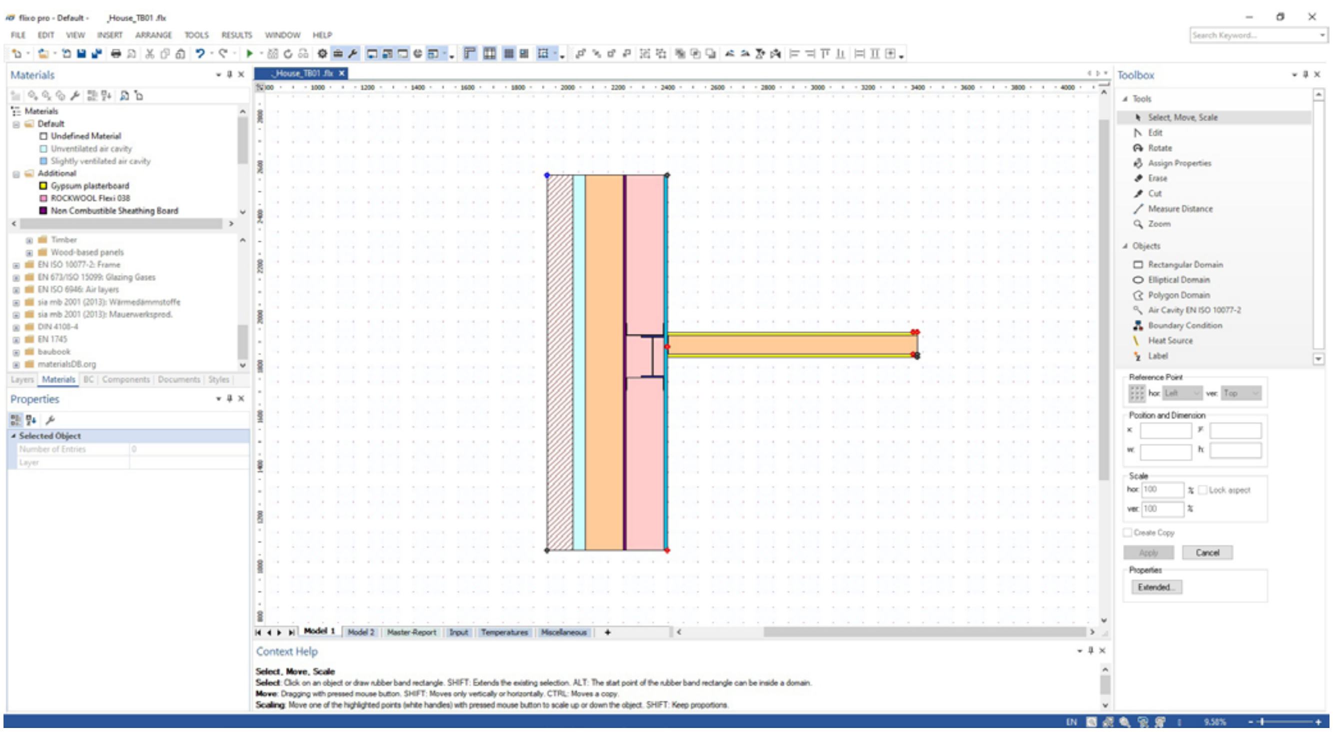
2.4 THERMAL BRIDGING ANALYSIS TOOL

2.4.1 What is Flixo?

Flixo is a tool to analyse the thermal properties of a design or construction, and to document those results (see Figure 13). It calculates and gives an overview of temperatures and heat flux densities; it shows temperatures in specific places along with other global thermal properties. With Flixo, thermal bridges can be analysed at the planning stage and their effects minimised through changes in the design. Flixo supports the new version of the EN ISO 10077-2 standard and complies with all current standards for the calculation of thermal bridges (Flixo, 2024).

FIGURE 13

Flixo Software Interface



2.4.2 Workflow in Flixo

Typical Flixo workflow is divided into the following parts:

- **Entering Model Geometry:** Start by creating a new project and defining the geometry of the building element or importing an existing CAD model into Flixo. Input the different construction layers, such as insulation, walls, and windows, including their dimensions and materials.
- **Defining Materials:** Assign the thermal properties (e.g., thermal conductivity, heat capacity) to each material layer based on their specifications.
- **Defining Boundary Conditions:** Set the boundary conditions for the model, including indoor and outdoor temperatures, as well as other relevant environmental factors.
- **Running Calculations and Evaluating Results:** Run the analysis to calculate temperatures, heat flux densities, and U-values for the modelled elements. Review the results for thermal performance and identify any areas where heat loss or gain may be significant.

2.5 MODELLING AND SIMULATION

For the purpose of this research, the following three Junctions of a typical LGSF two-storey UK housing are examined and labelled for convenience as TB01, TB02, and TB03, where “TB” denotes “Thermal Bridging.” These junctions are as follows:

a) TB01 - External Wall to Intermediate Floor
b) TB02 - Window Jamb
c) TB03 - External Corner

2.5.1 TB01 - External End Wall to Intermediate Floor

Figure 14 demonstrates the typical detail with concrete facing bricks and Figure 15 represents the detail with multicellular clay bricks with insulating external render.

FIGURE 14

TB01a - External End Wall to Intermediate Floor with Concrete Facing Bricks - Detail

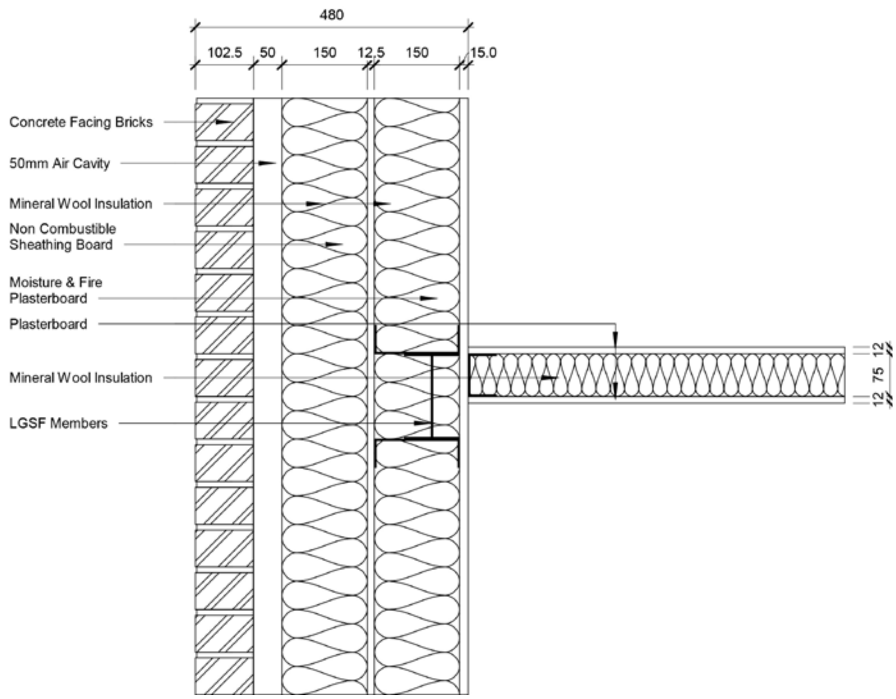
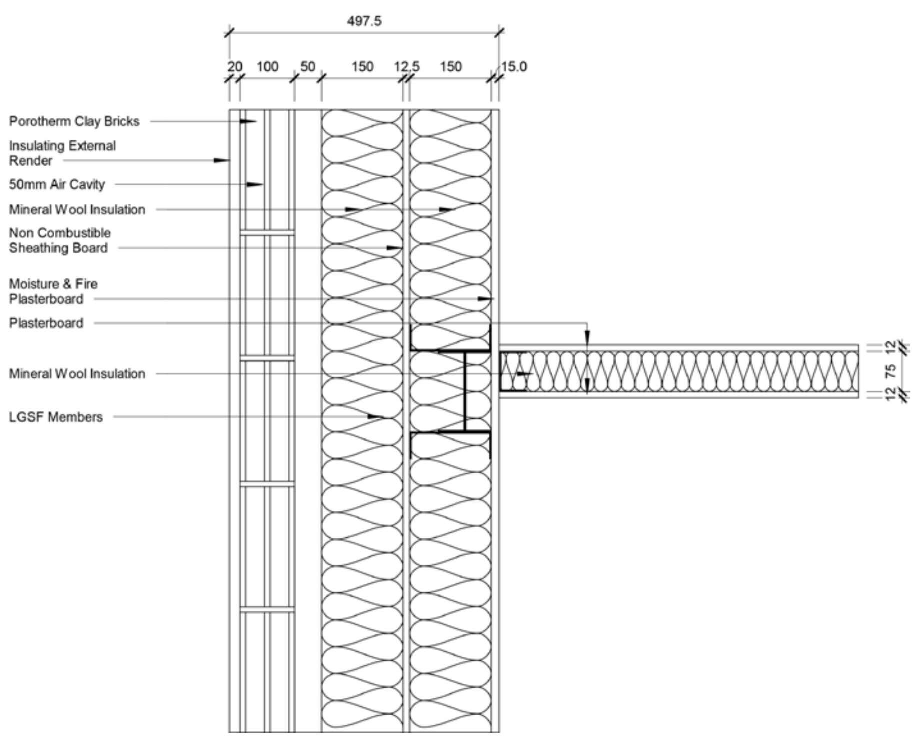


FIGURE 15

TB01b - External End Wall to Intermediate Floor with Multicellular Clay Bricks - Detail



The below Figures 16 and 17 show the modelling of both the above details in Flixo. The thermal conductivities of the different materials are sourced from their technical specifications documents, while the boundary conditions are based on the BRE Guide (BR 497)

FIGURE 16

TB01a – External End Wall to Intermediate Floor with Concrete Facing Bricks – Flixo Model

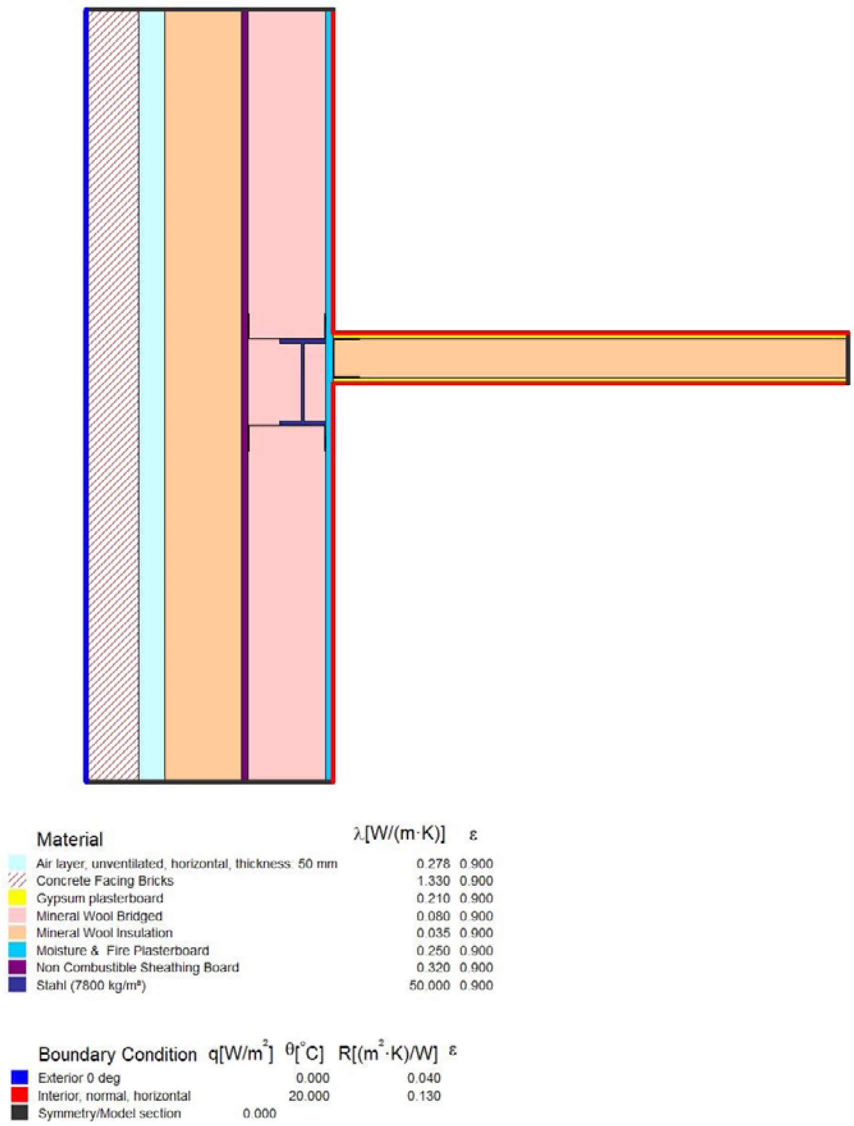
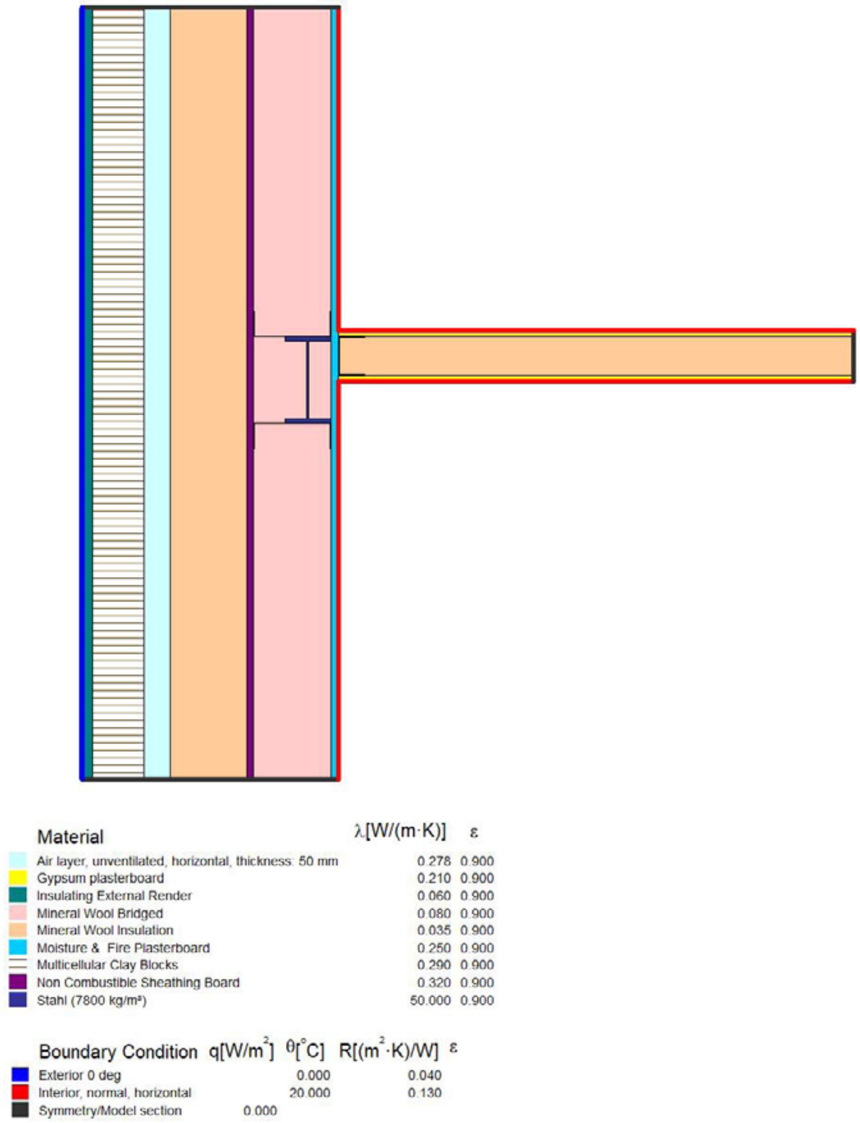


FIGURE 17

TB01b - External End Wall to Intermediate Floor with Multicellular Clay Bricks and Insulating External Render – Flixo Model



2.5.2 TB02 – Window Jamb

Figure 18 demonstrates the typical detail with concrete facing bricks and Figure 19 represents the detail with multicellular clay bricks with insulating external render.

FIGURE 18

TB02a – Window Jamb with Concrete Facing Bricks - Detail

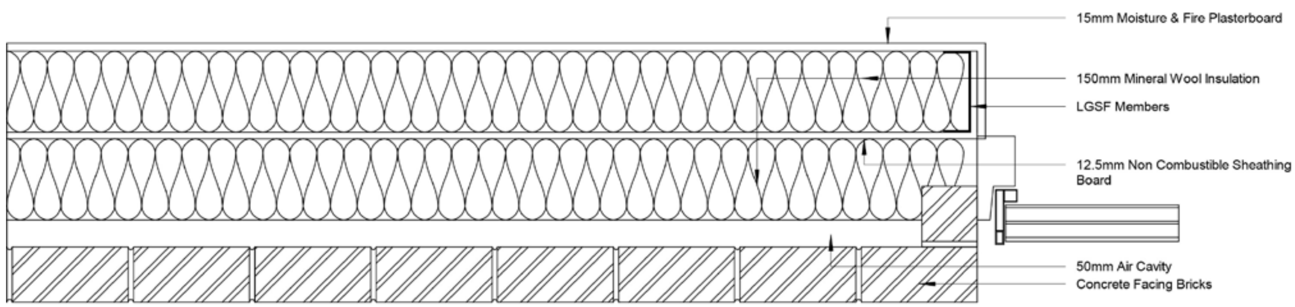
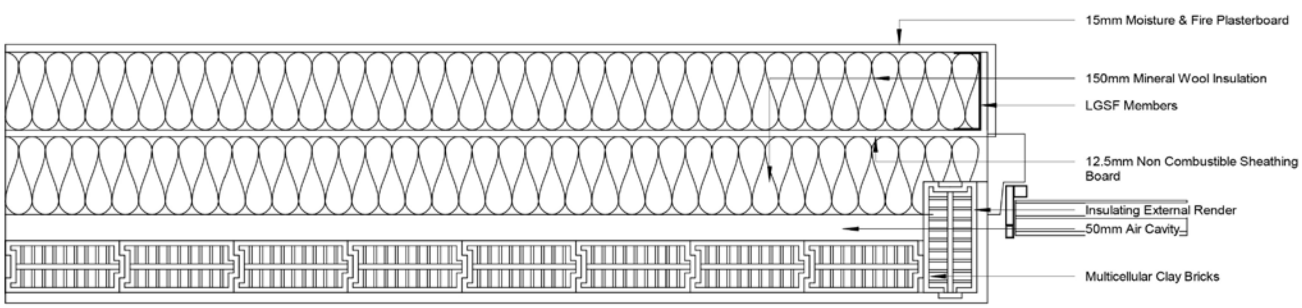


FIGURE 19

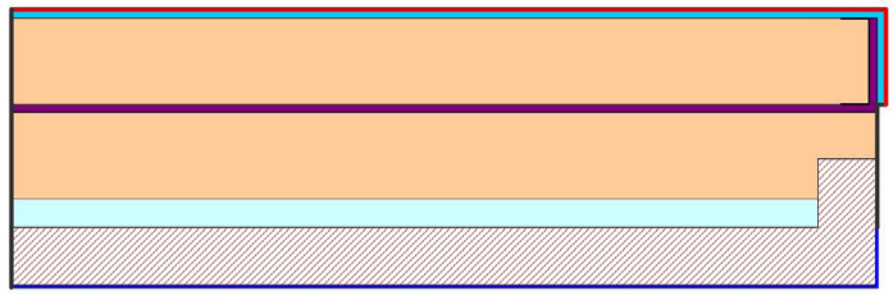
TB02b - Window Jamb with Multicellular Clay Bricks and Insulating External Render - Detail



The below Figure 20 and 21 show the modelling of both of the above details in Flixo. The thermal conductivities of the different materials are sourced from their technical specifications documents, while the boundary conditions are based on the BRE Guide (BR 497).

FIGURE 20

TB02a – Window Jamb Detail with Concrete Facing Bricks – Flixo Model

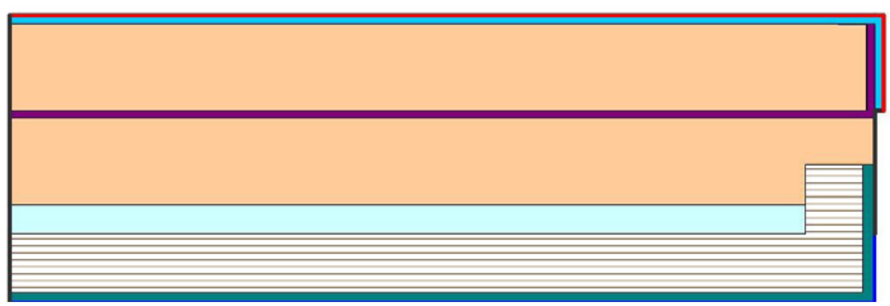


Material	λ[W/(m·K)]	ε
Air layer, unventilated, horizontal, thickness: 50 mm	0.278	0.900
Concrete Facing Bricks	1.330	0.900
Mineral Wool Insulation	0.035	0.900
Moisture & Fire Plasterboard	0.250	0.900
Non Combustible Sheathing Board	0.320	0.900
Stahl (7800 kg/m³)	50.000	0.900

Boundary Condition	$q[W/m^2]$	θ[°C]	$R[(m^2 \cdot K)/W]$	ε
Exterior 0 deg		0.000	0.040	
Interior, normal, horizontal		20.000	0.130	
Symmetry/Model section	0.000			

FIGURE 21

TB02b – Window Jamb Detail with Multicellular Clay Bricks and Insulating External Render – Flixo Model



Material	λ[W/(m·K)]	ε
Air layer, unventilated, horizontal, thickness: 50 mm	0.278	0.900
Insulating External Render	0.060	0.900
Mineral Wool Insulation	0.035	0.900
Moisture & Fire Plasterboard	0.250	0.900
Multicellular Clay Blocks	0.290	0.900
Non Combustible Sheathing Board	0.320	0.900
Stahl (7800 kg/m³)	50.000	0.900

Boundary Condition	$q[W/m^2]$	θ[°C]	$R[(m^2 \cdot K)/W]$	ε
Exterior 0 deg		0.000	0.040	
Interior, normal, horizontal		20.000	0.130	
Symmetry/Model section	0.000			

2.5.3 TB03 – External Corner

Figure 22 demonstrates the typical detail with concrete facing bricks and Figure 23 represents the detail with multicellular clay bricks with insulating external render.

FIGURE 22

TB03a - External Corner with Concrete Facing Bricks - Detail

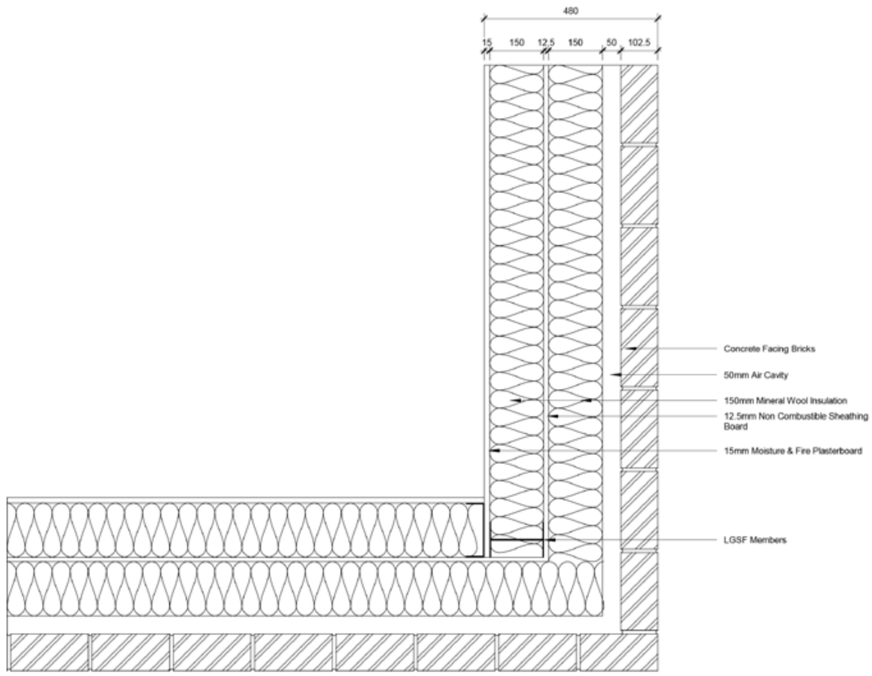
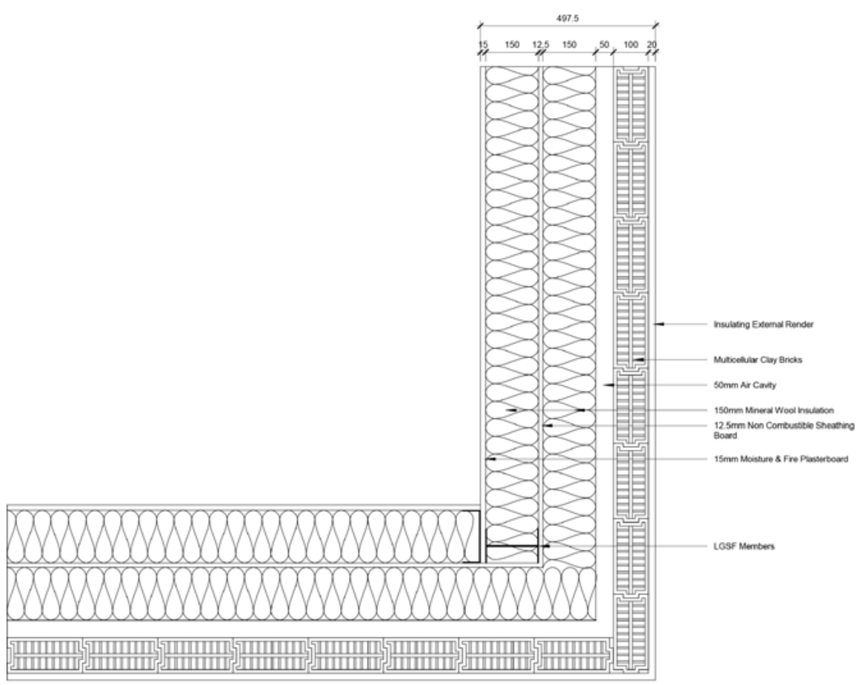


FIGURE 23

TB03b - External Corner with Multicellular Clay Bricks and Insulating External Render - Detail



Figures 24 and 25 show the modelling of both of the details in Flixo. The thermal conductivities of the different materials are sourced from their technical specifications documents, while the boundary conditions are based on the BRE Guide (BR 497).

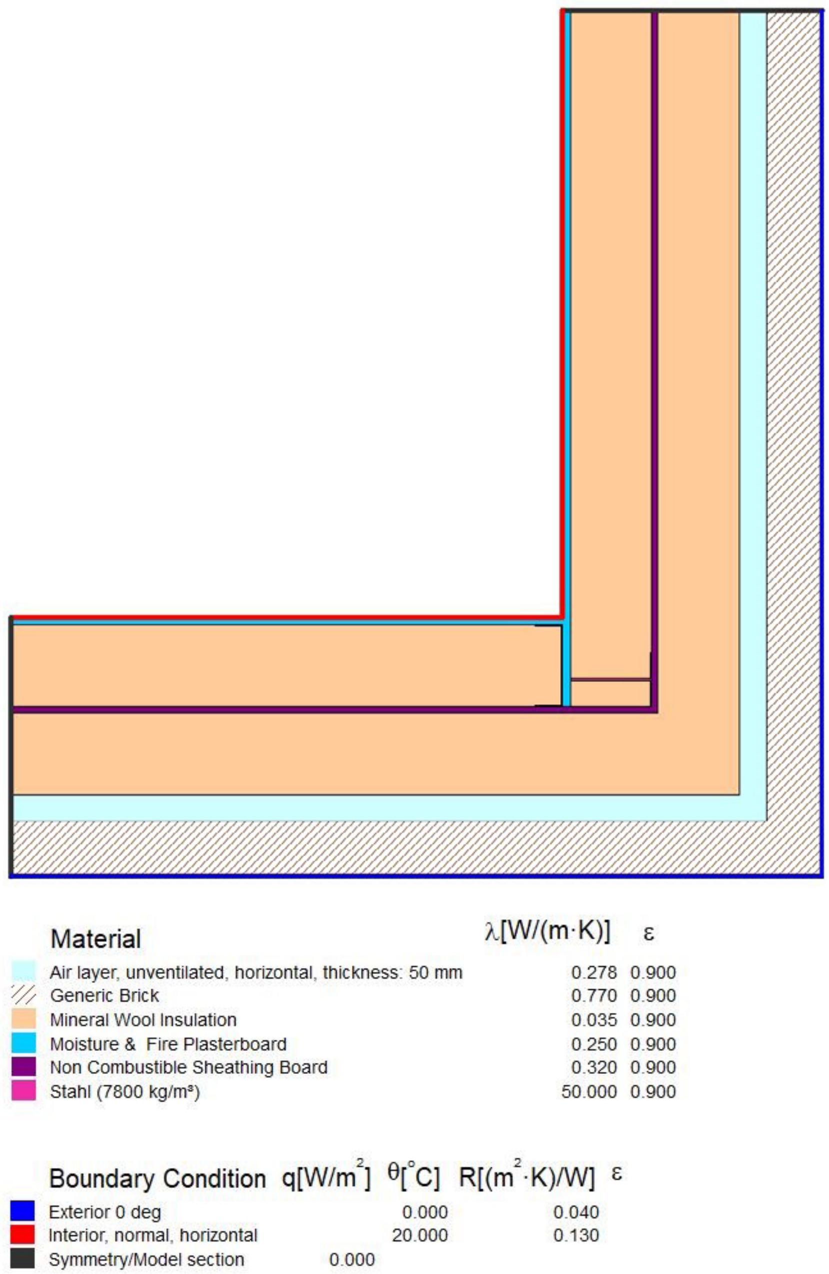
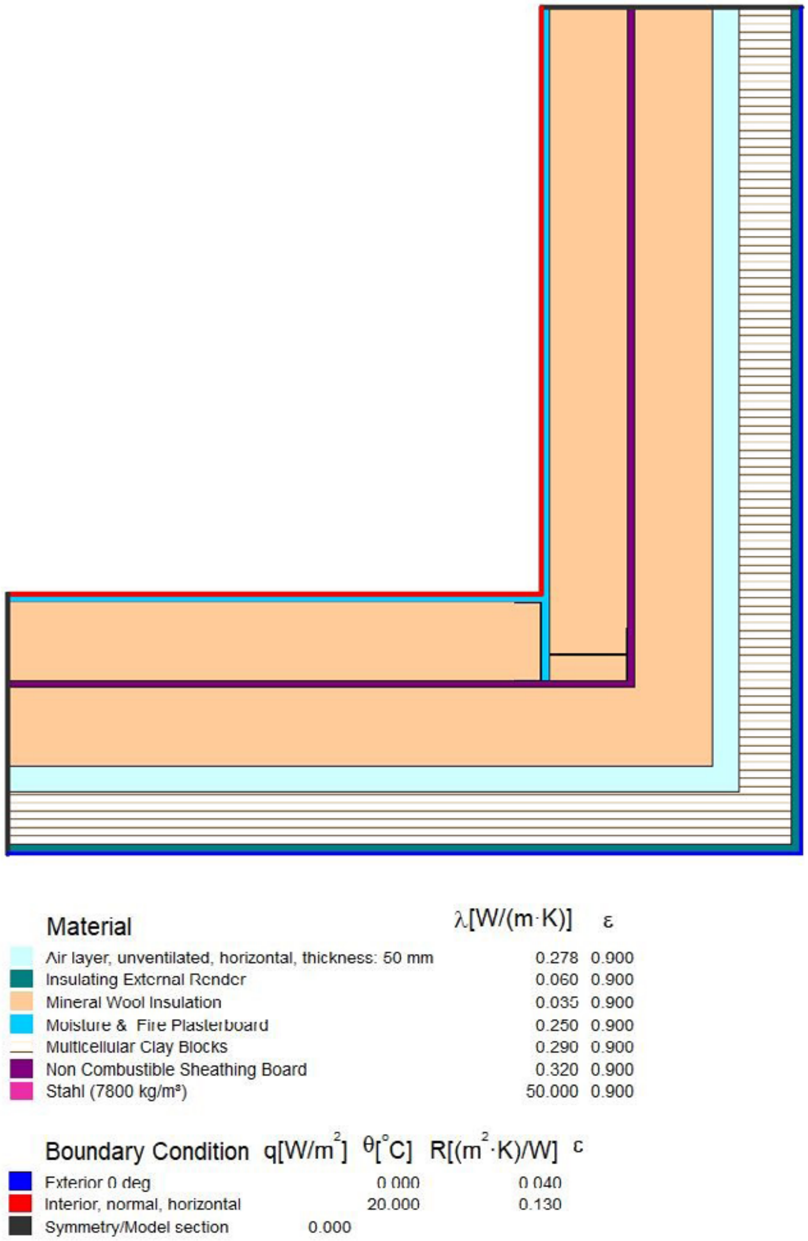


FIGURE 24

TB03a – External Corner Detail with Concrete Facing Bricks – Flixo Model

FIGURE 25

TB03b – External Corner Detail with Multicellular Clay Bricks and Insulating External Render – Flixo Model



3. Results and Discussion

This section presents the results from the simulation carried out in Flixo for all the three junctions

3.1 TB01 - EXTERNAL END WALL TO INTERMEDIATE FLOOR

FIGURE 26

(a) U and Ψ (Psi Value) for TB01a

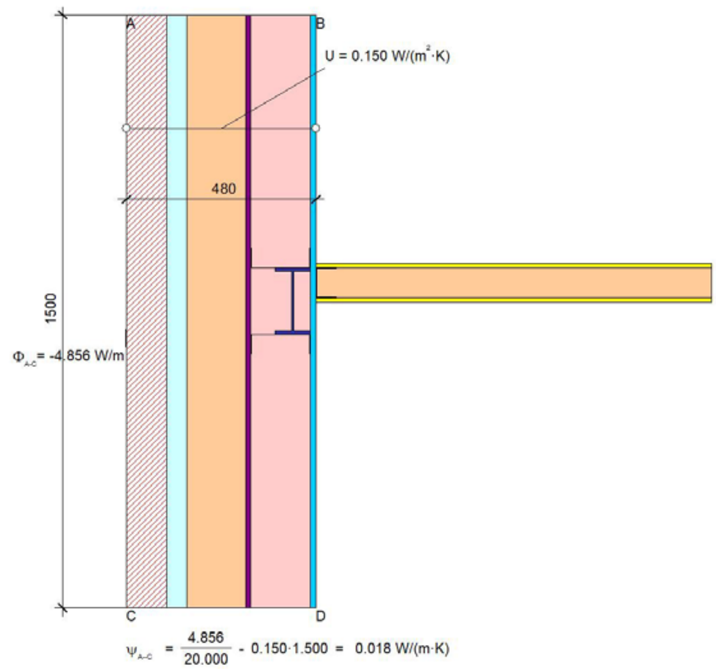


FIGURE 26

(b) Temperature Field for TB01a

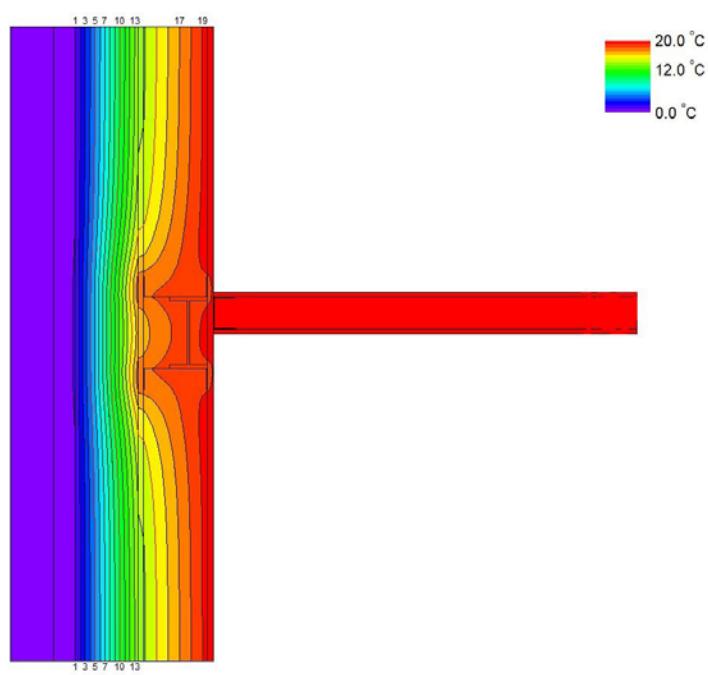


FIGURE 27

(a) U and Ψ (Psi Value) for TB01b

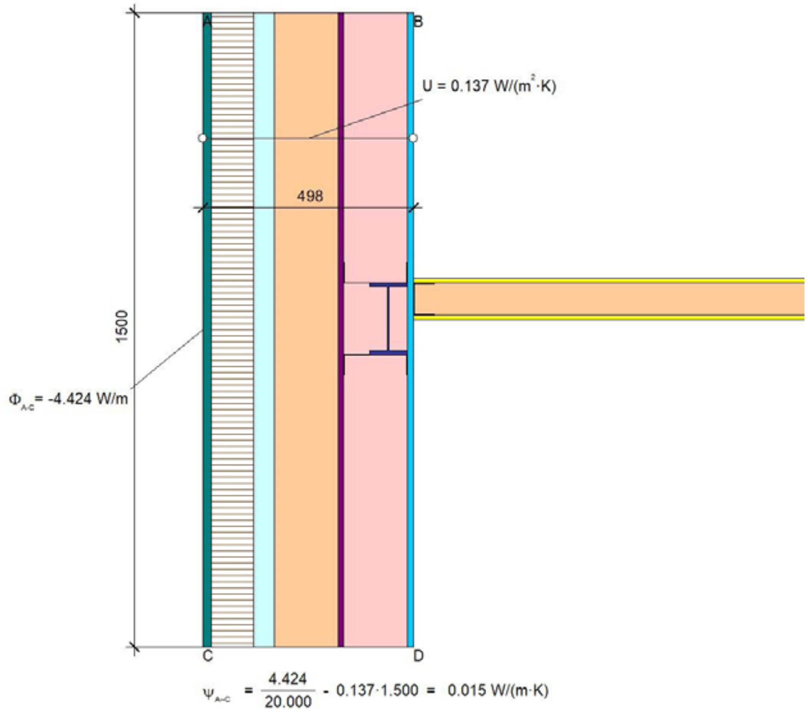
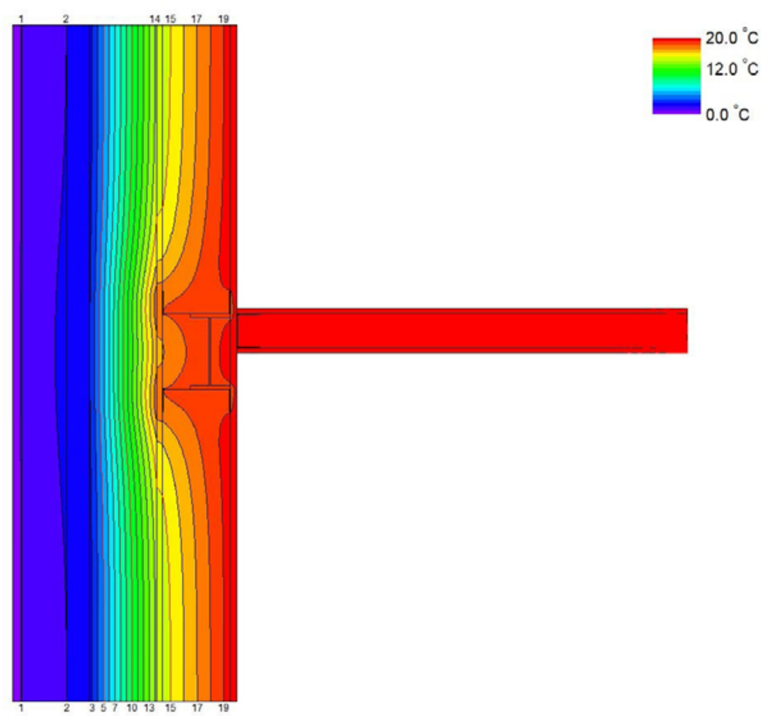


FIGURE 27

(b) Temperature Field for TB01b



3.2 TB02 – WINDOW JAMB

FIGURE 28

(a) U and Ψ (Psi Value) for TB02a

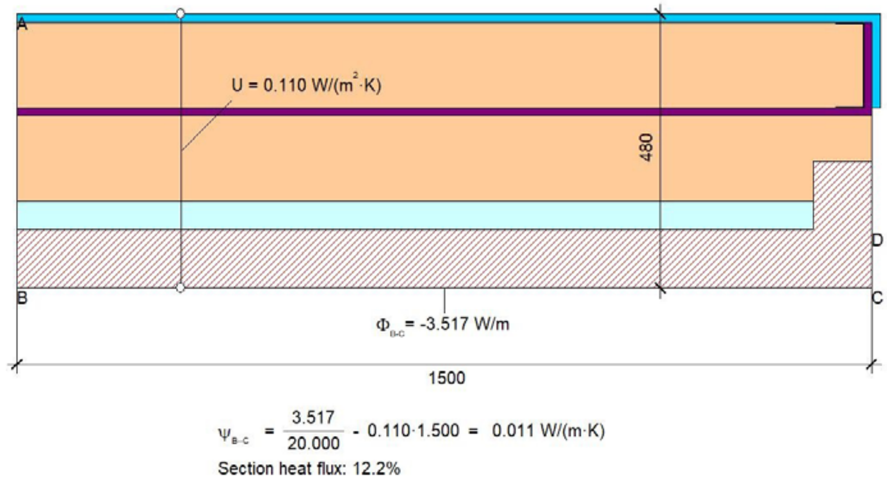


FIGURE 28

(b) Temperature Field for TB02a

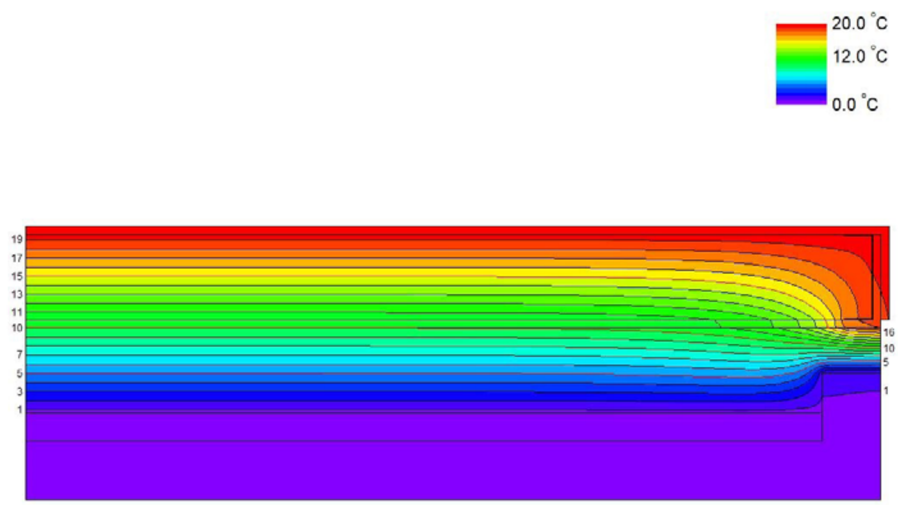


FIGURE 29

(a) U and Ψ (Psi Value) for TB02b

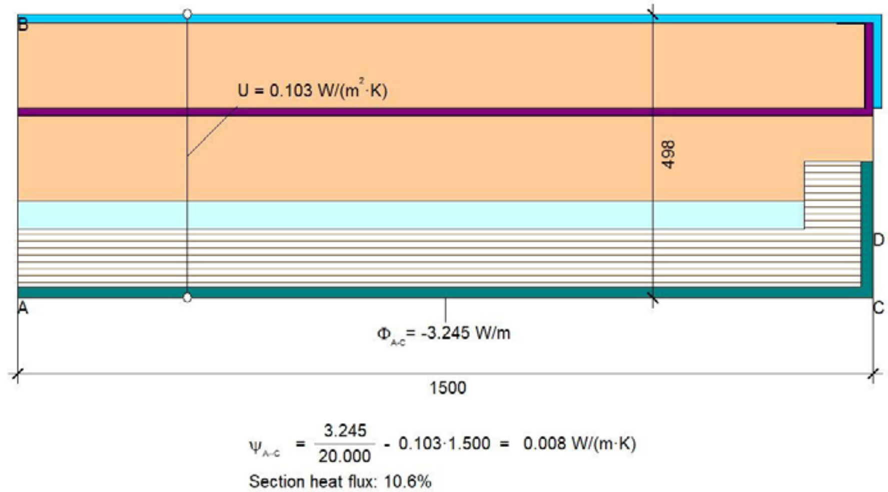
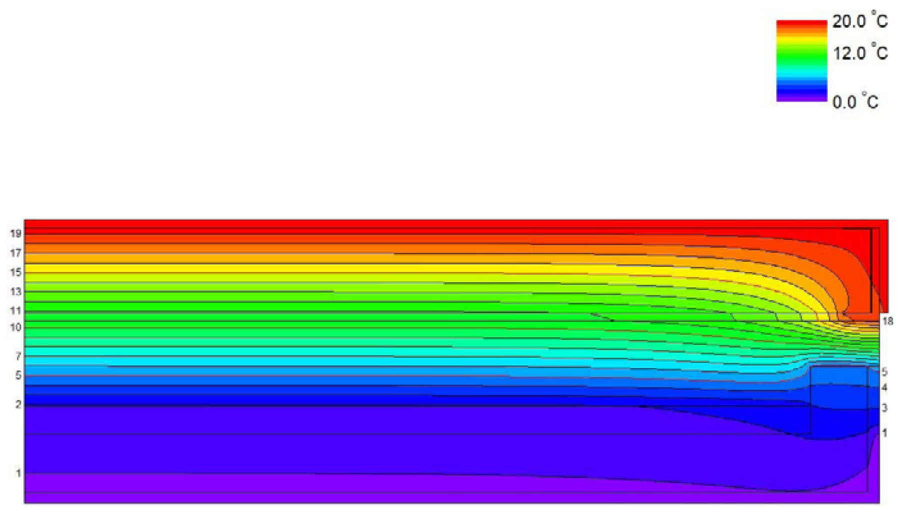


FIGURE 29

(b) Temperature Field for TB02b



3.3 TB03 - EXTERNAL CORNER

FIGURE 30

(a) U and Ψ (Psi Value) for TB03a

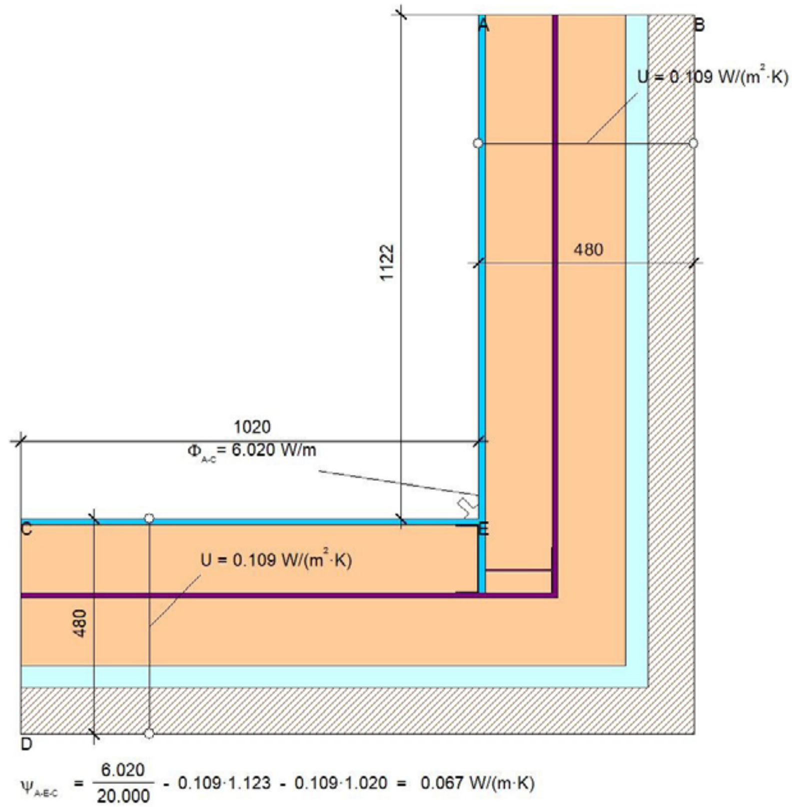


FIGURE 30

(b) Temperature Field for TB03a

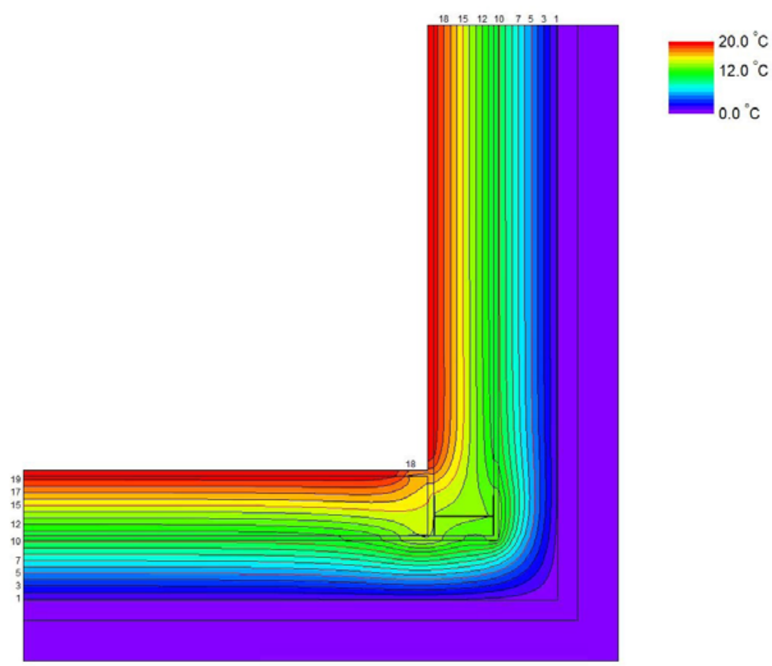


FIGURE 31

(a) U and Ψ (Psi Value) for TB03b

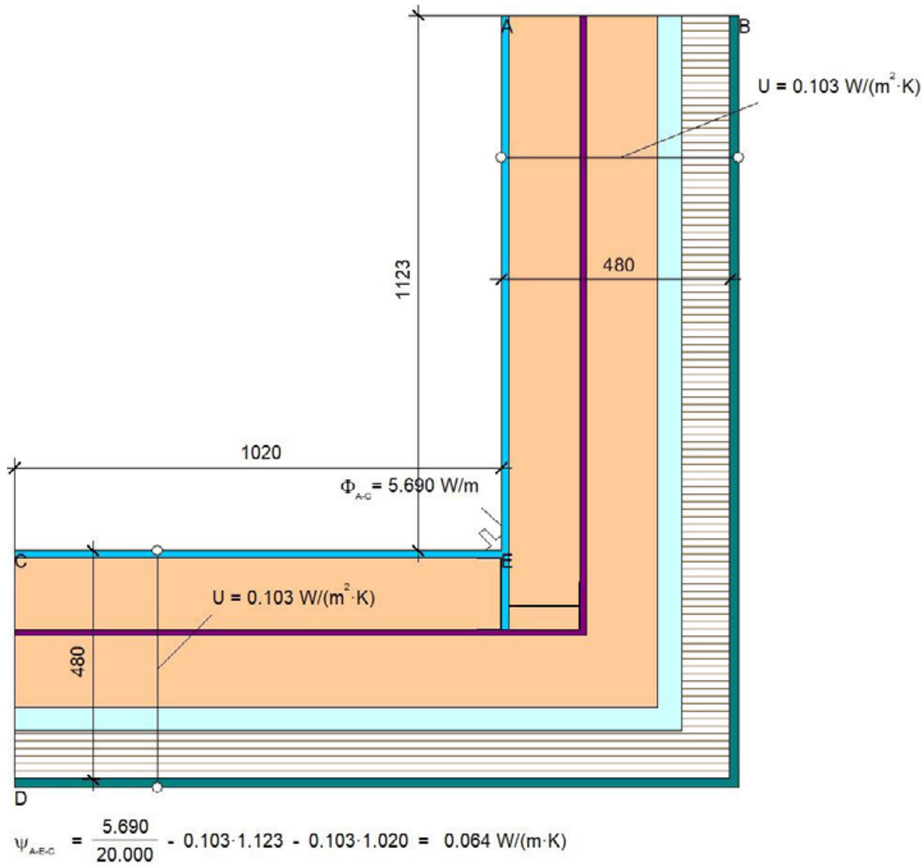
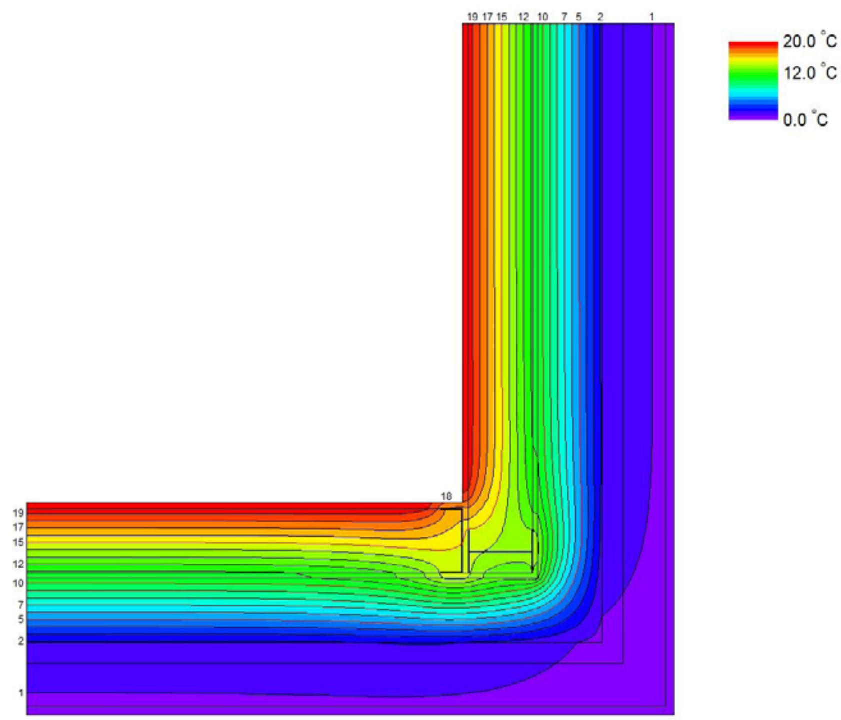


FIGURE 31

(b) Temperature Field for TB03b



The results indicate a reduction in the U value across all three thermal bridges. Specifically, TB01 shows a 13% decrease, while TB02 and TB03 exhibit reductions of 6%, as illustrated in Figure 32. On average, this results in an 8% reduction in the U value of the wall.

Additionally, the psi values have also decreased, as depicted in Figure 33. TB01 shows a 17% reduction, TB02 a 27% reduction, and TB03 a 4% reduction. On average, this translates to a 16% decrease in psi values.

To assess the impact of these improved values on energy consumption, a SAP calculation was performed on a typical two-storey, three-bedroom LGSF house in the UK. The calculation used average values, with U values improved by 8% and psi values enhanced by 16% for each linear thermal bridge. The SAP results demonstrated a reduction in space heating energy consumption from 1005 kWh to 939 kWh, representing a 7% decrease.

FIGURE 32

U Value Comparison

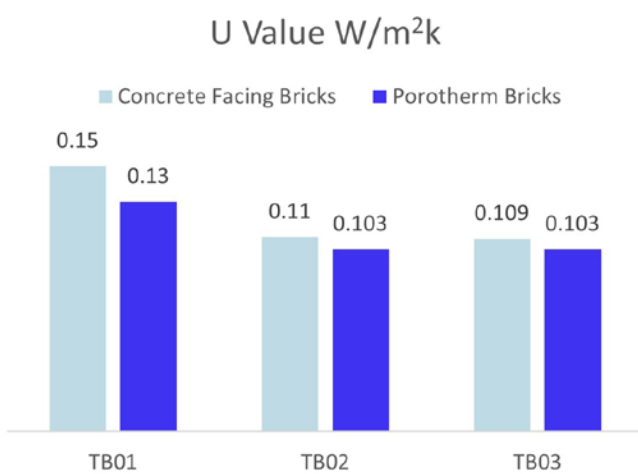
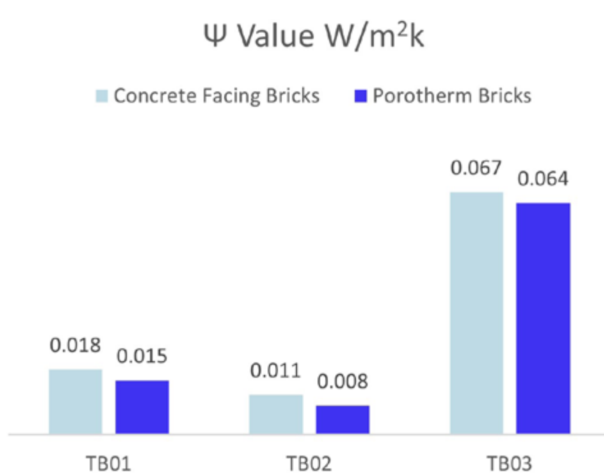


FIGURE 33

Ψ (Psi Value) Comparison



4. Conclusion

4.1 FINDINGS

This research indicates that Light Gauge Steel Construction (LGSC) combined with multi-cellular bricks is notably more effective in mitigating thermal bridging compared to the traditional use of concrete facing bricks, which are commonly used in the UK. The average U-value of walls decreases by 13% when using multicellular bricks along with insulating external render for external cladding compared to concrete facing bricks.

Additionally, significant reductions in psi-values (which quantify the linear thermal transmittance across junctions) are observed: 17% in TB01, 27% in TB02, and 4% in TB03. These reductions indicate a substantial decrease in heat loss through thermal bridging at various types of junctions.

Beyond their superior thermal performance, multi-cellular bricks offer several other advantages. They support fast, dry, and safe construction practices while being sustainable and efficient. These benefits make multi-cellular bricks a comprehensive alternative to concrete facing bricks, providing a holistic solution for modern building requirements.

4.2 LIMITATIONS AND RECOMMENDATIONS

The lightweight nature of Porotherm bricks, while generally an advantage, may require careful handling to avoid damage. Installation techniques may also differ from those used with standard bricks, necessitating additional training or expertise. Also, depending on the region, Porotherm bricks might be less readily available compared to more conventional brick types, potentially causing delays or requiring special ordering. Additionally, in housing projects where the façade needs to blend with existing brick structures, a rendered Porotherm façade might not be ideal.

This research focused on analysing three linear thermal bridge junctions to assess the impact of multi-cellular bricks compared to concrete facing bricks in LGSF housing construction. To gain a comprehensive understanding of the effects, it is advisable to expand the study to include other linear thermal bridges that might occur in such constructions. Additionally, conducting a SAP analysis with the corresponding U and psi values for each linear thermal bridge junction for both concrete facing bricks and multi-cellular bricks in a typical LGSF UK house would be beneficial for comparing space heating energy consumption accurately.

4.3 APPLICATION TO ATKINSRÉALIS PROJECTS

Housing projects have been a key focus area for AtkinsRéalis, spanning from high-end residential to social housing developments. The company's portfolio includes a diverse range of housing projects. Presently, AtkinsRéalis is actively engaged in several social housing initiatives, and this research could be valuable for designing housing projects using LGSF. Beyond housing, the team can also apply this research to other low-rise LGSF construction projects, such as schools.

Acknowledgement

I would like to extend my gratitude to Julian Birbeck (Associate Director, AtkinsRéalis, London) for his guidance and support in writing this research paper.

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Civil and Structural Engineering

02: Carbon Assessment of Tunnel Linings: Three Lining Type Examples

Significance Statement

In an era of urgent climate risk, this paper provides essential insights for tunnel lining design engineers aiming to play their part in the transition to Net Zero emissions. By analyzing the embodied carbon of different lining types — Precast Concrete, Sprayed Concrete, and Spheroidal Graphite Iron—this research offers practical strategies for low-carbon tunnel lining design and identifies key carbon reduction opportunities. Innovative optioneering, design efficiency, material selection and specification choices are explored.

Énoncé d'importance

En cette ère de risque climatique urgent, ce document fournit des informations essentielles pour le corps ingénieur en conception de revêtements de tunnel qui cherchent à jouer leur rôle dans la transition vers le net zéro. En analysant le carbone intrinsèque de différents types de revêtements, à savoir le béton préfabriqué, le béton projeté et la fonte à graphite sphéroïdal, cette recherche offre des stratégies pratiques pour la conception de revêtements de tunnel à faible teneur en carbone et identifie les principales possibilités de réduction du carbone. Des options novatrices, l'efficacité de la conception, le choix des matériaux et les choix de spécifications sont explorés.

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Abstract

This paper aims to assist tunnel lining design engineers in evaluating and understanding the embodied carbon of their designs by providing relevant examples of different types of linings, as well as guidance on aspects of tunnel design where the most significant carbon savings may typically be found.

To do this, three similarly sized examples of different lining types have been selected:

1. Pre-Cast Concrete (PCC) segmentally lined tunnel
2. Sprayed Concrete Lining (SCL)
3. Spheroidal Graphite Iron (SGI) Lining

The material quantities for a 1 m length of each of the above lining types were calculated. An appropriate carbon factor was then applied to these quantities, and the total embodied carbon was calculated. Tunnel design aspects with potential for carbon reduction are highlighted.

KEYWORDS

Tunnel linings; Embodied carbon; Carbon reduction; Net Zero; Tunnel design

1. Introduction

In view of the predicted damaging impacts of climate change and the commitment of numerous governments around the world to achieve Net Zero carbon emissions within the next few decades, it is widely recognised that new infrastructure projects must reduce and ultimately eliminate the carbon emissions these projects would otherwise generate. To achieve this goal, engineers of static structures need to expand their traditional expertise to include an understanding of the carbon emissions associated with their designs. Armed with this knowledge, engineers can then target carbon reductions through optioneering, design efficiency, material selection, and specification. It is expected that the specific consideration of carbon reduction opportunities will become a basic scope item of standard design work.

This paper aims to assist tunnel lining design engineers in evaluating and understanding the embodied carbon of their designs by providing relevant examples of different lining types and offers guidance on the aspects of design where the most significant savings may typically be found.

To do this, three similarly sized examples of lining types have been selected for comparison:

1. Precast Concrete (PCC) segmental lining
2. Sprayed Concrete Lining (SCL)
3. Spheroidal Graphite Iron (SGI) lining

The material quantities in a 1-metre length of each of the above lining types were calculated. An appropriate carbon factor was then applied to these quantities, and the total embodied carbon was calculated. Areas for potential carbon reduction in tunnel lining designs are highlighted.

2. General Calculation Principles

2.1 CARBON ACCOUNTING VERSUS CARBON-CONSCIOUS DESIGN

A Whole Life Carbon Model (WLCM) may be developed at the project level and updated at certain project key stages. In this regard it may be considered as a form of carbon accounting that requires a complete design for assessment and is usually carried out by specialists. In the UK, PAS 2080:2016 *Carbon Management in Infrastructure* has been developed to manage this process.

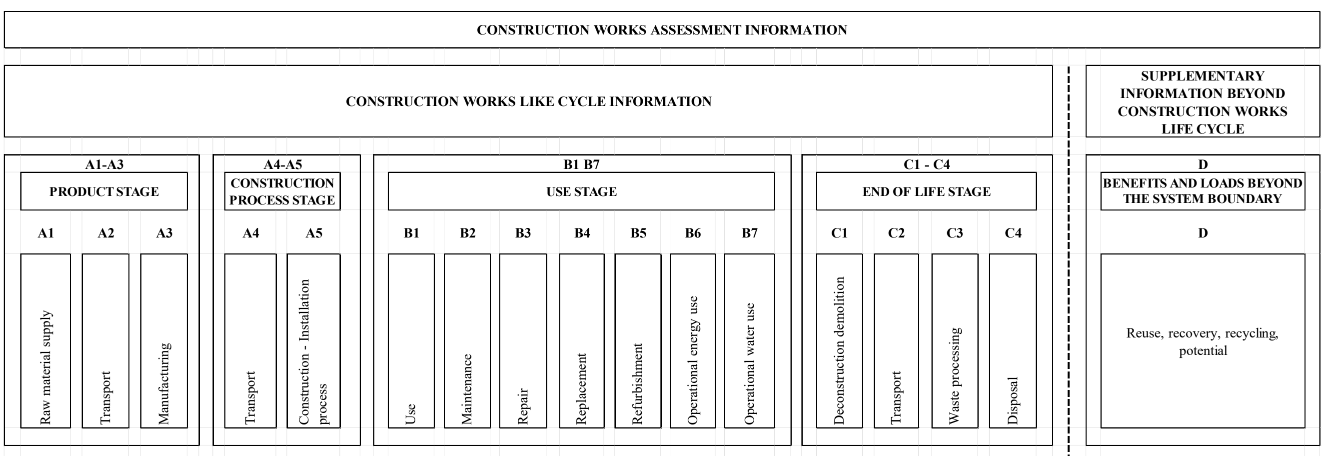
This paper is intended to encourage design engineers to engage in a slightly different approach, sometimes referred to as "carbon-conscious design". This involves an active, "short-cut" carbon assessment—carried out by individual design engineers for the aspects of design they are responsible for—to help inform design decisions as they are made.

2.2 EMBODIED CARBON VS WLCM FOR TUNNEL LINING DESIGNS

WLCM recognises the life cycle stages shown in Figure 2-1.

FIGURE 2-1

Life Cycle Stages from BS EN 15804 Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products, Permission to reproduce extracts from British Standards is granted by BSI Standards Limited (BSI). No other use of this material is permitted



WLCM assessments carried out on recent high-profile tunnel projects are given in Table 2-1. From this it can be observed that the embodied carbon of the structural materials is the largest source of WLCM for current tunnel projects.

TABLE 2-1

Carbon by Stage Recent Tunnel Projects

Project	Thames Tideway (Thames Water Utilities, 2013)	Silvertown Tunnel (Transport for London, 2016)	Lower Thames Crossing (Highways England, 2023)
Description	Main tunnel 25km, 6.5-7.2 m diameter, plus several branch structures	1.4km twin road tunnel, 10.66 m diameter ID	23km highway, including 4.25km tunnel, 16 m diameter
Embodied carbon in materials (Product stage A1-A3)	84%	68.4%	62%
Transport of materials and construction (Construction process stage A4-A5)	13.5%	19.1%	36% [c]
Operational emissions (Use stage B1-B7)	2.5% [a]	12.5% [a, b]	1.7% [b, c]

Notes:

a. Assumes grid electricity will be net zero by 2035
b. Traffic emissions not included
c. Assumes renewable electricity supply source

To simplify the comparison, this paper focuses on the embodied carbon in the materials used for the lining only, i.e. Product Stage A1-A3, or "Cradle to Gate".

The construction process stages (A4 & A5) are not considered in this exercise, as these are specific to individual projects and difficult to generalise. For example, the operation of a tunnel boring machine (TBM) consumes a significant amount of electricity. The carbon emissions associated with that could be substantial or negligible, depending on how the electricity that supplies the construction site is generated, which varies by location. A PCC lining could also be installed by other methods without using a TBM. It should be noted however, that the term "Embodied Carbon" typically includes emissions associated with all A1-A5 stages.

The “Use” stages B1-B7 are also not considered in this exercise as tunnels are generally designed to a long design life, often exceeding 100 years, without planned maintenance, refurbishment or repair of the structural linings. A WLCM would consider carbon emissions from operating the tunnel (e.g. lights, ventilation, sump pumps). The choice of equipment may influence tunnel design in terms of the space requirement and therefore the required size of tunnel. Hence there may be a balance to strike for the optimal overall carbon choice. A tunnel lining designer who actively considers A1-A5 carbon stages can help manage the interface with Mechanical and Electrical designers, informing decisions about equipment choices. The carbon emissions associated with operation of the tunnel also depend on how energy is generated, which varies with location. In addition, under current climate commitments, energy generation is expected to decarbonise over the new few decades. Therefore, for most new tunnels, only the first years of operation are likely to contribute to the project’s carbon emissions, reducing the significance of stage B6 substantially compared to the total WLCM figure.

End-of-life stages (C1-C4) are also not considered. Redundant tunnels are sometimes backfilled, but tunnel linings are rarely demolished and recycled. This is also true for temporary support, which is often left in the ground. There are many instances of tunnels being used well beyond their design life or repurposed for new functions. In addition, the long design life of tunnels (often 100+ years) suggests that any assumptions made today about end-of-life treatment will likely be outdated by new technology and practises available at that time in the future, ideally emission-free. It is observed that the priority for Engineering Net Zero is to achieve net zero carbon emissions by 2050, which is well within the design life of any new tunnels planned today. Hence, the end-of-life stages C1-C4 has little relevance for today’s tunnel lining designers. In contrast, embodied carbon, emitted at the front-end of the project’s design life, has the most significant impact and is the stage where tunnel lining design engineers have the greatest influence.

2.3 A1-A3 CARBON CALCULATION

In essence, assessing cradle-to-gate carbon in a structure is very simple:

Equation 1:

$$\sum \text{Material quantity} \times \text{Carbon Factor} = \text{Total Carbon}$$

In this regard, it is analogous to cost estimation. Material quantities can be calculated using any common method, ranging from simple hand calculation to sophisticated automatic generation from BIM models. For most designers seeking a quick and easy assessment, a simple spreadsheet calculation is often the most convenient option.

2.4 CARBON FACTORS

Carbon factors are usually expressed in units of mass of carbon dioxide equivalent (CO_2e) emitted per mass or volume of material, e.g. $kgCO_2e/kg$ or $kgC0_2e/m^3$. The "equivalent" accounts for other greenhouse gasses emitted, converting their global warming potential into the equivalent impact of $C0_2$.

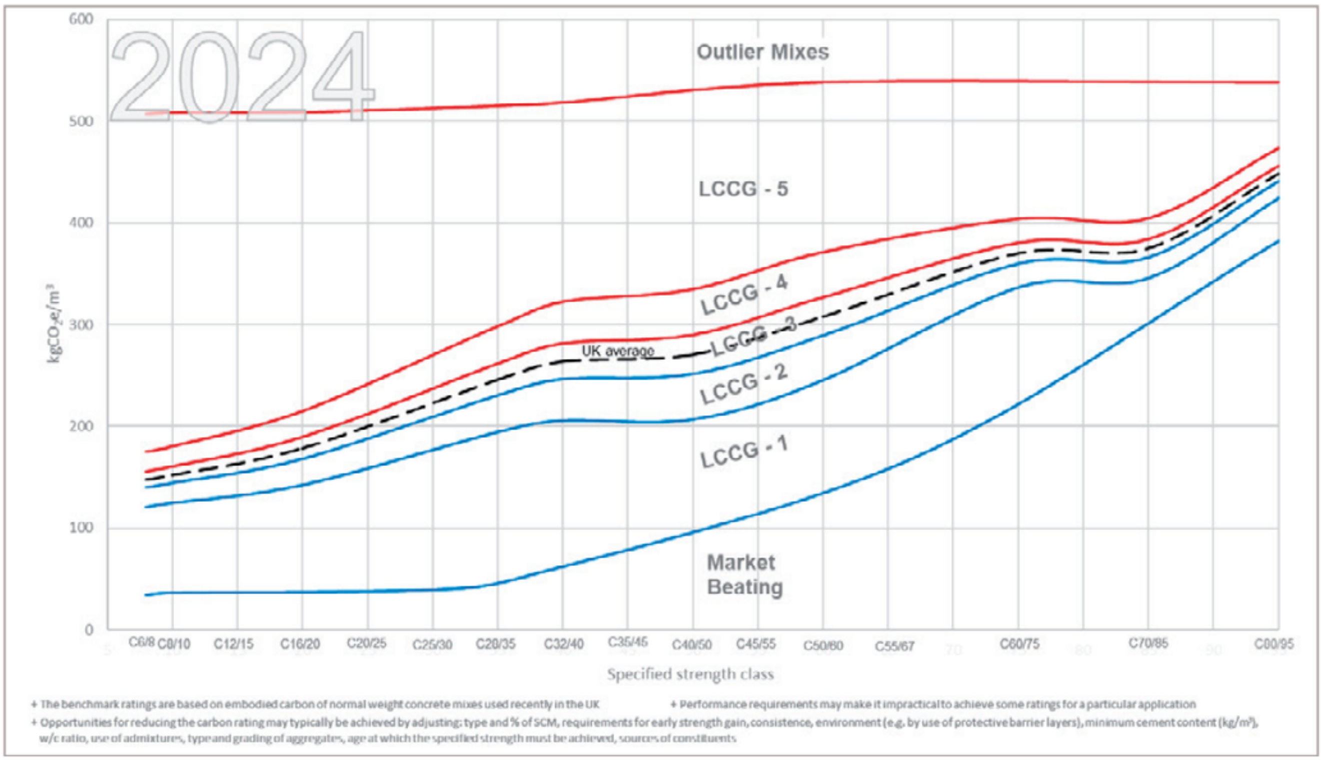
2.4.1 Generic Carbon Factors

There are several sources of carbon factors for structural materials. During the design stage, it is appropriate to use generic, industry-wide database carbon factors. These factors can be updated with specific product information as materials are procured, providing greater accuracy.

For concrete, the Lower Carbon Concrete Group publishes an annual Market Benchmark of embodied carbon (UK Lower Carbon Concrete Group, 2024) for concrete produced in the UK, categorised by strength class. This represents the best available information source for embodied carbon of concrete in the UK, prior to knowing the exact composition of the concrete mix.

FIGURE 2-2

LCCG Market Benchmark for embodied concrete 2024 (UK Lower Carbon Concrete Group, 2024). Note this graph is due to be amended and republished annually



The carbon factor of steel varies depending on the technology employed at the steel mill. It is also a global commodity, especially for common items such as rebar. Therefore, it is recommended to use a worldwide average carbon factor for steel unless accurate embodied carbon information is available for the specific product or the steel mill where it was produced. A standard for "green steel" is being developed and implemented by Responsible Steel, an international body working toward a standard and certified system for sustainable steel production. It is expected that the quality of carbon data available to designers will improve over time.

Other key sources from the UK include:

- The Inventory of Carbon & Energy (ICE) database, which was developed at the University of Bath. (University of Bath, 2019) Note that an updated revision to this database is expected before the end of 2024.
- OP Gibbons, JJ Orr. *How to calculate embodied carbon, 2nd edition.* The Institution of Structural Engineers, Mar 2022.

Major clients, for example National Highways, have also developed their own Carbon Tools, from which carbon factors can be obtained.

These factors may have been estimated for the UK market and may not be accurate for different parts of the world.

All these carbon factors are likely to change over time as the electricity and transport networks decarbonise, and manufacturing processes change. Therefore, it is essential to always seek the latest factors available.

2.4.2 Environment Product Declarations

Specific products may have an Environmental Product Declaration (EPD), which give "global warming potential" carbon factors. These should be used when specific products are known or may be used as an estimate when a generic figure is unavailable but the specific product has not yet been selected.

EPDs cover a wide range of environmental aspects associated with a specific product. The relevant information for carbon assessment is found in the row of the Results Table labelled "Global Warming Potential" (GWP) for A1-A3 stages.

FIGURE 2-3

Example of a results table from an EPD for "SikaRapid-800", a concrete admixture

LCA: Results

DESCRIPTION OF THE SYSTEM BOUNDARY (X = INCLUDED IN LCA; MND = MODULE OR INDICATOR NOT DECLARED; MNR = MODULE NOT RELEVANT)

Product stage			Construction process stage		Use stage							End of life stage				Benefits and loads beyond the system boundaries
Raw material supply	Transport	Manufacturing	Transport from the gate to the site	Assembly	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction demolition	Transport	Waste processing	Disposal	Reuse-Recovery-Recycling-potential
A1	**A2**	**A3**	**A4**	**A5**	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**C1**	**C2**	**C3**	**C4**	**D**
X	X	X	X	X	MND	MND	MNR	MNR	MNR	MND	MND	X	X	MND	X	X

RESULTS OF THE LCA - ENVIRONMENTAL IMPACT according to EN 15804+A2: 1 kg SikaRapid-800 ECO

Parameter	**Unit**	**A1-A3**	**A4**	**A5**	**C1**	**C2**	**C4**	**D**
GWP-total	kg CO_2 eq	1.06E+00	9.11E-03	9.29E-02	2.83E-04	6.27E-03	1.45E-02	-3.28E-02
GWP-fossil	kg CO_2 eq	1.14E+00	8.71E-03	5.7E-02	2.7E-04	6E-03	1.49E-02	-3.26E-02
GWP-biogenic	kg CO_2 eq	-8.62E-02	3.94E-04	3.59E-02	1.23E-05	2.71E-04	-4.42E-04	-1.66E-04
GWP-luluc	kg CO_2 eq	2.38E-04	3.96E-07	2.45E-06	1.25E-08	2.72E-07	2.75E-05	-3.56E-06
ODP	kg CFC11 eq	2.02E-12	8.95E-16	2.59E-14	2.82E-17	6.15E-16	3.51E-14	-2.19E-13

EPDs are produced by organisations independent of the manufacturer, in accordance with EN 15804 and/or ISO 14025 standards, though they are typically funded by the manufacturer. There are several internet-based sites which keep a library of EPDs (e.g. the Built Environmental Carbon Database (BECD, n.d.)), and manufacturers or suppliers often make their EPDs available on their websites, making them relatively easy to find via an internet search engine.

As carbon assessments become more common place, EPDs are expected to become available for an increasing number of products. Requesting manufactures and suppliers for such documents can also encourage them to commission them.

2.5 ACCURACY AND PURPOSE

The purpose of these assessments is to focus design attention on the largest sources of embodied carbon. Therefore, the precise contribution of smaller, detailed items is less critical compared to the larger quantities of structural materials. While it is possible to question or debate specific input factors, the results will not be relied upon for safety. Therefore, the exact accuracy of the assessment tends to be of lesser importance, as long as the largest sources of carbon are reasonably estimated and relatively correct. Parts of the construction industry are now developing and implementing systems to record and track the embodied carbon of the materials they are using through existing invoicing systems to produce a more accurate record (CN Decarbonising Construction 2024, 2024). It is anticipated that the accuracy of generic design carbon factors will improve over time as the quality of the source data behind their generation improves.

3. Calculations Examples

To provide example carbon calculations for tunnel linings, three similarly sized tunnels with different types of linings were selected for assessment. The key features of these example tunnel linings are given in Table 3-1.

TABLE 3-1

Example tunnel linings selected for comparison

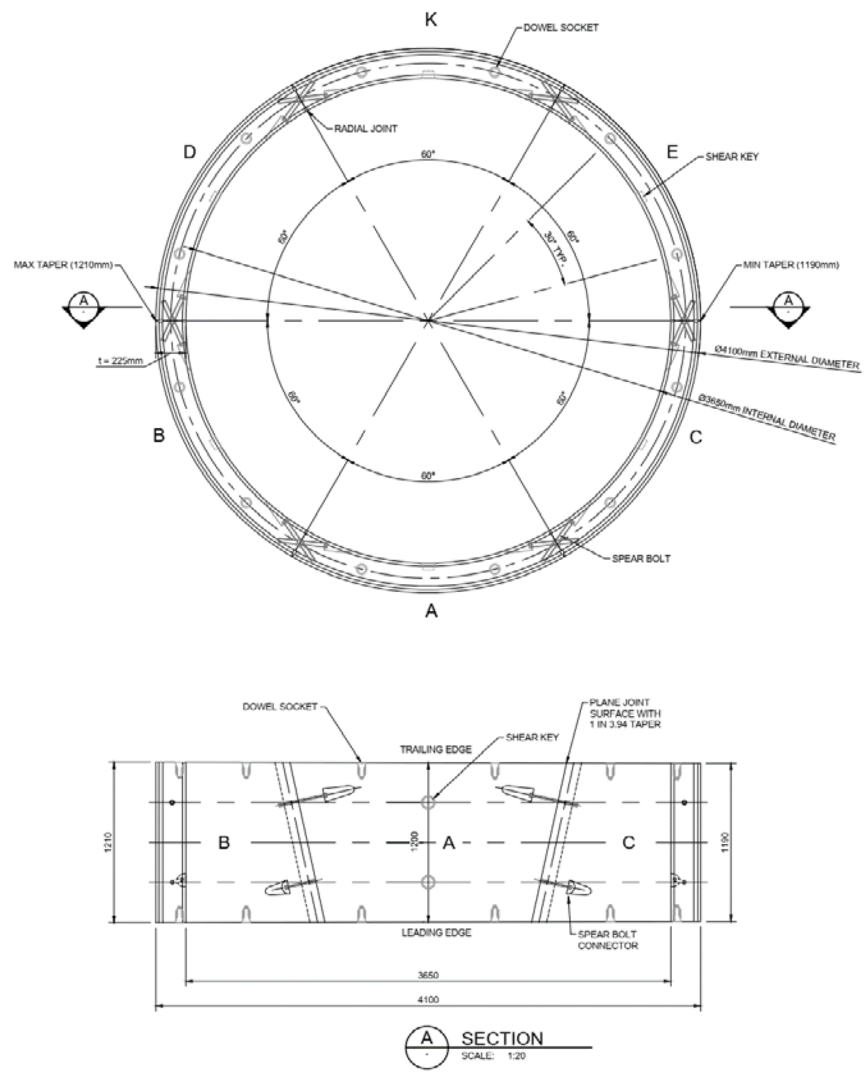
Tunnel Lining Type	Example Project	Internal Diameter	Permanent Lining Thickness	Construction Methodology	Temporary works assumption
Precast Concrete (PCC) Segmentally Lined Tunnel	Humber Feeder 9	3.65m	225mm	TBM	Annulus gap backfilled with two-component grout
Sprayed Concrete Lining (SCL)	Bond Street Station Upgrade Pedestrian passage	Oviform, 3.856m width	Primary Lining: 250mm; Secondary lining: 250mm + cast in-situ invert and regulating layers	Heading and bench SCL construction	Included with primary lining
Spheroidal Graphite Iron (SGI) Segmentally Lined Tunnel	Crossrail Contract C305 Cross-passage	3.75m	Flange depth: 140mm Skin thickness: 22mm;	"Hand-mined" assisted by appropriate lifting tools	Timber heading with grout backfill

3.1 PRECAST CONCRETE (PCC) SEGMENTALLY LINED TUNNEL

For this example, the material quantities were estimated based on the Precast Concrete (PCC) lining used in the Humber Feeder 9 Project. This tunnel was constructed using a TBM and featured a PCC lining with two-component grout backfill for the annulus gap. Most of the lining segments were made of steel fibre-reinforced precast concrete, with a small portion designed with conventional steel reinforcement bars.

FIGURE 3-1

PCC Lining – extract from Drawing HFP-ATK-3-DR-T-0001 Rev AB (National Grid, 2020) reproduced by permission of National Grid



The materials identified were assigned an assumed carbon factor, as shown in Table 3 2. Each of the materials was quantified and multiplied by their corresponding embodied carbon factor (ECF) using Eq. 1 to obtain the embodied carbon per metre of PCC tunnel (for both steel fibre-reinforced and conventional bar-reinforced sections).

TABLE 3-2

Materials and assumed carbon factors for PCC Tunnel Lining

Material	Material Spec	Carbon Factor (kgCO²e/kg)	Source
Concrete	C50/60 40% GGBS (Shay Murtagh, n.d.)		
CEM1		0.840	(University of Bath, 2019)
GGBS		0.0796	(BRE Global, 2019)
Aggregate	Coarse & fine	0.0075	(University of Bath, 2019)
Steel Fibres		1.99	(Instytut Techniki Budowlanej (ITB), 2022
Polypropylene Fibre		3.18	(SIka, n.d.)
Super Plasticiser		1.88	(University of Bath, 2019)
Water		0	
Dowel	Dowel Polyamide 6 & 6.6 + steel M16	1.99	(University of Bath, 2019)*
Gasket	M 38566 Gasket	3.16	(International Rubber Co, 2024)
Spear Bolt	Bolt Polyamide (socket) + C45 or Steel grade 8.8 (bolts)	1.99	(University of Bath, 2019)*
Backgrout	Assumed mix (Aldrian, 2021)		
CEM1		0.912	(University of Bath, 2019)
Bentonite		0.492	(EFFC, n.d.)
Plasticiser		1.88	(University of Bath, 2019)
Activator		1.33	(University of Bath, 2019)
Water		0	
Timber Packer	Plywood assumed	0.681	(University of Bath, 2019)

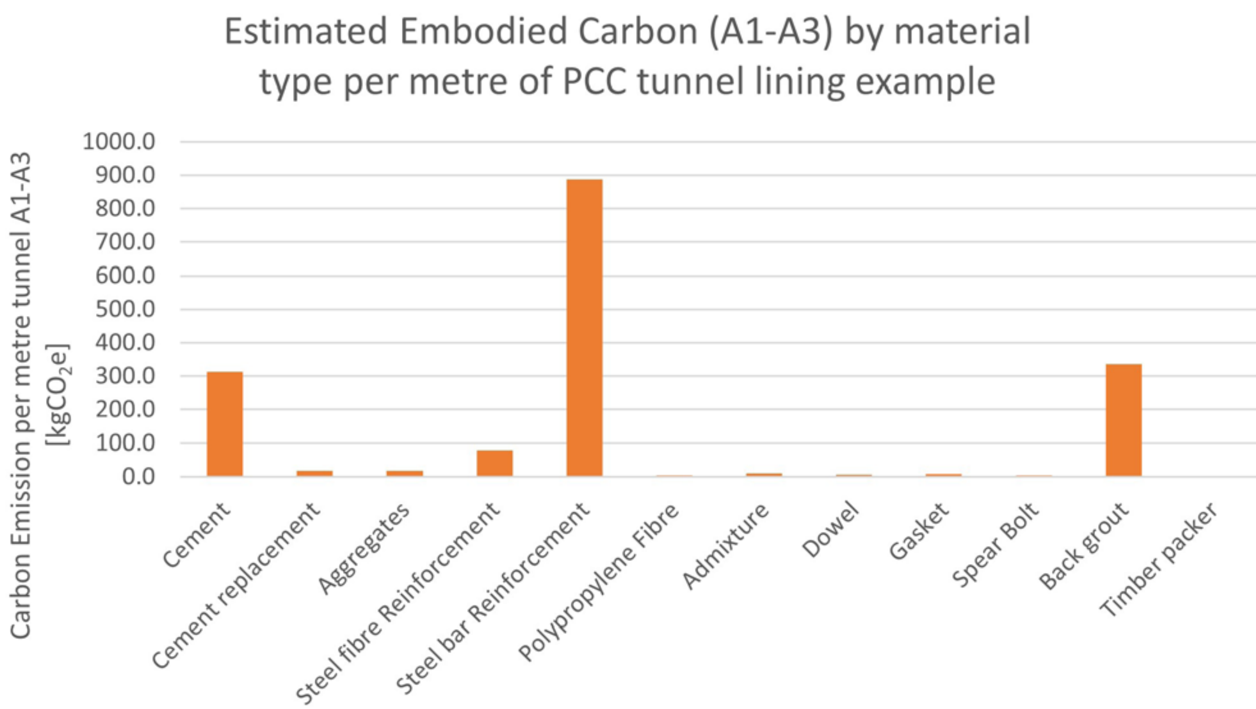
*For purposes of this exercise, the dowel and spear bolt were assumed to be made from steel only.

Whilst most quantities were calculated from the dimensions provided in the drawings, the annular gap was not specified and was therefore assumed to be 150mm. The tail skin grout was identified as a two-component mixture, with the mix design assumed based on literature. The embodied carbon of each individual material within the grout mix was calculated and summed to obtain the total embodied carbon of the tail skin grout per metre of tunnel.

The results are shown in Figure 3-2 and indicate that the carbon footprint is dominated by steel bar reinforcement, cement and grout materials, with steel fibre reinforcement contributing to a lesser extent.

FIGURE 3-2

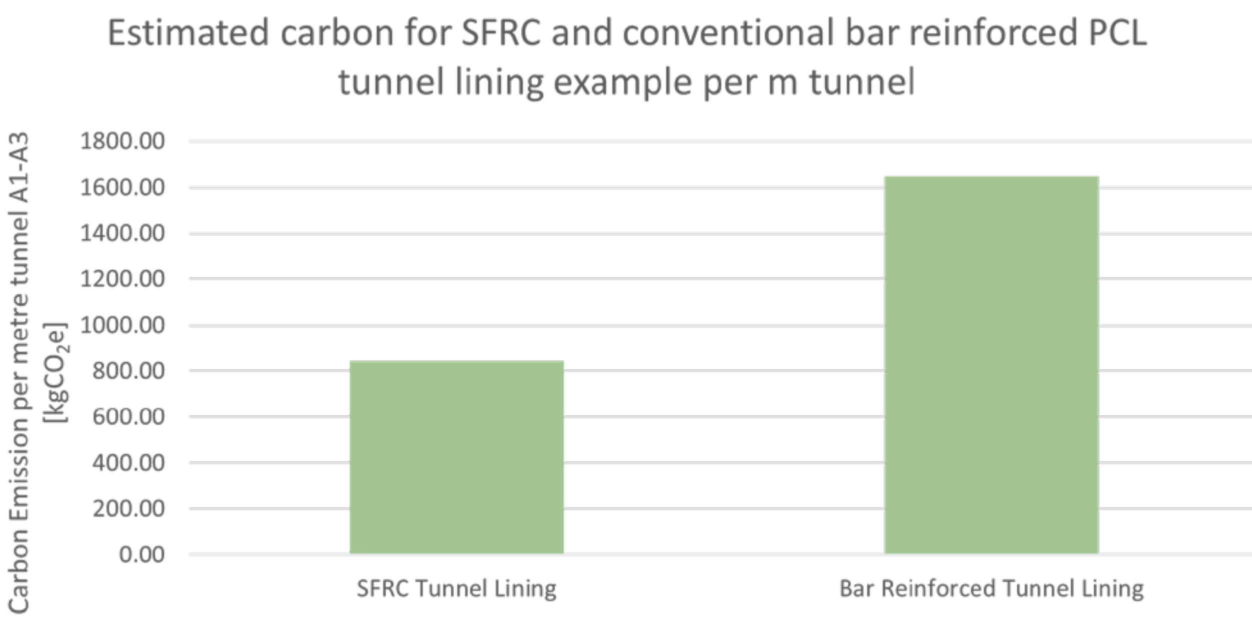
Embodied carbon per metre for example PCC tunnel lining



As shown in Figure 3-3, segments reinforced with conventional steel bars were calculated to have approximately double the carbon impact as steel fibre-reinforced segments. However, it should be noted that in this project, bar reinforcement was only included in segments where the anticipated loads required it, and as such it is not a true like-for-like comparison.

FIGURE 3-3

Embodied carbon for SFRC and conventional bar reinforced example PCC lining



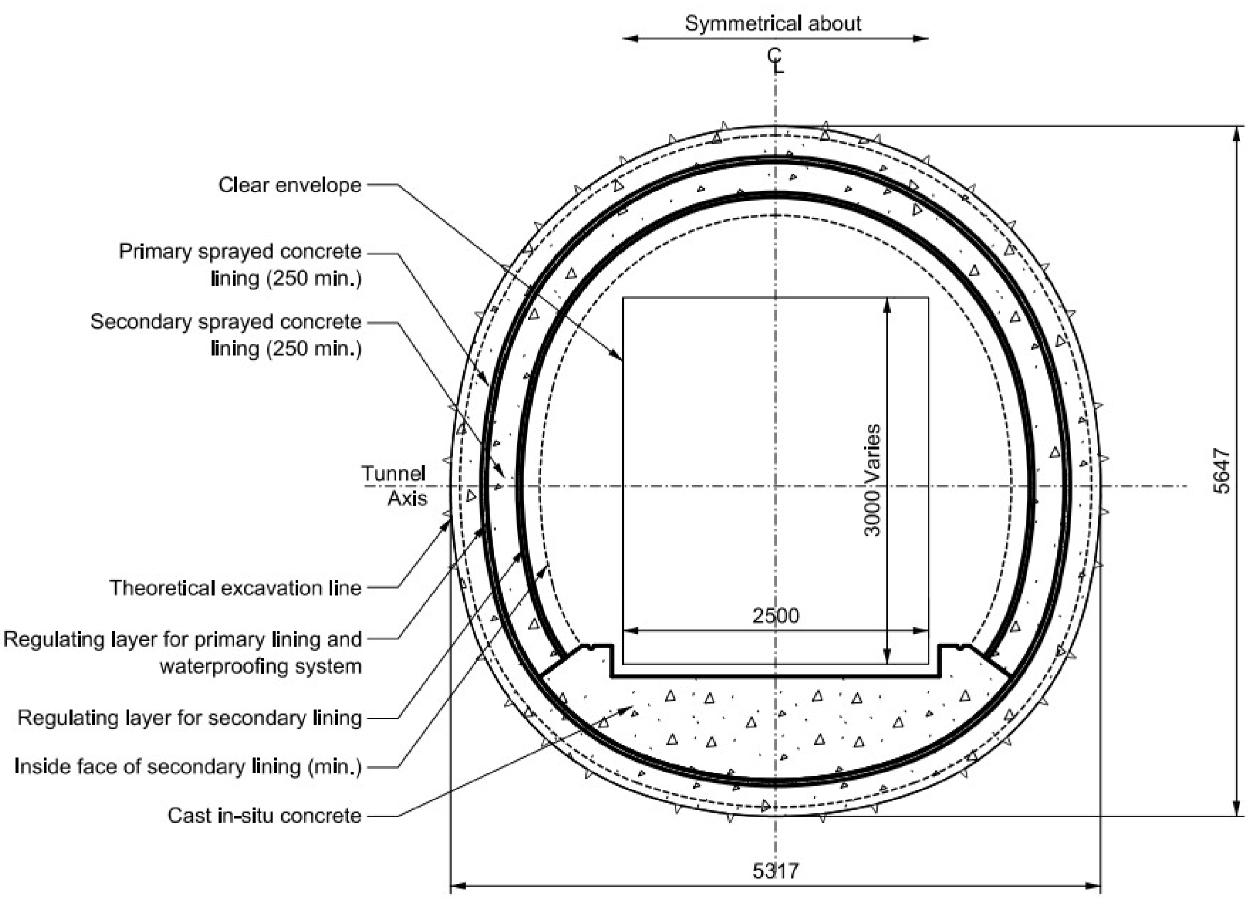
3.2 SPRAYED CONCRETE LINING (SCL)

A typical section from the Bond Street Station Upgrade was used as an example for estimating the embodied carbon in SCL. The tunnel has an oviform shape with varying radii.

For this example the primary lining is considered temporary and the secondary lining permanent. Note that SCL lining design philosophies that consider the primary linings as contributing to the permanent lining will achieve greater material efficiencies than this example.

FIGURE 3-4

SCL Lining from Bond Street Station - extract from Drawing BSU-CLO-05-DR-T-0227 Rev P6 (London Underground Limited, 2012) Reproduced by permission of Transport for London



As shotcrete mix designs were unknown, typical mixes matching the strength class were assumed from HS2 Project shotcrete trials (HS2, 2021) and a published EPD from a rail project in Norway (EPD International AB, 2021). It is important to note that sprayed concrete mixes typically have a much higher cement content than equivalent strength cast concrete to achieve early strength requirements without thermal curing. In this example the secondary lining C40/50 shotcrete mix has a CEM1 content of 480kg/m^3 whereas the C50/60 precast concrete mix in the previous example only had a CEM 1 content of 244kg/m^3. However, it is worth mentioning that low-carbon sprayed concrete mix design is a subject of ongoing research, and lower-carbon mixes replacing up to 80% of the CEM1 content in a sprayed concrete mix with supplementary cementitious materials (SCMs) to achieve a greater than 50% embodied carbon reduction have already been demonstrated (Smith, 2022).

No carbon factor information was found for the spayed waterproofing membrane (made from Ethylene-vinyl acetate polymer), so this layer was omitted from the assessment, as was the cast in-situ Kwikastrip in the primary lining joint.

TABLE 3-3

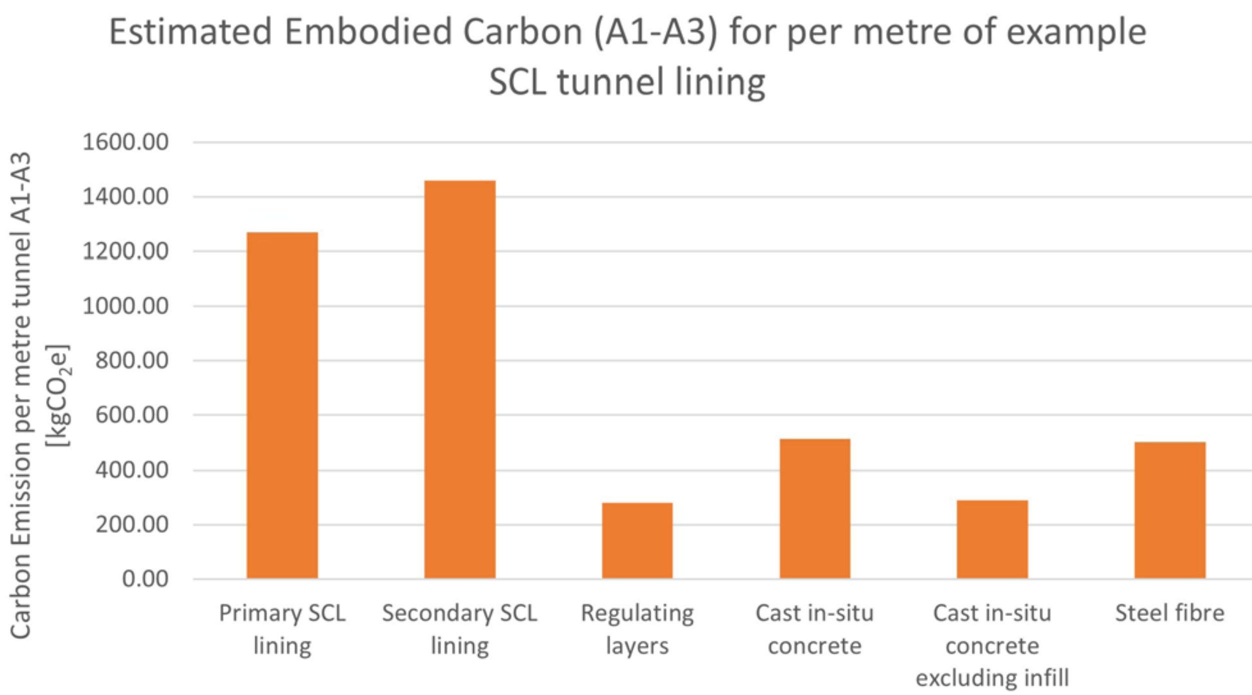
Materials and assumed carbon factors SCL Tunnel Lining

Material	Material Spec	Carbon Factor (kgCO^{2}e/kg)	Source
Sprayed Concrete			
Primary Lining	C30/37	0.141	(EPD International AB, 2021)
Secondary Lining	C40/50	0.237	(HS2, 2021)
Regulation layer	C30/37 (assumed)	0.141	(EPD International AB, 2021)
Steel fibre		1.99	(University of Bath, 2019; Instytut Techniki Budowlanej (ITB), 2022)
Cast in-situ concrete	C32/40	0.112	(University of Bath, 2019)

Results of the assessment are shown in Figure 3-5.

FIGURE 3-5

Embodied carbon per metre for example SCL tunnel lining



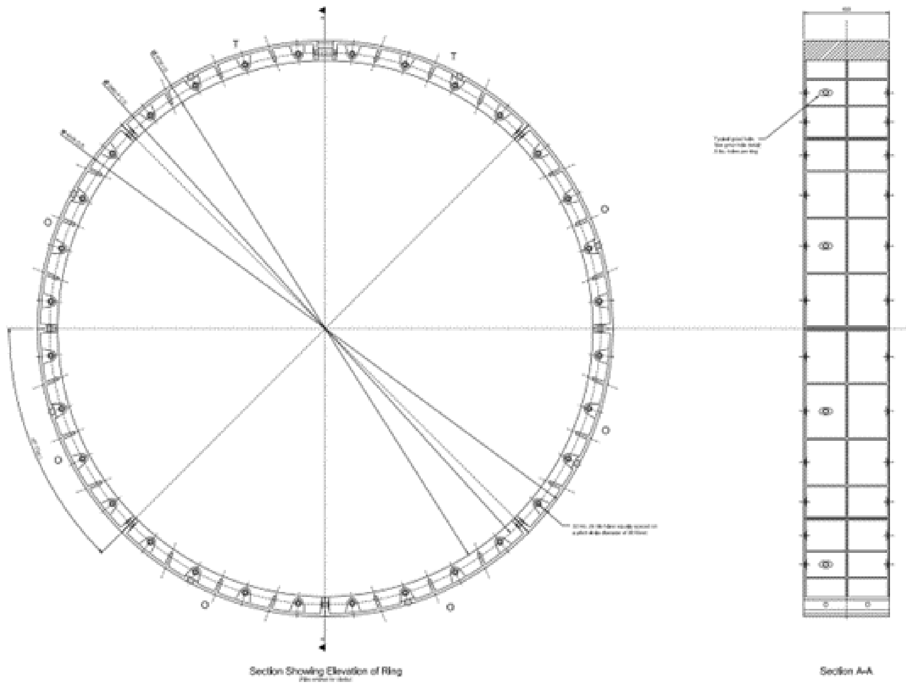
In can be observed from these results that the cast in-situ invert contributes to the embodied carbon. Since the tunnel's curved shape required a flat surface for its intended use, part of the invert concrete volume may be regarded as "infill" rather than a structural requirement. The "infill" portion of the invert represents a design opportunity for material replacement and carbon reduction.

3.3 SPHEROID GRAPHITE IRON

The example used for cast iron quantification is from the Crossrail Contract C305 Cross-passage. The tunnel is "hand-mined" and temporarily supported before the cast iron was installed.

FIGURE 3-6

SGI Lining– extract from Drawing C122-OVE-C4-DDB-CR001_Z-22004 (Crossrail Ltd, 2011) Reproduced by permission of Transport for London

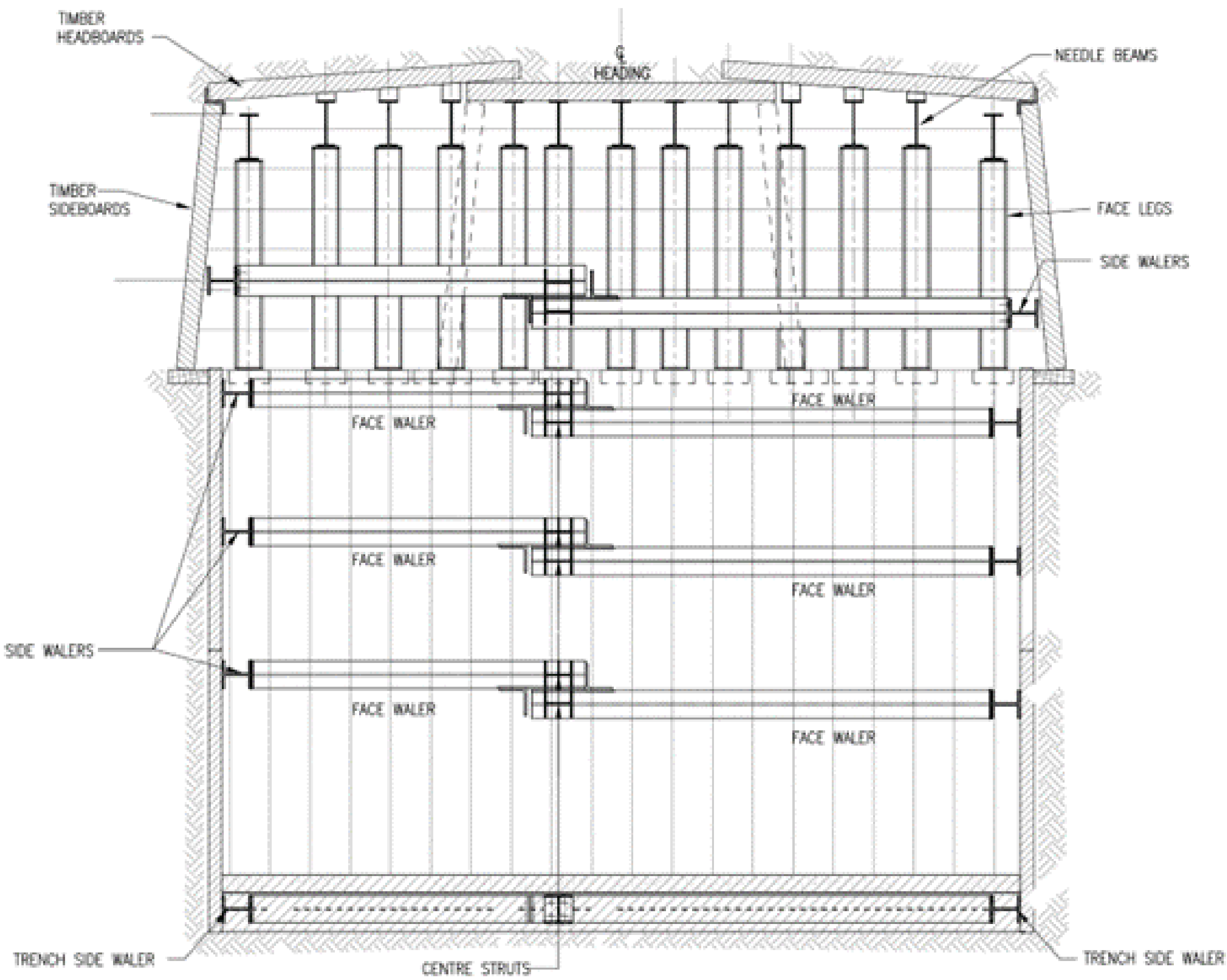


The temporary support consisted of a timber and steel beam heading, however, as the drawings of this temporary support were unavailable, the arrangement and quantities of the timber heading were assumed and estimated based on similar drawings from the Bond Street Station upgrade project. It is assumed that some of the temporary support would be "lost" in the ground and not recovered. It should be noted that SGI linings do not necessarily require timber headings for temporary works. Other cross passages on Crossrail were constructed with an SCL temporary lining. Timber headings were assumed for this exercise merely to extend the variety of the examples.

However, due to the lack of Crossrail drawings, it was challenging to accurately estimate the backfill grout volumes. For simplicity, a uniform thickness of 200mm and a PFA grout mix was assumed.

FIGURE 3-7

Example Temporary Support Timber Heading - extract from Drawing CoLOR-BND-8799-DWG-TUN-001429 (London Underground Limited, 2014) Reproduced by permission of Transport for London



The carbon factors assumed for the SGI tunnel lining are shown in Table 3-4. Note that for simplicity, gaskets, lead caulking and timber packing were omitted from the calculation.

TABLE 3-4

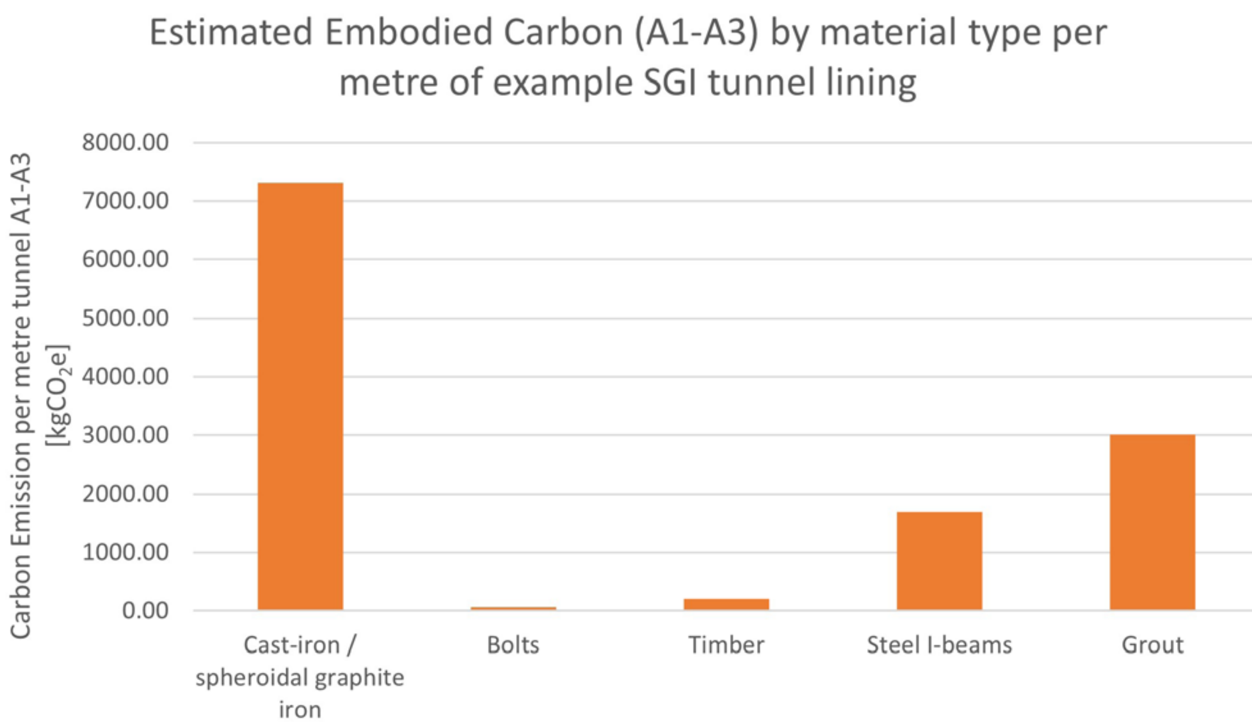
Materials and assumed carbon factors for SGI Tunnel Lining

Material	Material Spec	Carbon Factor ($kgCO^2e/kg$)	Source
Permanent Lining			
SGI	Assumed density 7300kg/m^3 (Material Properties, n.d.)	1.882	(Highways England, 2023)
Backgrout	Assumed mix: density 1825kg/m^3, mix ratio 1:1 (PFA : Cement)	0.62	(United Kingdom Quality Ash Association, 2006)
Bolts	M20 grade 8.8	1.99	(University of Bath, 2019)
Temporary Support			
Timber Headings	Grade C24, assumed density 420kg/m^3	0.263	(The Institution of Structural Engineers, 2022)
Steel I-beams	Grade S355	2.45	(University of Bath, 2019)

The results are shown in Figure 3-8 and indicate that SGI is the dominant contributor to the carbon footprint. Additionally, depending on how the temporary works are configured and the volume of backgrout required, temporary works can also have a large impact on the overall carbon footprint.

FIGURE 3-8

Embodied carbon per metre for example SGI tunnel lining

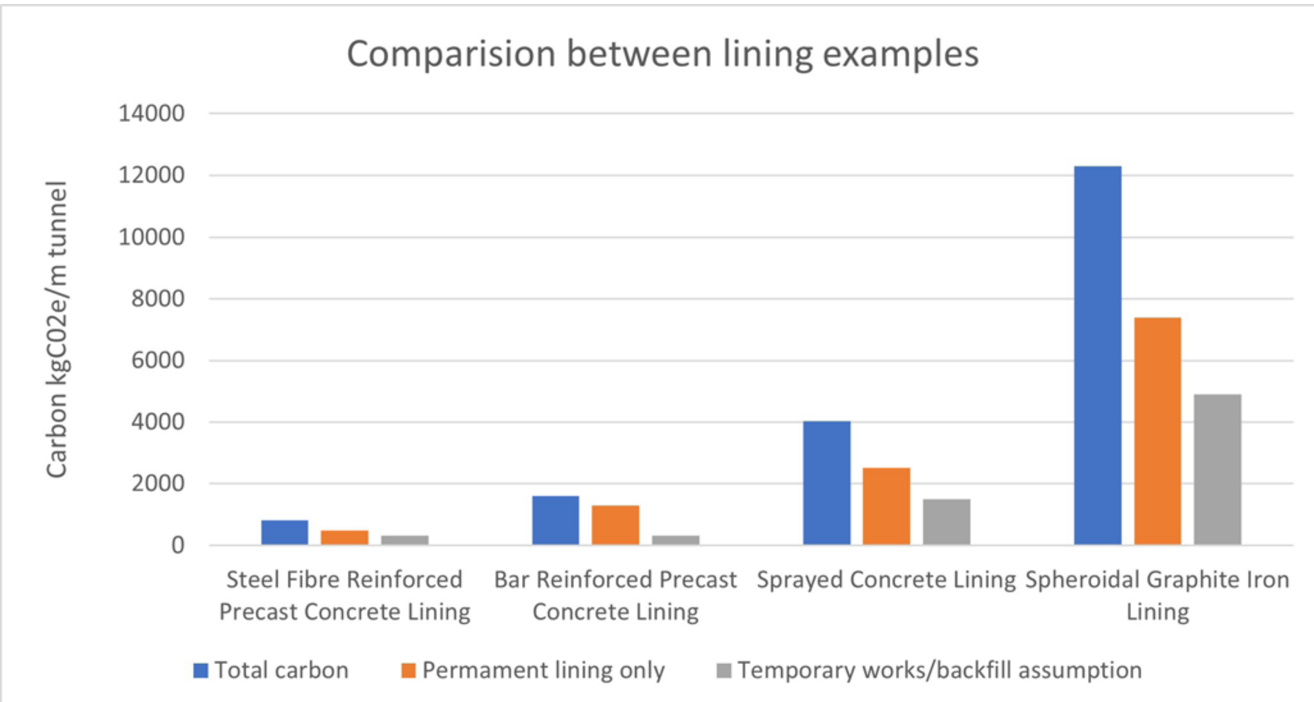


3.4 COMPARISON

A comparison of the embodied carbon of the example tunnel linings is given in Figure 3-9.

FIGURE 3-9

Comparison of example tunnel lining type embodied carbon



From these results its it clear that SGI linings have a carbon impact multiple times more than cementitious linings. The high carbon impact of the temporary timber heading is largely due to the additional backfill and steel sections which were arbitrarily assumed. Alternative temporary support methods could reduce this impact significantly.

These results indicate that the SCL lining example has a higher carbon factor than the PCC lining example. However, it is important to note the following:

- The example SCL tunnel is larger than the PCC tunnel, containing a volume of cementitious material in the secondary lining approximately double that of the PCC example lining.
- The SCL calculation does not account for the potential increase in the actual thickness of lining due to over-excavation or waste from rebound. Good practise might assume the actual volume of shotcrete used to be 1.4 – 1.5 times the theoretical design volumes. (The International Tunnelling and Underground Space Association, 2024)
- The carbon factor of electricity used to operate the construction equipment was not included. In the case where a Tunnel Boring Machine (TBM) is used to construct PCC linings, this energy consumption could be significant, depending on the source of electricity. However, the energy required for excavation and operation of the equipment for SCL construction is only a small fraction compared to the energy required to operate a TBM.
- The embodied carbon of the construction equipment was not included. The embodied carbon of a TBM, especially if it is not recovered and refurbished for reuse on another project, may be another factor to consider. Other construction methodologies are unlikely to have such significant pieces of equipment as single-use items.
- The post processing of tunnel spoil has also not been considered in this exercise either, the carbon impact of which varies depending on geology and relocation & disposal/reuse requirements. However, a slurry TBM for example, that may require a separation plant to separate water and recover bentonite from the excavated material, is likely to have a higher carbon impact than ground that can be excavated and transported without any extra processing.

4. Carbon Reduction Focus Points

4.1 MATERIALS

As previously discussed, the primary structural materials account for the majority of emissions due to their embodied carbon assuming today's manufacturing technology.

4.1.1 Concrete

Concrete production has been estimated to contribute up to 8% of global greenhouse gas emissions. (Robbie M, 2018). The dominant fraction of those emissions occurs during the manufacture of its key binder ingredient, Ordinary Portland Cement (OPC).

Cast in-situ tunnel linings typically require high-performance blended cements for increased durability and low porosity, which have a lower carbon factor compared to pure Portland Cement concrete mixes.

Until recently, blended cements and cement-less alkali-activated cementitious materials (AACMs) have been promoted as low-carbon alternatives. As a general rule-of-thumb, reducing the cement fraction in the concrete mix (by using a blended cement or lower-strength concrete) will reduce the embodied carbon in that concrete mix. However, all the AACMs and other "Low Carbon Concretes" products currently available in the UK rely on Supplementary Cementitious Materials (SCMs) such as ground granulated blast furnace slag (GGBS), a by-product of the steel industry and/or pulverised fuel or fly ash (PFA), a by-product of coal fire power stations. Both of these materials are becoming increasingly scarce and may eventually become unavailable altogether as steel industry transitions to decarbonised processes and coal-fired power stations are decommissioned.

Therefore, as an already fully utilised supply constrained product, use of GBBS to lower embodied carbon emissions in one project over another will not reduce global emissions. In the UK, concrete durability standards effectively mandate the use of GBBS or PFA materials in particular circumstances. Current recommendations from the UK Lower Carbon Concrete Working Group in their publication, *The efficient use of GGBS in reducing global emissions* (The UK Lower Carbon Concrete Working Group, 2023), include continuing to use GGBS where technically required, but advises that any use beyond these requirements (i.e. to lower the embodied carbon of the concrete), should come from well-established supply chains and used in proportion cognisant of the global constraints.

Designers are encouraged to adopt performance-based rather than prescriptive-based material specifications, allowing for local innovative and creative solutions.

The search is ongoing for alternative SCMs, with the goal of replicating the performance benefits offered by existing SCMs. At the same time the alternative cement manufacturing processes are being sought to reduce or indeed eliminate emissions from OPC production.

In the interim, the primary strategy for designers to mitigate the impact of concrete use on global warming is to minimise the quantity required in their designs.

4.1.2 Steel

Steel, the other ubiquitous construction material, is also responsible for around 10% of global energy emissions (International Energy Agency, 2023), and is the other main source of embodied carbon in tunnel structures. In tunnel construction, which demands long design life and is often inaccessible for repairs, steel is typically used within concrete as reinforcement, where it is protected from corrosion.

One key advantages of ground structures, however, is their ability to function as compression structures, configured in circular and arch shapes. These shapes harness the surrounding ground to provide both support and compression, such that tensile stress does not develop in the lining. Where there is no tension, concrete structures do not require tension steel and therefore open up the following carbon reduction possibilities:

- Use of steel fibres instead of rebar (where appropriate).
- Replacement of steel with synthetic materials (i.e., GRFP or synthetic fibres) or other novel alternatives such as basalt fibres. Although synthetic materials tend to have a higher carbon factor per kilogram compared to steel, their lower weight may (but not always) result in overall carbon savings.
- Use of cement mixes with low heat of hydration, reducing the need for thermal crack steel reinforcement.
- Use of specific low carbon product e.g. steel fibres made from recycled steel in an electric arc furnace with a low carbon factor, which are becoming available in the market.

These choices need to be balanced against factors such as fitness-for-purpose, durability and cost. Additionally, tunnelling methodologies that require steel beam sections for temporary support (e.g. in conjunction with timber headings) or permanent support (such as cast in-situ box structures) should be avoided if possible.

Steel manufactures are also pledging to decarbonise their processes. Very low-carbon products are emerging for niche applications, albeit at a premium. For example ArcelorMittal's XCarb sheet pile, which is produced in an Electric Arc Furnace by recycling steel scrap and powered by renewable energy. However, common structural items such as rebar are part of a global supply chain, and without knowing the source of the materials, designers should rely on industry-average figures. The Designer could also consider specifying a maximum embodied carbon factor as part of the design.

4.1.3 Spheroid Graphite Iron

Now in limited production in the UK, SGI has a notably high carbon factor. It is almost a historic material and in view of the global drive towards Net Zero by 2050, should no longer be preferred for new construction.

4.2 CONSTRUCTION METHODOLOGY/TEMPORARY WORKS

4.2.1 Backfill Grouting

Construction using PCC or SGI linings will usually have a gap between the excavated ground and the back of the lining, which must be filled to prevent excessive settlements or ground collapse above the tunnel. In the case of a TBM constructed tunnel using PCC segments, the annular gap can be continuously filled from ports at the end of the TBM shield tail skin as the machine advances. In contrast, a tunnel excavated with traditional hand mining and timber primary supports there may be a substantial depth between the back of the permanent lining and the primary timber support, in addition to grout placed behind timber boards.

As this backfilled space is not usually considered part of the permanent tunnel support, it is often not indicated on design drawings. The grout used for backfill may not be fully specified by the permanent works designer, leaving the contractor to propose a suitable grout mix that ensures the voids are completely filled based on their chosen methods and equipment.

However, there is a great range of materials that could be used to grout that space, with an equally variable range in associated carbon impact. The *BTS Specification for Tunnelling* (Brtitish Tunnelling Society Institution of Civil Engineers, 2010) recognises general-purpose cement grouts for cavity grouting, composed of cement and water, possibly mixed with sand or PFA. Unsurprisingly, grout mixes with a high proportion of cement will have a significantly higher carbon factor than grouts with higher proportions of other components.

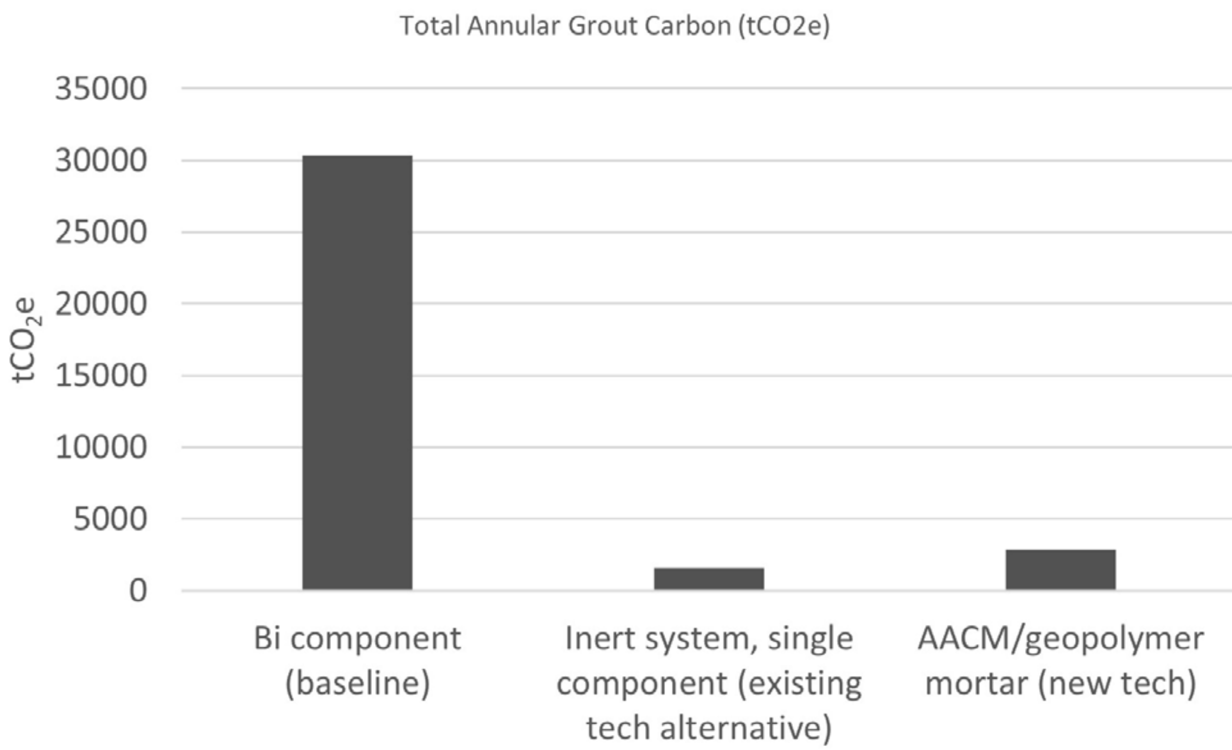
TBM tailskin grouting may use a bi-component grout, where Component A contains retarders to prevent clogging in the lines as it is pumped along the previously constructed tunnel to the face of the tunnel under construction, and Component B includes a set accelerator that is added at the point of injection. While these bi-component grouts are favoured for their convenience, they tend to have a high cement content and therefore high carbon factor. Single-component grouts, which although take longer to set, are a viable alternative. Research suggests mixes with well graded filler material generating a high internal friction have been successful in resisting Archimedean forces (floatation) prior to set (Shirlaw, 2004). Single-component grouts range from "inert" or cementless grouts, to reactive with high cement content, although all have generally lower carbon than bi-component grouts.

It is also now possible to make a cement-free, two-component grout using a geopolymer. This was recently developed for use by MC-Bachhemie and Porr Bau on the Stuttgart 21 project to avoid problems with swelling Anhydrite Rock (MC-Bauchemie/Porr Bau GmbH, n.d.) while offering a much lower carbon factor due to the absence of cement. However, it relies heavily on SCM's, which is likely subject to supply constraint.

When selecting a backfill grout, factors like ground conditions, constructability factors and component material availability must be carefully considered. Still, this is one area where significant carbon savings may be made through a conscious choice of grout mix that avoids a high cement content. A recent study for an upcoming major tunnel project highlighted the potential for a 90-95% carbon reduction by using a cementless grout compared to bi-component alternatives.

FIGURE 4-1

Comparison of carbon content of different annular grout types for an upcoming major project



4.2.2 Ground Treatment

Ground treatment is often required for groundwater control or ground improvement to enable safe excavation or limit settlement. Cementitious grouts are commonly used across various methods, including permeation grouting, fissure grouting, jet grouting, compaction grouting, compensation grouting, backfill grouting, and foam concrete infill. Cementitious grouts, in whatever form, are likely to have a high carbon impact.

Alternatives that could be considered include:

- Mechanise construction methodologies – e.g. TBMs and cross-passage machines can mitigate the need for grouting for ground water control, thereby reducing the use of cementitious grout.
- Slurry wall panels.
- Ground freezing, provided a green energy source is available.
- Compressed air, provided special attention is given to safe systems of work.
- Active depressurisation/dewatering, when powered by a green energy source
- Grout alternatives e.g. Keller's Neutrogel® (Hancock, 2021).
- Novel materials that can be sprayed directly against wet surfaces (Dimmock, 2022).
- Expanding foams, pea gravel, glass beads etc. as alternatives for infill.

4.2.3 SCL Profile and Thickness Control

To date the emphasis has been on ensuring a minimum lining profile thickness is met for safety. Similar concern needs to be on avoiding an over excavated profile for carbon reduction. In hard rock tunnelling using drill & blast methods, typical blast patterns can result in very significant over-excavation which can in turn result in thickened structural linings. Soft ground excavation under spiles or canopy tubes likewise generates very significant overbreak compared to the design minimum. Nevertheless advancements in robotics, scanning technology, and digital processing can provide better control and real-time information to construction teams to excavate and spray SCL lining more accurately with less material.

Use of sheet membranes can require significant additional shotcrete to smooth the surface profile to receive the membrane. Therefore carbon savings may come from the use of sprayed membranes for waterproofing that do not require regulating layers or can be used as a finishing layer without a secondary lining (Dimmock, 2022). Exploring options such as accepting a rougher finish with protruding fibres or clipping protruding fibres to avoid placement of additional materials in regulating layers may be another way to reduce embodied carbon.

It should be noted that SCL is generally preferred where the tunnel is too short to justify use of segmental lining, or where the tunnel geometry varies. In such situations the embodied carbon of a segmental lining would be significantly higher than the idealised tubes used as examples in this paper.

4.2.4 Temporary Support Counted as a Part of Permanent Support

In some cases, due to design responsibility boundaries, initial ground support and primary linings are considered as temporary and excluded from the design of the secondary permanent lining. This is especially wasteful when viewed from an embodied carbon perspective.

Design compartmentalisation philosophy should be avoided. Instead, efforts should be made to incorporate the initial ground support into the permanent lining design, maximising material efficiency and minimising duplication.

5. Conclusions

5.1 CARBON ASSESSMENT

In tunnel lining design, the embodied carbon of key materials (primarily concrete, grout, and steel) dominates the WLCM assessment. These materials are the components over which tunnel design engineers typically have the greatest influence.

An embodied carbon assessment of the materials used in a tunnel is in essence a simple calculation, well within the capability of most engineers. It involves a calculation of material quantity and selection of appropriate carbon factor from database source or product specific EPD.

5.2 PCC vs SGI vs SCL

SGI linings have an embodied carbon impact that is generally many times greater than that of cementitious linings and for this reason, SGI should be viewed as historical material that is no longer preferred.

For the examples selected for this paper, SCL construction method was calculated to have a higher embodied carbon than a SFRC PCC lining. While current sprayed concrete technologies typically result in higher embodied carbon than quality cast concretes, there is potential scope to better optimise the thickness of typical SCL lining designs. Moreover, lower carbon SCL mix designs are a subject of ongoing research.

Among the examples evaluated, the PCC lining example was found to have the lowest A1-A3 carbon. However, this does not include the carbon impact of operating the TBM equipment, the impact of which is linked to the method of source energy generation. SFRC PCC concrete has approximately half the embodied carbon impact as conventional bar reinforced linings, based on current materials' manufacturing methods.

5.3 CARBON REDUCTION LEVERS IN TUNNEL LINING DESIGN

Structural materials, i.e. concrete, cementitious grout, steel or SGI dominate the embodied carbon in tunnel linings, and embodied carbon is the major factor influencing the WLCM of a tunnel lining.

Broad strategies for carbon reduction relevant for tunnel lining design include:

- Where there is design choice opportunity, use of circular compression structures in place of box bending structures to reduce the need for tension steel and enable the use of SFRC or alternative fibre-reinforcing materials.
- Consideration of the existence of temporary ground support measures in the permanent design instead of a compartmentalised design approach. This promotes collaboration between the design and the contractor, resulting in more efficient use of resources.
- Increased use of mechanised construction which can avoid the need for grouting for ground water control (Again, this favours close cooperation between the design and the contractor).
- For SCL construction, paying attention to maximum as well as minimum lining thicknesses:
    - Advances in robotics, scanning and digital processing allow for more precise control.
    - Excavation methods chosen to minimise overbreak.
    - Reducing eliminating the need for cementitious regulating layers by using sprayed membranes or intrinsically watertight concrete rather than sheet membranes.

- Selection of materials that may be suitable for annular or cavity grouting. Choosing a non-cementitious material or low cement grout mix may significantly reduce the carbon impact of the tunnel and is one area where a significant reduction could be made. This must be balanced against the supply availability of the component materials, logistics and constructability.

Ultimately, net-zero tunnel lining design will be made possible from the availability of net-zero concrete and steel. Much promising research and development is underway to find alternative low-carbon SCM sources and transforming the manufacturing processes of both cement and steel to reduce their carbon impact. Therefore, the carbon impact of these materials is likely to change over time. Tunnel Design Engineers are encouraged to stay informed about advancements in material technology and continuously seek innovative ways to incorporate these developments into their designs.

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03: Maximising Carbon Savings – How to Maximise Mode Shift to Sustainable Modes Whilst Building Less

Significance statement

When developing transport schemes, the greatest influence on carbon impacts can be achieved early in the scheme development process. However, there is little guidance covering these important early stages. This paper employs the UK Department for Transport's Transport Analysis Guidance (DfT, 2018a) to highlight best practice for scheme development and selection. The presented recommendations aim to ensure the promotion of transport schemes that effectively reduce user carbon emissions whilst minimizing the emissions embodied in infrastructure. Using this approach will help to reduce carbon emissions and, in many cases, will also enhance the overall value and viability of transport schemes.

Énoncé d'importance

C'est au début du processus d'élaboration de systèmes de transport qu'il est possible d'avoir le plus grand impact sur la réduction des émissions de carbone. Cependant, peu de ressources d'orientation existent sur ces premières étapes importantes. Ce document s'appuie sur le document Transport Analysis Guidance (DfT, 2018a) du ministère des Transports du Royaume-Uni pour mettre en lumière les pratiques exemplaires en matière de développement et de sélection de systèmes. Les recommandations présentées visent à assurer la promotion de systèmes de transport qui réduisent efficacement les émissions de carbone des personnes qui les utilisent en réduisant au minimum les émissions contenues dans les infrastructures. L'utilisation de cette approche contribuera à réduire les émissions de carbone et, dans de nombreux cas, améliorera également la valeur et la viabilité des systèmes de transport.

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Abstract

The greatest opportunity to reduce carbon is during the early stages of scheme development. Whole Life Carbon Management (WLCM) involves applying the PAS2080 (BSI, 2023) Carbon Reduction Hierarchy of "Avoid, Switch, Improve" to scheme development whilst ensuring scheme performance requirements are met. This paper will provide case study information to support decision making whilst applying the hierarchy.

This paper will challenge the transport planning profession to focus on the Avoid part of the PAS2080 hierarchy – i.e., challenging the need for a new physical asset in the first place and using existing assets/networks, e.g., through behavioural change programmes. For example, 15-minute neighbourhoods are inherently low carbon. By focusing on local provision of shops and services, these enable people to travel shorter distances, which are more viable by walking and cycling.

This paper presents recommendations on how to maximise mode shift and reduce carbon emissions in transport schemes whilst building less on the ground, framed against Transport Analysis Guidance (TAG) steps, with lessons learnt for highway, public transport, and active travel schemes. The paper will focus on Stage 1 of TAG covering early stage optioneering.

KEYWORDS
Whole Life Carbon Management (WLCM); Transport planning; Carbon reduction; Embodied carbon; Active Travel; Public transport

1. Introduction

1.1 PURPOSE OF THIS PAPER

The impacts of transport schemes on carbon depend on the net balance of emissions over the scheme's whole lifecycle. Emissions include those generated through construction, operation, maintenance, and decommissioning of any infrastructure, equipment, and vehicle fleet and the impact on user emissions during the scheme's lifetime. Decisions made throughout the selection and development of scheme options to address the transport problems or opportunities in an area can have an impact on the emissions of the scheme implemented.

Whole Life Carbon Management (WLCM) matters at all stages of scheme development. Transport Planners can influence carbon early in scheme development, where the greatest impact can be had. As schemes are developed, designs can become baked-in and opportunities for carbon reduction are narrowed. Early stages (e.g., strategy/options assessment) give the greatest opportunity to reduce both transport user emissions (through influencing demand) and embodied carbon, particularly through the amount and type of infrastructure (affecting the quantity/type of materials). It is important that opportunities to reduce carbon are maximised through the scheme development process through to implementation.

A structured framework covering options development is already covered by the Department for Transport's (DfT) Transport Analysis Guidance (TAG), with guidance on appraisal of carbon impacts in TAG unit A3 on Environmental Impact Assessment (DfT, 2024). Within this framework of TAG, our goals as Transport Planners need to include optimising emissions impacts by maximising mode shift from the private car to sustainable modes whilst minimising embodied emissions, particularly from construction. Delivering the best outcomes from our projects, whilst building less on the ground, should in turn help reduce scheme costs and improve benefits generated. Therefore, this paper seeks to complement TAG by highlighting best practice to specifically reduce carbon in the context of the appraisal process (DfT, 2018a).

Sharing lessons learnt and continuous improvement are critical if we are to rapidly decarbonise the transport network. This paper covers practical examples identified by the authors through engaging with designers and practitioners in the industry, drawing on lessons learnt to maximise mode shift whilst building less on the ground for highway, public transport, and active travel schemes.

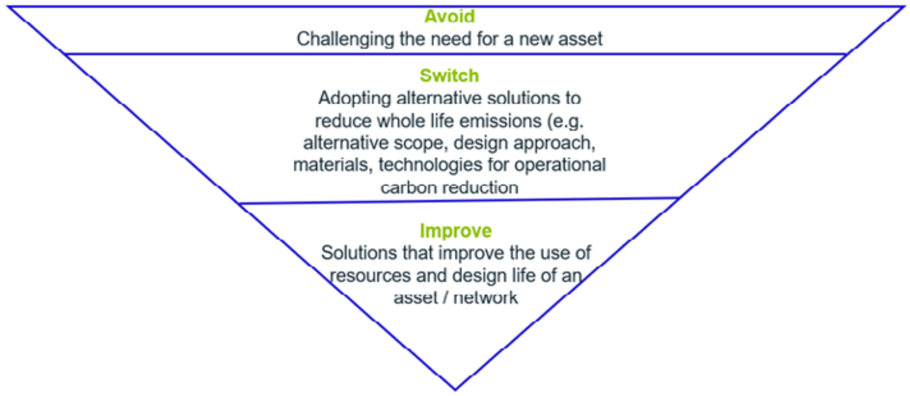
This paper focuses on option development to address identified transport problems in an area. This is assumed to be set in the context of a Local Transport Plan (LTP) or decarbonisation strategy recognising the wider issues of transport decarbonisation, whilst also recognising that some schemes may not originate in this way. Options development is a vast subject; therefore, the authors have sought to focus on specific areas which are considered to have a large impact in reducing carbon. It is hoped that this paper will stimulate debate and inform the evolution of options development to holistically take account of carbon.

1.2 CONTEXT - CARBON IN THE OPTIONEERING PROCESS

Reducing carbon in the optioneering process is about mindset, undertaking an approach which is proportionate to the stage of scheme development and understanding the likely carbon hotspots, savings opportunities, and the ability to influence them. WLCM involves applying the PAS2080 (BSI, 2023) Carbon Reduction Hierarchy (Avoid, Switch, Improve) to scheme development whilst ensuring scheme performance requirements are met. Covering all stages of scheme development and the full project lifecycle, WLCM should apply a proportionate approach, increasing in detail as the scheme progresses.

FIGURE 1

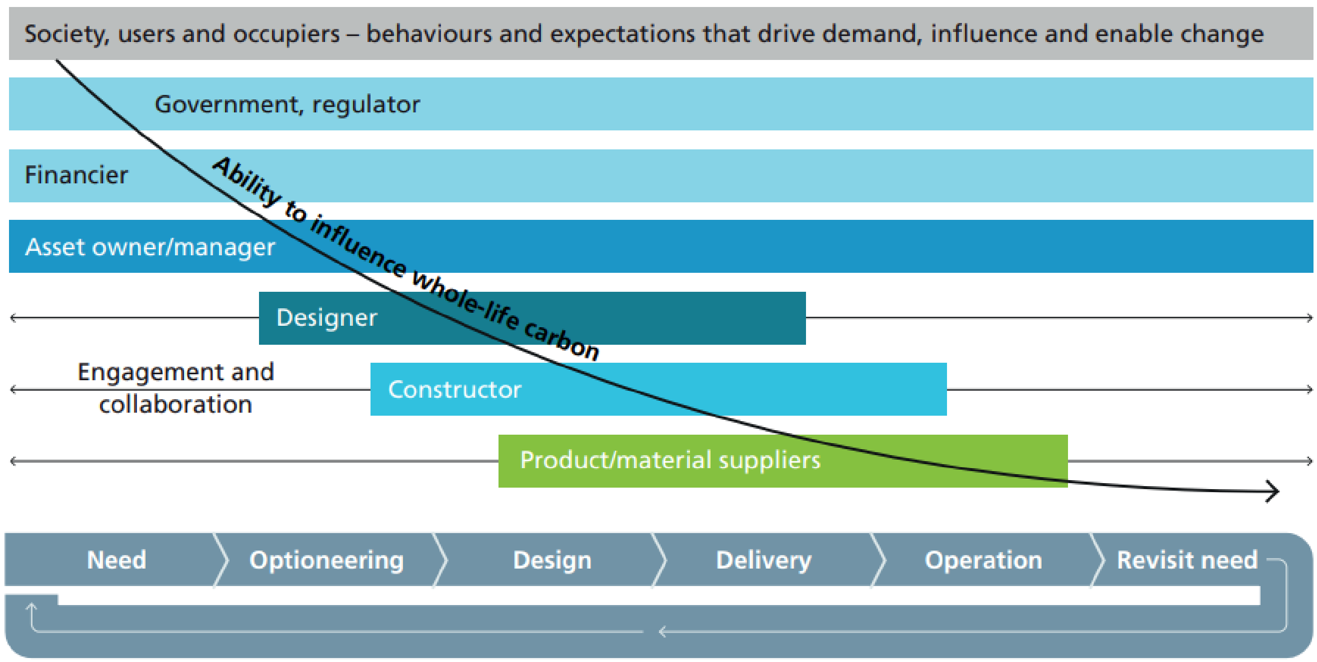
Avoid, Switch, Improve Framework



Being involved from an early stage, Transport Planners have valuable opportunities to influence and reduce carbon with the transport sector. PAS2080 (BSI, 2023) shows that the ability to accelerate decarbonisation throughout the project lifecycle is highest at the need (strategy) stage followed by optioneering stage. With tight delivery programmes and budgets, there is a risk that insufficient consideration is given to carbon issues, and key decisions are fixed from an early stage, whether that is the mode(s) of the scheme, its alignment or standard of the route. Integrating WLCM into the decision-making process from the outset will ensure that carbon considerations are embedded into project optioneering, development, and delivery.

FIGURE 2

Level of opportunity to influence carbon through the design process (Institution of Civil Engineers, 2023)



1.3 METHODOLOGY

This section outlines the methodology employed in the development of this paper. The methodology consists of several key steps, including literature review, interviews, and data analysis.

1.3.1 Literature Review

A literature review of academic and industry publications and guidelines was conducted to establish a theoretical foundation for the paper. Key documents included the DfT's TAG, PAS2080 (BSI, 2023), and other relevant publications. This review helped identify current best practices, frameworks, and guidelines for carbon reduction in transport planning.

1.3.2 Interviews

To gather practical insights and real-world examples, semi-structured interviews were conducted with colleagues, who are practitioners in the transport planning industry. These interviews focused on three types of transport schemes: active travel, public transport, and highways. The interview questions were defined as follows:

- What are the biggest carbon hotspots (e.g., involving carbon intensive materials and/or large amounts of materials)?
- How can these hotspots be engineered out or reduced at an earlier stage of scheme development (e.g., making better use of existing assets)?
- How do we avoid key design decisions being baked in at an early stage (e.g., type/standard of route)?
- How to maximise mode shift whilst minimising infrastructure requirements?
- What are the lessons learnt that can be applied to future projects?

1.3.3 Data Analysis

The qualitative data collected from the interviews were synthesised by identifying which recommendations fall under each step of the TAG process to provide targeted insights. To aid hotspot identification, benchmarked data was analysed covering raw material supply, transport, and manufacturing. For the user, carbon data was obtained from the Decarbonisation Policy Playbook (Van Baar and Foster-Clark, 2023) which uses available data from research and evaluation to estimate the impacts of potential measures on CO_2e emissions for 30 types of intervention.

1.4 STRUCTURE OF THIS PAPER

The remainder of this paper is structured as follows:

- Section 2 outlines the key influences on carbon emissions covering user and embodied carbon and what this means for scheme optioneering.
- Section 3 presents lessons learnt on applying carbon management during options development framed against each step of TAG (Stage 1) with practical examples where the authors have engaged with designers and practitioners.
- Section 4 presents the conclusions of this paper and what actions transport practitioners can take to consider carbon from an early stage on projects.

2. Key Influences on Whole Life Carbon Emissions

2.1 OVERVIEW

This section outlines the key influences on whole life carbon emissions to give context on how to consider carbon during the option development process. Overall, WLCM is about balancing (and minimising) user emissions/savings and emissions from construction, operation, and maintenance. The use of benchmarked data is important to identify carbon hotspots and inform decisions made at an early stage. The following benchmarked data focuses on user and embodied carbon emissions which are typically the largest sources of carbon for transport infrastructure schemes, noting that maintenance and operation should not be forgotten in WLCM and can be the least studied and assessed.

2.2 USER CARBON

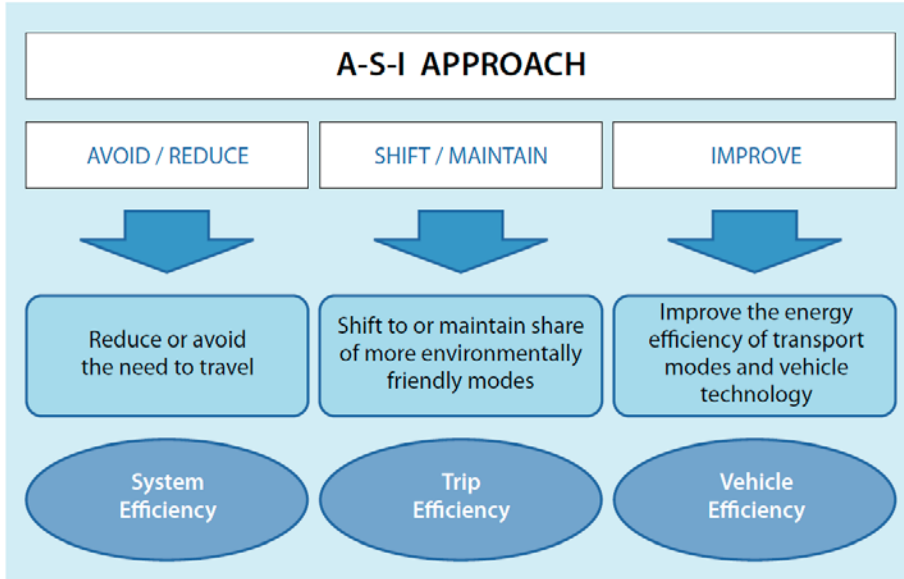
2.2.1 Evidence on User Carbon

The key factors affecting user carbon emissions are vehicle kilometres driven by vehicle type, vehicle fleet composition, and driving styles and conditions (particularly traffic speeds and road layout). At the strategy and optioneering stage, it is important to proportionately use evidence to understand the travel market, identify carbon hotspots, and then shape the scheme around these factors. It is important to first understand the nature of carbon emissions in the geographic area being studied: carbon hotspots based on origin-destination patterns, numbers of trips, the length of those trips and an understanding of why people and goods are moving around.

Transport policy measures can then be scoped to help tackle these hotspots. The Decarbonisation Policy Playbook (Van Baar and Foster-Clark, 2023) groups measures using the Avoid, Shift, Improve framework (Sustainable Urban Transport Project, 2011). The Avoid, Shift, Improve framework (see Figure 3) is a useful way to generate and frame transport options at an early stage - this comprises avoiding and reducing the need for motorised travel, shift to more sustainable modes and improving transport modes. Meanwhile, the PAS2080 (BSI, 2023) hierarchy of Avoid, Switch, Improve is about how to deliver projects to achieve the desired outcomes, whereas Avoid, Shift, Improve is the policy framework that should be used to decarbonise user emissions.

FIGURE 3

Avoid Shift Improve Framework (Sustainable Urban Transport Project, 2011)



Integrated multi-modal solutions will play an important role in providing more attractive alternatives to support mode shift. As part of this process, it is critical to understand potential 'in-scope' trips: those trips that can be realistically influenced by the measures under consideration. This should take account (for example) of catchment areas of mobility hubs and public transport stops. Importantly, this will help sustainable travel schemes to perform strongly in value for money terms for business cases.

To have a significant impact on user carbon there is a need to influence trips over longer travel distances and influence a large proportion of the population. This paper presents evidence from the Decarbonisation Policy Playbook (Van Baar and Foster-Clark, 2023) developed by AtkinsRéalis and SYSTRA to analyse transport user carbon emissions. The playbook uses available data from research and evaluation to estimate the impacts of potential measures on CO_2e emissions for 30 types of intervention and can be used as part of a proportionate approach at options development stage.

The playbook also shows that complementary types of intervention can expand the effectiveness of other types of schemes. For example, local area/liveable neighbourhoods can increase the catchment of active travel schemes by making it safer and easier to access cycle superhighways (or similar) to continue the onward journey. In contrast, increasing highway capacity has been proven to induce traffic and thus increase user carbon emissions (DfT, 2018b), hence any highway improvement needs to be set within a strong policy context, in which mode shift from car is being enabled. Carefully designed highway improvements can help to tackle congestion hotspots, to reduce emissions from petrol and diesel vehicles resulting from low-speed traffic.

When considering potential interventions, unintended consequences should be considered. For example, whilst Electric Vehicles reduce carbon compared to internal combustion engines, they are not carbon neutral (e.g., embodied carbon from construction, energy consumption depending on the source). There is a risk that EVs are driven farther (because they are cheaper to run), increasing severance and reducing physical activity with increased particulate emissions from brake and tyre wear. Their role therefore needs to be considered holistically with the other modes to avoid unintended consequences.

Behavioural and demand management measures can have a large impact on in-scope trips, in particular business travel plans within inner urban areas which would already have a higher level of sustainable travel provision. Demand management measures, such as road user charging and parking measures, are needed to tip the balance between the attractiveness of different modes, but it is important that these measures are supported with high quality sustainable alternatives.

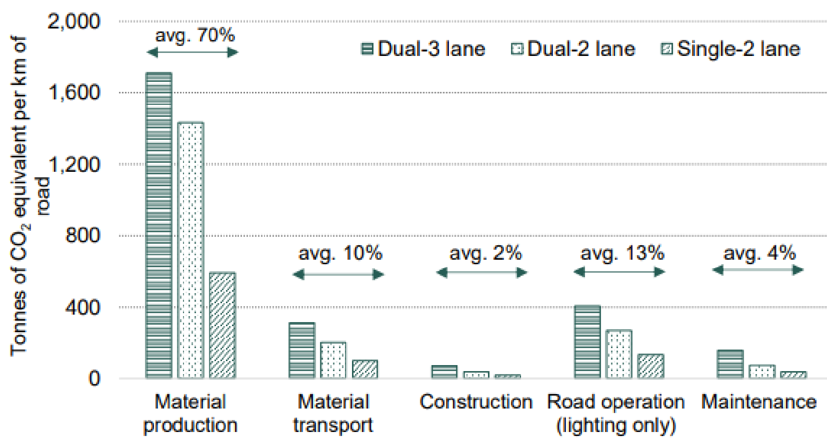
2.3 EMBODIED (CAPITAL) CARBON

Figure 4 shows the whole life carbon impacts of some of the key components of the road transport infrastructure (construction of a new road, lighting operation, and maintenance of the built asset), based on Decarbon8's Measuring Road Infrastructure Carbon Report (Lokesh, Densley-Tingley & Marsden, 2022). It shows that material production makes up one of the largest proportions of carbon emissions in a highway scheme's lifecycle (noting this does not include user emissions which would typically be high for a highway scheme). To reduce the need for new materials in the first place, it is important to follow the principles for a circular economy: elimination of waste and pollution, re-using/recycling, and regenerating natural systems.

The largest hotspot is material production, with emissions generated being the result of the material's carbon intensity multiplied by its quantity. Therefore, it is important to influence the scheme at an early stage to adjust alignments and standards to minimise the amount of carbon intensive materials at the outset (e.g., concrete and steel for structures). Construction materials for highway schemes typically include concrete, asphalt, and steel, all of which are carbon intensive.

FIGURE 4

Decarbon8: Life cycle carbon emissions associated with different scales of asphalt pavement construction (Lokesh, Densley-Tingley & Marsden, 2022)



It is then possible to explore different types of schemes in more detail through the use of typical cross-sections to enable identification of carbon hotspots. The single carriageway example in Figure 5 has been developed in line with PAS2080 (BSI, 2023) and uses typical Manual of Contract Documents for Highway Works (MCHW) items and covers lifecycle stages A1-A3 for raw material supply, transport, and manufacturing which are typical hotspots for highway schemes (see Figure 4).

Table 1 shows that for a typical 1 km of construction, active travel generates the least embodied carbon from A1-3 compared to new roads or Bus Rapid Transit (BRT). This is to be expected given narrower cross-sections and shallower construction depths for typical active travel schemes. The following carbon hotspots have been identified based on benchmarked data (see Figure 5 for an example of a single carriageway):

- Dual carriageway: the largest hotspot is pavement due to accommodating four running lanes, hard strips, and central reservation. Principal structures feature highly due to the inclusion of structures for grade separated junctions (on the assumption that junctions are not at grade), followed by the need for road restraint systems for safety and creating new drainage. Other items that have been included in these calculations include signage, electrical works, lining, and fencing.
- Single carriageway: again, the largest hotspot is pavement due to accommodating two traffic lanes followed by creating new drainage and footways. Other items, albeit a much lower carbon contributor, include fencing, signage, street lighting, and lining. This example includes nominal allowance for structures, for example culverts over local watercourses. Comparing with dual carriageway highlights the need to challenge the standard of route i.e., dual vs. single carriageway and the requirements for structures (for example, grade separated junctions).
- BRT (guided system typology): the largest hotspot is pavement with reinforced concrete slab and a high content of rebar followed by creating new drainage and kerbing.
- Active travel (shared use path typology): the largest hotspot is the material used for the active travel route itself (assuming hot rolled asphalt, dense bitumen macadam, and type 1 material) followed by drainage (depending on drainage requirements).

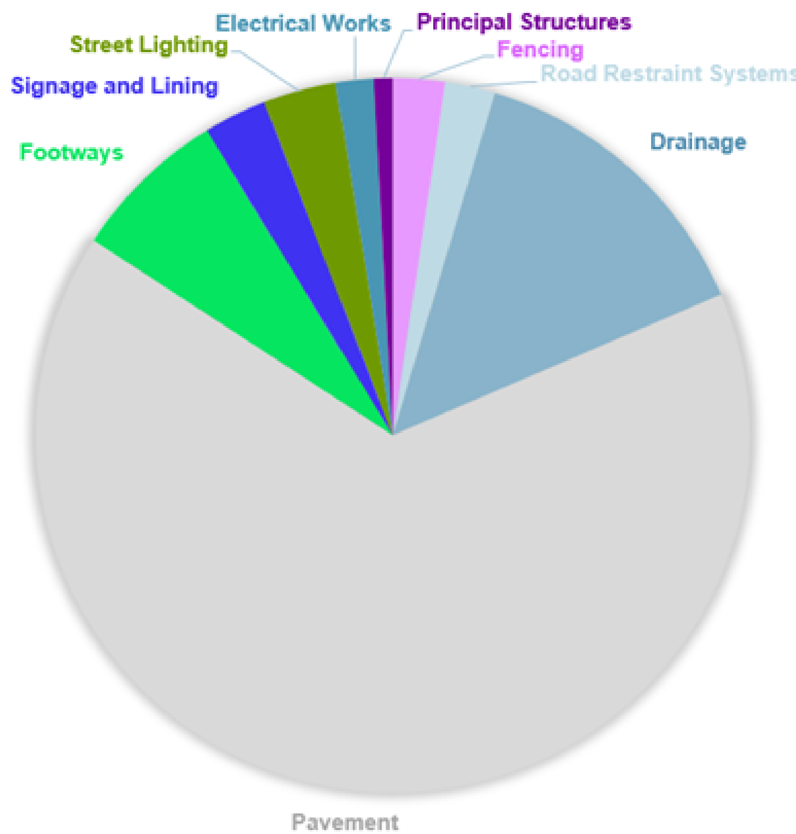
TABLE 1

Estimates of Most Likely Carbon Output by Scheme Type (A1-3) - Based on 1 km of Typical Construction

Scheme Type	Baseline Most Likely Carbon Output (tCO_2e)
Dual Carriageway	1,799
Single Carriageway	667 (see Figure 5 for breakdown)
Bus Rapid Transit (guided system)	527
Active Travel (urban)	187

FIGURE 5

Carbon Hotspots: Highways - Single Carriageway (A1-A3) example



3. Applying Carbon Management During Options Development (TAG Stage 1)

The approach to carbon reduction is informed by both carbon assessment and management. Stage 1 of TAG (see Figure 6) on option development (DfT, 2018a)[1] covers early stage optioneering, culminating in producing an Options Assessment Report (OAR), which is the focus of this paper.

TAG requires carbon assessment to be carried out as part of an economic appraisal, as outlined in TAG Unit A3 on Environmental Impact Assessment (DfT, 2024). Carbon assessments are the estimation of transport related carbon emissions in identified scenarios or the emissions impacts of an option. Carbon assessments also inform decision making as part of carbon management, the process to understand and improve a project's WLC impacts, with a Carbon Management Plan (CMP) being a structured approach to managing carbon.

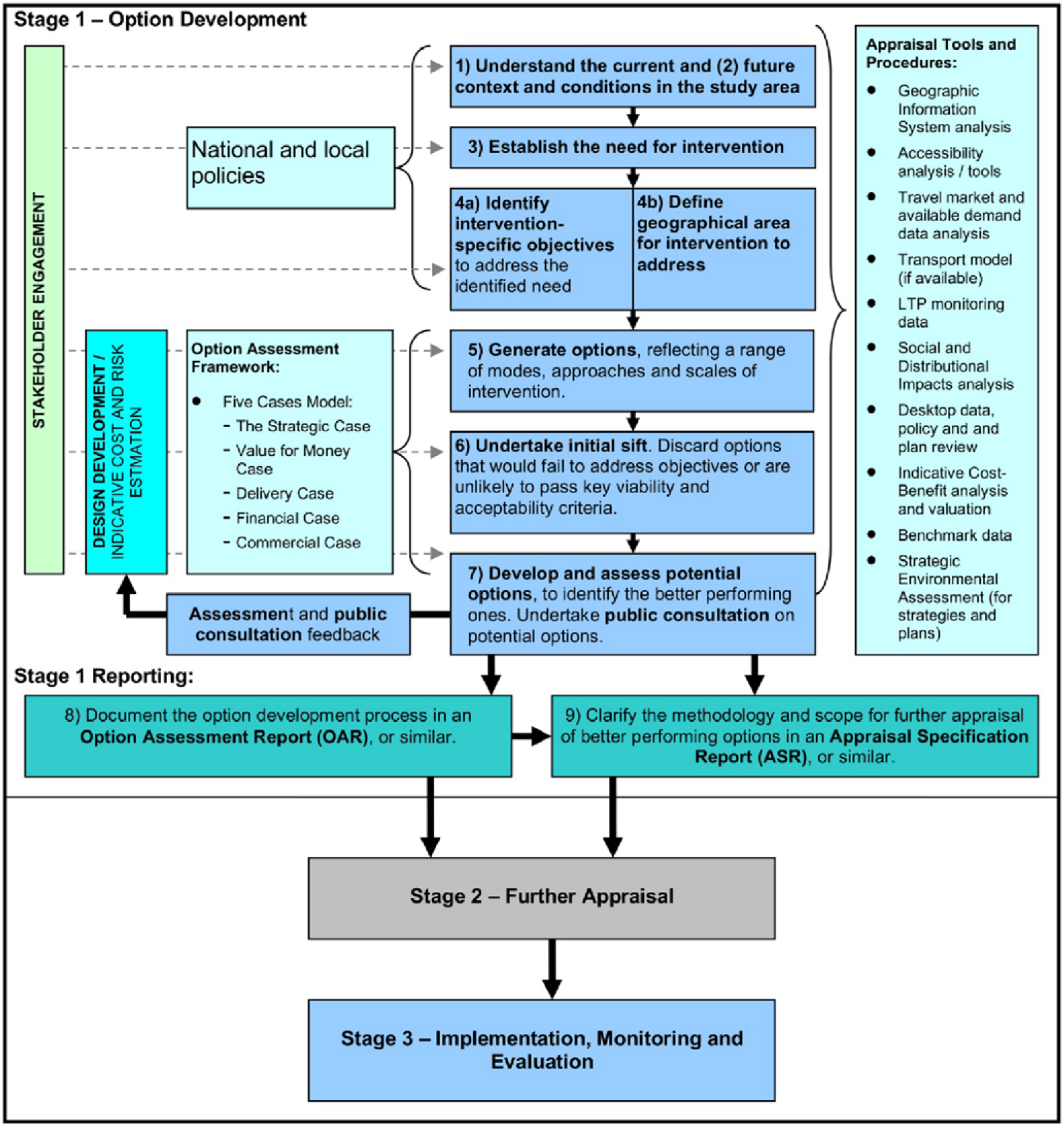
Alongside requirements in TAG for carbon assessment, many funding bodies require carbon management to be undertaken. For example, the DfT's Business Case guidance requires the project's whole life carbon management approach and carbon reduction targets to be covered in the Management Dimension (DfT, 2022).

There are many parallels with transport planning best practice such as understanding the travel market, challenging the need for the scheme, the standard of scheme and route alignment. Therefore, transport practitioners can embed carbon reduction approaches into existing ways of working. This section presents recommendations on how to maximise mode shift whilst building less on the ground, framed against TAG, with lessons learnt for highway, public transport, and active travel schemes.

[1] TAG Steps 8 and 9 cover documenting options assessment and clarifying the appraisal methodology which are outside the scope of this paper.

FIGURE 6

Steps in the TAG Stage 1 Process (DfT, 2018a)



Beyond option development, Stage 2 involves the further appraisal of a small number of better performing options, before implementation in Stage 3. Stage 2 involves an increasing level of design detail and refinement, enabling detailed appraisal to be undertaken with sufficient detail to give confidence in the feasibility of the design and enable cost quantification. Since this paper focuses on early-stage scheme development, Stage 2 and 3 are out of scope. However, it is expected that the level of carbon assessment and management would similarly increase, considering the nature/complexity of the scheme.

It is recognised that not all transport schemes have a carbon reduction / sustainable travel focus and may not have been conceived via an LTP and/or decarbonisation strategy. However, following the approach outlined in this paper should help shift the balance of the types of schemes that are being promoted in the transport industry. This approach may also help to encourage consideration of complementary measures that help to reduce user carbon emissions and improve the effectiveness of the schemes that we plan, design, and deliver.

3.1 STEP 1 & 2 – CURRENT AND FUTURE CONDITIONS

Understand the Primary Drivers Affecting User Carbon

Schemes should ideally be informed by a clear area-wide strategy, recognising that some schemes may not originate in this way. For some schemes, carbon may not be the primary driver, for example the scheme could have been conceived to better connect two towns, or to increase active travel in a local neighbourhood. Understanding the current and future conditions needs to include analysis of the primary drivers affecting travel demand and user carbon, including the origins/destinations and length of journeys (vehicle kilometres) and mode share, both now and in the future.

Where reducing user carbon is a primary consideration, key sources of evidence include the current projections of vehicle fleet composition and how might this affect the scheme, the underlying barriers to greater uptake and the root causes of car use in the area. Even where carbon is not the primary driver for a project, there can be synergies with other issues. For example, tackling poor air quality and health, physical inactivity, and severance would all contribute to saving user carbon.

A study conducted by AtkinsRéalis for a county council in the southeast provides an example of a scheme that did not originally have a carbon reduction focus. Initially, only a bypass was being considered. The problem statement, and scheme objectives, were reframed given the carbon challenge and need to reduce vehicle kilometres travelled in the area. As a result, wider options were considered including active travel, public transport, and junction improvements. This has the potential to substantially reduce embodied and user carbon to support this authority in its ambitions to achieve net zero carbon emissions.

It is important to understand what is within the influence of the scheme promoter. For a local authority, it is important to work with neighbouring authorities, National Highways, Network Rail, and combined authority, if relevant, to develop a holistic vision for the area. Steps 1 and 2 are fundamental in making the case to the senior client team and elected members on the types of measures that are needed to make meaningful impacts on user carbon emissions, particularly if difficult decisions are needed around roadspace reallocation and/or changing the balance from the types of schemes that have historically been delivered.

3.2 STEP 3 – ESTABLISH THE NEED FOR INTERVENTION

Base the need on decide and provide, not predict and provide

As part of establishing the need, transport planners and engineers should apply “decide and provide” principles (and not the “predict and provide” used in the past), with a clear vision of how we want networks and places to be in the future. Highway schemes have typically been developed based on “predict and provide” principles, and these types of schemes require rigorous challenge to ascertain their need. Practitioners need to determine appropriate levels of traffic demand, which are consistent with a decarbonised transport future, which should inform design principles and the vision for the future transport system.

A decarbonisation pathways project by AtkinsRéalis for a shire authority provides an example of creating a future vision for the transport system. The project compared potential business as usual futures with alternative decarbonisation pathways to bridge the growing gap between ambitions and reality/forecasts. This set the strategic context of how the shire authority will deliver a decarbonised network with a stronger focus on behaviour change.

Decarbonising the transport network often involves difficult decisions around reallocating roadspace from the private car to sustainable modes due to limited roadspace. Research can support the need for roadspace reallocation and help disprove that reducing road space for cars leads to increased congestion elsewhere. For example, analysis of traffic data from 11 streets in Barcelona during the COVID-19 pandemic showed that streets where roadspace was relocated to public transport and active travel had a 14.8% average traffic reduction compared to other streets in the city. This reduction was achieved without a significant increase in traffic on adjacent or nearby roads, with only a slight increase in traffic of 0.7% on immediately adjacent parallel streets (Nello-Deakin, 2022). Similarly, a comprehensive review of 46 Low Traffic Neighbourhoods (LTN) schemes in London (Possible, 2023) shows a 46.9% mean reduction (32.7% median) in traffic across London compared to traffic counts prior to the implementation of the LTNs.

Again, where carbon is not the primary driver for the scheme, the need to reduce carbon can be integrated with other sustainability policy drivers. For example, increasing physical activity, improving air quality, and improving multi-modal accessibility to local communities. Focusing on a “decide and provide” approach will help to reduce scheme costs by avoiding over-providing infrastructure capacity.

3.3 STEP 4A – IDENTIFY INTERVENTION SPECIFIC OBJECTIVES

Include a Carbon Objective

Development of objectives needs to link to the problems identified in Steps 1 and 2 and the need for intervention in Step 3, underpinned by policy. National transport policy includes the need to reduce carbon and the majority of regional and local authority transport agencies have declared climate emergencies. It is therefore important that schemes have a carbon objective, that carbon is included in any multi-criteria assessment and included in ongoing project decision making. Key considerations include whether the focus of any carbon objective(s) is on WLC, or specific types of emissions such as focusing on transport network decarbonisation (Avoid, Shift, Improve) and/or reducing embodied carbon from construction and maintenance through applying the PAS2080 (BSI, 2023) hierarchy (Avoid, Switch, Improve), or other sources of emissions such as operational emissions. A WLC objective is considered to be the minimum with other supporting objectives being optional.

Objectives could also be indirectly linked to carbon emissions, such as a target for mode shift towards sustainable modes or a reduction in vehicle kilometres driven. For example, the Belfast Glider bus rapid transit system focused on substantial shift to high quality transit services and led to significant impact by reducing intermediate length trips across the city. Objectives relating to nature recovery and climate resilience should also be considered. The objectives should also be based on clear "logic mapping" to establish how interventions would tackle the issues identified in Steps 1 and 2, and follow the "decide and provide principles" established in Step 3.

3.4 STEP 4B – DEFINE GEOGRAPHICAL AREA OF SCOPE FOR INTERVENTION TO ADDRESS

Understand the Carbon Intensive Movements

Shaping the scheme around carbon intensive travel movements will maximise the potential reduction in user carbon emissions. To have a significant impact on user carbon there is a need to influence trips over longer travel distances and to be able to influence a large proportion of the population. As well as reducing user carbon emissions, a focus on carbon intensive movements will help to improve the economic case of a scheme by maximising mode shift, which (for example) could increase public transport patronage, health impacts of active travel, and "decongestion" benefits on the road network.

3.5 STEP 5 – GENERATE OPTIONS

Generate Options that Align with Avoid-Shift-Improve Principles

When seeking to generate options to reduce carbon emissions, options should be generated around the Avoid-Shift-Improve framework in Figure 3, whilst considering:

- A range of modes, particularly those that will encourage a shift to sustainable modes.
- Carbon hotspots that could be avoided when generating alignments – can engineering constraints be avoided?
- Could interventions be packaged to expand the travel market (e.g., through local area/liveable neighbourhoods or mobility hubs)?
- Is there a package of smaller schemes that could deliver the same outcomes?
- Can complementary behaviour change measures to give potential users the capability and motivation to use the proposed infrastructure as part of the COM-B behavioural change model (Michie et al., 2011).

Whilst highways options that increase capacity do not specifically fit within the Avoid-Shift-Improve framework, sustainability thinking should be integrated into any highway related options. For example, highways options should be coupled with sustainable travel improvements on the new and alleviated route, and non-highway options should also be assessed.

The PAS2080 (BSI, 2023) Avoid-Switch-Improve can also be applied to option generation and development. As with any type of transport scheme, the need for the scheme should be challenged (the Avoid component of the hierarchy). In terms of the Switch component, it is important to challenge the specification of the scheme early in the development process. For example, schemes to improve bus journeys form a spectrum from targeted bus priority, BRT involving moving of kerb lines, through to fully-segregated guided busways. Overall, it is important that the level of infrastructure can be justified in response to the transport outcomes that are being sought.

Large-scale construction is not always required. Particularly in interurban and rural environments, bus lanes should only be provided if there is a clear justification, supported by bus delay data and evidence of the travel market. For example, there could be opportunities for 'bus gates" to provide buses a time advantage without building large amounts of bus lanes in interurban environments.

Integrate Option Development with Good Urban Design Principles

Regardless of mode, we need to be developing infrastructure that is suitable for towns and cities, considering where development sites are allocated and whether they are on existing transport routes. The success of any major transport scheme is dependent on good urban design principles, in particular good urban design practices are vital to support sustainable modes of travel. For example, even where new highway construction is required, it is important that active travel and placemaking are addressed as integral components on both the alleviated and new route. Even if detailed placemaking principles are left to a later stage, the requirement can be indicated on a plan for development at the next stage.

Maximise Mode Shift by Understanding the Travel Market

Shaping the scheme around the travel market based on Step 4b will help maximise bus patronage and active travel route usage, encouraging mode shift, thus reducing user carbon emissions, as well as improving the Economic Case of the scheme. The catchment can be expanded through reconfiguring bus routes around the scheme. Furthermore, provision of mobility hubs and liveable neighbourhoods enable people to safely access bus routes via cycling and wheeling. The geographic area of scope can be extended by bringing together complementary interventions, for example local area/liveable neighbourhoods programmes can improve access to strategic cycling networks.

In terms of encouraging modal shift to bus, reducing bus journey times is important, but demand management may be required to improve the perceived attractiveness of buses in relation to private cars (for example, through the introduction of road user charges or limiting parking). This approach is likely to be more viable in larger towns and cities, where there are a wider range of travel alternatives. In contrast, people living in villages and rural areas are more reliant on cars for accessing services. It is important to understand the travel market, to enable people to access jobs and services without a car, in both urban and rural areas; for example, residents living on the outskirts of a city may travel to secondary retail locations that are less accessible by public transport.

Maximise Mode Shift Through Inclusion of Behavioural Change Programmes

Consideration should be given to integration of behavioural change measures in scheme options to improve their effectiveness, for example in helping to increase mode shift. It is recognised that many sources of scheme funding are specifically for "capital" funding (scheme construction) whereas behavioural change programmes are "revenue" funded and alternative sources of funding may need to be sought.

Behavioural change measures are key to maximising mode shift because infrastructure schemes to encourage sustainable travel modes of transport may not be sufficient in their own right. In many cases, infrastructure upgrades only address part of the challenge in encouraging behaviour change, and other mechanisms are also needed. The COM-B behaviour change framework (Michie et al., 2011) addresses the Capability, Opportunity, and Motivation factors that influence people's behaviour, and this has been applied in a wide range of settings, including the transport sector. This theory provides a framework for understanding the elements required for behaviour change. Each element is detailed below:

1. **Capability** refers to the user's psychological and physical capacity to change their behaviour. For instance, encouraging sustainable modes of transport involves enhancing people's capability by providing bike maintenance workshops, cycling lessons, and affordable public transport.
2. **Opportunity** related to factors that make behaviour change possible or convenient. In terms of encouraging sustainable modes of travel, this would include providing infrastructure that makes sustainable modes of transport safe, convenient, and appealing such as wide, attractive footways, dedicated bike lanes, secure cycle parking, and well-connected public transportation networks.
3. **Motivation** refers to the users' mental processes that spur the behaviour change. To encourage sustainable modes of travel, public campaigns and community events can highlight the benefits of using these modes, such as improved health, improved air quality, and cost savings.

It is vital to prevent users from "relapsing" back to less suitable modes of transport by identifying the key triggers and barriers that may hinder sustained behaviour change. This could include factors such as convenience or cost and often does not need to involve major infrastructure improvements.

3.6 STEP 6 – UNDERTAKE AN INITIAL SIFT

Include Carbon in Sifting Criteria, Supported by Benchmarked Data

Given the importance of carbon reduction in national, regional and local policies, it is important to capture carbon in the scheme objectives (see Step 4a) and options sifting criteria. The sifting criteria used to narrow the long-list of options should be aligned with the objectives developed in Step 4a.

Challenges may arise during the sifting stage, with competing objectives pointing to different solutions, for example unlocking new homes and jobs vs. reducing carbon through the number of vehicle kilometres driven. Wherever possible, planners should have identified options that deliver benefits across all the objectives, through the decide and principles described in Step 3, and logic mapping developed in Step 4a. However, there will be tensions between objectives on occasions. Sensitivity tests, using different weightings for different criteria can help test the sensitivity of sifting scores whilst enabling the narrative of the decisions made to emerge.

Options should be assessed against WLC objectives using benchmarked data to support scoring of carbon in a proportionate way. It is important to remember that existing data may not be readily available for some options and professional judgement may be required for all or some aspects of the lifecycle. For the sift stage, and all other stages where assumptions and benchmarked data are used, it is crucial to ensure that processes, decisions, data sources and assumptions are clearly documented.

3.7 STEP 7 – DEVELOP AND ASSESS POTENTIAL OPTIONS

Step 7 of TAG involves developing potential options to a sufficient level of design/specification and collecting sufficient evidence to be able to distinguish the relative costs, benefits and impacts of the options under consideration (DfT, 2018a). The level of design development at Step 7 can vary greatly, generally from a "line on a map" through to preliminary design. We have assumed that early-stage designs will be developed at this stage, but if this is not the case, the recommendations below should be applied at a subsequent stage.

Ensure Options Developed are of an Appropriate Standard

It is important to get schemes "right first time" delivering a high-quality scheme that provides an appropriate standard of route. It is neither cost-effective nor carbon-effective to deliver a sub-standard scheme that needs to be upgraded at a later date.

There is a need to avoid overengineering and consider a "do less" approach as the first option (whilst meeting design standards). Having challenged the need for the scheme (regardless of mode), it is important to consider the infrastructure requirements for schemes at an early stage. Robust decision-making processes are needed to balance between reducing carbon-intensive infrastructure requirements (e.g., retaining walls) and maintaining a standard of provision that is comfortable and safe for the users.

Proportionately Embed WLCM Early in the Design Process

It is important to proportionately embed WLCM from an early stage when there is the greatest opportunity to reduce whole life carbon through decision making as part of the optioneering process. Carbon should be part of the decision-making process alongside other considerations (e.g., safety, cost, time and quality), with key decisions being recorded in a carbon tracker and/or design decision log.

Invest Early in Specific Areas of Scheme Development

To avoid cost escalations at a later stage, it helps to invest early in specific areas of scheme development. It is critical at this stage to determine where to invest the effort, for example accelerating discrete areas of scheme design to inform decision making. Tools are available at the optioneering stage to enable the right decisions to be made at an earlier stage, such as the use of benchmarked carbon data. Constraints mapping enables the designer to avoid/minimise bridges and go through the best alignment possible. Similarly early consideration of land clearance can help to save carbon. Extensive land clearance and felling of established trees removed a carbon “sink,” replacement planting of saplings will require years of growth before they can start to capture significant amounts of carbon as fully established trees.

Engagement with stakeholders and supply chains is another opportunity for early investment. Taking a strategic view at a programme level (as opposed to the scheme level) will enable long-term partnerships and strategic procurement discussions to take place. For example, introduction of a low carbon material might not be justifiable for a small scheme, but it could be justifiable across a portfolio of schemes.

Early Consideration of Nature-Based Solutions will Help Improve Environmental Performance of Schemes

Options to deliver a measurably positive improvement natural habitats (e.g., woodland creation, natural flood management, habitat regeneration) should firstly be considered as part of Step 5 on options generation before being developed in Step 7. As with other areas of scheme development, proportionality at an early stage is key, as is avoiding impact on established nature in the first place. Provision can be made in the scheme’s footprint, for example including land for pocket parks or rain gardens, or noting a recommendation for the next stage to consider green bus stops. In particular, adjusting an alignment to reduce the amount of a route through flood plains will help to reduce the amount of structures required, saving cost and carbon. Regardless of whether there is a statutory requirement, setting a project-level target to increase biodiversity can help to give it prominence in the scheme development process - in the UK developers must deliver a biodiversity net gain of 10% (DEFRA, 2024).

3.8 SUPPORT STRONG LEADERSHIP (APPLICABLE DURING ALL STEPS)

Strong leadership is needed from both scheme promoters and their professional advisers throughout the scheme development to ensure carbon is a key part of decision making. There should also be mechanisms to enable members of the team to constructively challenge where key aspects of a project need to be revisited or where difficult decisions are needed (e.g., on roadspace reallocation).

It is important that the difficult decisions on a scheme are made at an early stage before the design becomes fixed. Once the Development Consent Order (DCO) (or planning application equivalent) is approved, it is too late to make significant changes, it is only possible to adjust the finer details of the design. Otherwise, there can be resistance from implementing savings (e.g., carbon, cost, programme) due to the cost/programme/reputational risk of the implications of varying from the approved DCO, which is where strong leadership is needed.

To help build support for a scheme it is important to explain why a scheme is needed and the benefits. The early phases of scheme development are about persuading political representatives and statutory bodies on the right thing to do (showcase the art of the possible), although there can be challenges in follow on phases where schemes are then included in locations that they are not suitable. This highlights the importance on having an evidence base of previously successful schemes to persuade political representatives and stakeholders.

Incorporating behaviour change measures and co-design of improvements can help to improve local support, but the challenge can be the funding of sustainable travel measures. Measures such as marketing and travel planning, alongside infrastructure improvements, can help to ensure a comprehensive approach to encouraging sustainable travel. Early actions in these areas are key to maximising the carbon-reducing potential of sustainable travel.

Schemes involving roadspace reallocation can be contentious but have the potential for a large decrease in user carbon emissions. The Decarbonisation Policy Playbook (Van Baar and Foster-Clark, 2023) evidences a high of trip reduction for local area/liveable neighbourhood measures. These types of measure have the benefit of not requiring heavy infrastructure (with the exception of key corridors where the users would need more protection). Strong leadership is needed to address public concerns and effectively implement these schemes.

Finally, as part of strong leadership, it is important to allow teams to innovate. By the client setting high level outcomes related to good design as part of the procurement process, this gives the designers the ability to think creatively, which will help to deliver better designs that meet outcome and cost requirements.

4. Conclusions

Transport Planners have a real opportunity to reduce carbon on projects from an early stage where the greatest impacts can be had. We need to be developing schemes that maximise mode shift to sustainable modes, whilst building less, through bringing carbon into the decision making process at an early stage.

The following lessons have been identified by engaging with practitioners for this paper, framed against Steps 1-7 on options development in TAG Stage 1:

- **Step 1 & 2 - Understand current and future conditions:** it is critical to understand the primary drivers affecting user carbon.
- **Step 3 - Establish the need for intervention:** thinking should be framed on “decide and provide principles”, not predict and provide.
- **Step 4a - Identify intervention specific objectives:** planners and engineers should integrate carbon objectives into the planning of all programmes.
- **Step 4b - Define geographical area of scope for intervention to address:** planners should understand travel demands and the most carbon-intensive movements.
- **Step 5 - Generate options:**
  - Options should be aligned with Avoid-Shift-Improve principles.
  - Options development should be integrated with good urban design principles.
  - There is the opportunity to maximise mode shift through better understanding of the travel market.
  - Mode shift can be maximised through inclusion of behavioural change programmes.
- **Step 6 - Undertake an initial sift:** Carbon objectives should always be included in sifting criteria, supported by benchmarked data.

- **Step 7 - Develop and assess potential options:**
  - Options should be developed to an appropriate standard, balancing the needs of transport users, whilst reducing infrastructure requirements.
  - WLCM principles should be integrated, to a proportionate degree, early in the scheme development process.
  - Early investment in specific areas of scheme development will help to mitigate risks at a later stage.
  - Early consideration of nature based solutions will help to further improve the environmental performance of the scheme.
- **Throughout all steps in the process,** strong leadership will help to embed the right behaviours, supporting ongoing challenge and innovation to better meet the needs of users and deliver more carbon-efficient solutions.

Following the principles described above will help to set the right foundations for the project. It will, of course, not be the end of carbon management in the project. Indeed, it will help set a strong basis for further development of designs and more detailed appraisal (in TAG Stage 2, see Figure 6) and provide a strong basis for the development of business cases and, ultimately, better projects.

Through considering carbon from an early stage, we can make carbon part of project decision making, ensuring schemes deliver the deliver the best overall outcomes to society whilst aiming to minimise carbon. Shaping schemes around the travel market should help to increase mode shift, value for money and scheme viability as well as reducing carbon. An early understanding of carbon hotspots means these can be considered before design decisions become baked-in when opportunities for carbon reduction can become narrowed. Early stages give the greatest opportunity to reduce carbon, both transport user emissions and embodied carbon, and transport planners have a real opportunity to influence.

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04: Evidence Review: Economic Appraisal for Investing in Local Highways Maintenance

Significance Statement

This article presents the findings of an evidence review undertaken for the UK Department for Transport (DfT) which aimed to demonstrate the benefit cost ratio (BCR) and value for money (VfM) of investing in local highway maintenance. It also examined how existing evidence can be improved to inform future spending decisions. The project involved engagement and collaboration with various groups within DfT, local authorities, and industry stakeholders. The final report will inform the upcoming Government Spending Review and help make the case for investment at local, regional, and national levels across England.

Énoncé d’importance

Cet article présente les conclusions d’un examen des données probantes entrepris pour le compte du ministère des Transports du Royaume-Uni (DfT), qui visait à démontrer le ratio avantages-coûts d’un investissement dans l’entretien des routes locales et démontrer la rentabilité des investissements en optimisant les ressources disponibles. Il a également examiné comment les données existantes peuvent être améliorées pour éclairer les décisions futures en matière de dépenses. Le projet a fait appel à la participation et à la collaboration de divers groupes au sein du ministère, des autorités locales et des parties prenantes de l’industrie. Le rapport final éclairera le prochain examen des dépenses publiques et aidera à justifier les investissements aux niveaux local, régional et national en Angleterre.

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Abstract

The purpose of this evidence review was to provide the UK Department for Transport (DfT) with an overview of the existing tools and methodologies designed for economic appraisal which are currently available and used by local road authorities in England to demonstrate the benefits of investing in local highway maintenance. The review was structured around eight research questions, which aimed to provide DfT with a better understanding of the economic benefits of investing in local highways maintenance. The focus of the evidence review was to demonstrate the Benefit Cost Ratio (BCR) and Value for Money (VfM) of investing in local highway maintenance; and to ascertain how the existing evidence can be improved to inform future spending decisions on local highways maintenance. This enhanced understanding will also serve as preparation for the next Government Spending Review, to make the case for investment at local, regional and national levels in England. Overall, funding for local highways maintenance provides good to very good return on investment, with a much lower risk than major projects to construct new infrastructure.

KEYWORDS
Local Highways; Maintenance; Economic appraisal; Value for money; Benefit cost ratio

1. Introduction

The local highway network is the largest physical public sector asset in England, valued at approximately £400 billion and maintained by local road authorities, who have a statutory obligation to keep it in a safe condition (Asphalt Industry Alliance, 2024). The local highway network totals almost 175,000 miles, which is 92% of the overall road length in England. As well as carriageways, the network also contains footways, cycleways, street lighting, structures, drainage, street furniture, trees, traffic signals, signs, and road markings. Local highways are much more than routes for traffic; they create the atmosphere of a place and provide corridors for utilities networks. When planned and maintained properly, they add to feelings of safety, security, and well-being and enable active travel, promoting social cohesion and economic development (CIHT, 2020).

Virtually every journey begins and ends on a local road, and maintaining the local highway network in good condition is crucial for society. Local roads provide access to basic goods and services, and even those who never drive still rely on the local roads when travelling by bus, or any active travel mode. The local network delivers food to supermarkets and goods to shops. It connects communities and, as social networks and extended families become more dispersed, transport plays an even bigger role in holding them together.

The Department for Transport (DfT) commissioned AtkinsRéalis to undertake an evidence review in response to a recommendation from an internal review "that DfT take additional steps to assess and demonstrate the Value for Money (VfM) of the funding at a wider programme level." The aim of the review was to provide DfT with a better understanding of the economic benefits of investing in local highways maintenance, especially following the Network North announcements in 2023, which included an additional £8.3 billion investment in local highways maintenance over 11 years (DfT, 2023). This enhanced understanding will also serve as preparation for the next Government Spending Review, to make the case for investment at local, regional and national levels in England.

1.1 OBJECTIVES

The focus of the evidence review was to demonstrate the BCR and VfM of investing in local highway maintenance; and to ascertain how the existing evidence can be improved to inform future spending decisions on local highway maintenance. The review covered all asset types within the remit of local highway maintenance, including pavements, structures, active travel provisions, lighting, etc.

The evidence review aimed to:

- Identify and examine relevant evidence, data, and tools that can be used for an economic appraisal of the VfM of spending on local highways maintenance.
- Analyse existing methodologies used to estimate the BCR and VfM of spending on local highway maintenance and identify and address evidence gaps.
- Provide recommendations for how economic appraisal tools can be refined and improved, focusing on strengthening the evidence for spending on local highway maintenance.

1.2 RESEARCH QUESTIONS

1. Review the published data over multiple years to understand the current total spending on local highway maintenance in England, including funding from DfT, funding from MHCLG, funding from other local authority sources such as council tax.
2. Collect real data on costs of different types of maintenance and evaluate how the costs have increased over time.
3. Synthesise and critically evaluate the evidence on the benefits and costs of government spending on local highway maintenance.
4. Synthesise available evidence and put forward suggestions in relation to the following question: How should the BCR and VfM be estimated at a national level of spending on local highway maintenance in England? What is the estimated BCR and VfM of this spending?
5. Synthesise evidence on what the typical BCR and VfM is for different types of intervention e.g., different types of maintenance, carriageway type, structure type, location. Provide recommendations on how the BCR and VfM should be calculated for these different types of schemes.
6. Synthesise and compare evidence of the typical BCR between different strategies to support evidence-led funding decisions. For example, assess the efficacy of long-term planned maintenance in mitigating carriageway deterioration and minimising future costs in comparison to patch and amend maintenance strategies.
7. Collate evidence on whole life costing and the relative VfM of proactive versus reactive maintenance.
8. Conduct case studies on approximately four local authorities, aiming to gain an understanding of their spending patterns, limitations, and challenges. The design of the case studies should build on previous research, such as a 2021 DfT-commissioned study which looked at how local authorities use funding such as the Potholes Fund and how this aligns with their broader approach to highways asset management.

2. Methodology

2.1 DISCOVERY

The discovery phase involved identifying and examining over one hundred sources to gather relevant evidence, data, and tools that are suitable for use of an economic appraisal of the VfM of spending on local highway maintenance. The discovery phase built on the "The Case for Investing in Local Highway Maintenance" report produced by AtkinsRéalis on behalf of the UK Roads Liaison Group (UKRLG) in 2021. During this phase, the existing economic appraisal tools and methodologies that are in use were reviewed and analysed to better understand the challenges and potential improvements to support analysis of the value for money of local highway maintenance.

2.2 ANALYSIS AND SCENARIOS

The data collated during the discovery phase was then analysed and synthesised to identify how BCR and VfM was currently being calculated and how it varied for different types of intervention e.g., different types of maintenance, carriageway type, structure type, location. During this phase, multiple investment scenarios and intervention types were analysed.

2.3 STAKEHOLDER ENGAGEMENT AND CASE STUDIES

Targeted stakeholder engagement was undertaken during the evidence review to gather the necessary data around different types of maintenance. Stakeholders included National Highways Transport (NHT) Network, CQC Efficiency Network, Local Council Roads Innovation Group (LCRIG), the UKRLG Boards and Road Surface Treatment Association (RSTA). For the case studies, five local authorities were chosen to provide a deep dive into the realities and practicalities of investing in highway maintenance: Derbyshire County Council, London Borough Hammersmith and Fulham, Manchester City Council, Sunderland City Council and Surrey County Council.

3. Discovery Phase Findings

3.1 FUNDING STREAMS

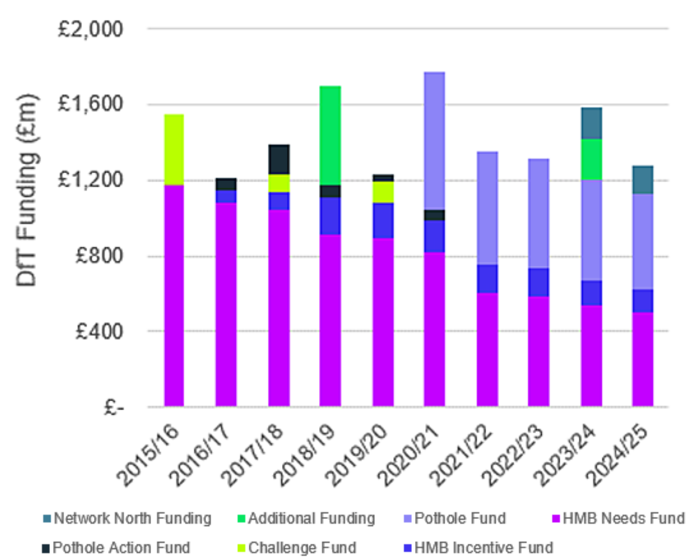
Local highways network maintenance is currently funded through a combination of central government allocation through DfT and contributions from other sources such as local authority raised funds. The DfT provides 92% of the central government capital funding to English highway authorities – equating to approximately 52% of authorities' total highways maintenance budgets (Asphalt Industry Alliance, 2024). This funding is not specifically allocated for highway maintenance or improvements and is currently uncertain from year to year, coming from multiple streams that are not ring-fenced and so can be diverted to local authority spending (CIHT, 2020), for example to local authority provision of social care.

Other additional funds come from sources such as the Ministry of Housing, Communities and Local Government (MHCLG), Environment Agency grants and regional and mayoral areas growth funding, although this represents a small proportion of local authorities' total highway maintenance budgets. Revenue expenditure is also used to fund maintenance activities through sources including council tax receipts, business rates, as well as through the Revenue Support Grant provided by the MHCLG. However, local government revenue funding has fallen in real terms by about 25% since 2010.

Figure 1 below shows the DfT contributions for local highway maintenance over the past 10 years, these figures have been uplifted to 2023 values using the CPI annual rate.

FIGURE 1

DfT historic funding for local highways maintenance over the past 10 years. Source: multiple DfT publications between 2014 and 2023



3.2 MAINTENANCE ACTIVITIES AND COSTS

The local highway network is a huge and complex system, and maintaining it includes the inspection, maintenance and renewal of roads, footways, cycle routes, bridges, tunnels, retaining walls, lighting, drainage, traffic signals, trees, land and much more. The State of the Nation report, last published in 2019 by UKRLG (UKRLG, 2019), provides an overview of England's Road infrastructure and asset quantities, condition and financial need required to bring the asset to a 'State of Good Repair' which is defined as an asset stock condition level which provides a safe and sustainable network at a low whole life cost, enabling road authorities to accomplish effective and efficient asset management.

DfT also produces an annual report outlining the condition of all the roads in England, covering surface condition and skidding resistance (DfT, 2023). This report is used to analyse and allocate the maintenance need; however, this only includes the conditions of the carriageways and does not cover any of the other assets that make up the network.

In recent times, inflation has led to the costs of maintenance activities rising significantly. This was determined by construction materials prices increasing and inflationary pressures driven by rising energy prices, significantly impacting products that involve energy-intensive manufacturing process. In 2022 the Building Cost Information Service (BCIS) forecast that although materials' prices were expected to fall in the short term, the inflationary pressures would keep labour costs rising, resulting in increases in both costs and tenders (BCIS, 2022).

- Research conducted by the Local Governments Association (LGA) and Association for Directors of Environment, Economy, Planning and Transport (ADEPT) found that councils are seeing a 22% increase in the cost of repairing a pothole, relaying a road surface and other maintenance costs (New Civil Engineer, 2022).
- An average of 20% increase in maintenance costs over the past 5 years was confirmed by multiple stakeholders engaged as part of this evidence review.
- The NHT CQC Efficiency Network reported that costs in the infrastructure sector were rising between 2017/18 and 2020/21 but slightly decreased in 2021/22; however, there was another increase in 2022/23 (NHT CQC, 2023).

3.3 BENEFITS OF WELL-MANAGED HIGHWAY INFRASTRUCTURE

Previous research estimates that overall, funding for local highways maintenance provides good to very good return on investment, with a much lower risk than major projects to construct new infrastructure. For every additional £1 invested, an absolute minimum return of £2.20 (Transport Research Laboratory (TRL), 2015), with further socio-economic benefits estimated to provide up to £5+ return (UKRLG, 2021).

Below is an overview of the evidence found during the discovery phase that demonstrates the types of benefits that local highway infrastructure in good condition brings to the community. The sub-sections below have been aligned to typical national, regional and local policy objective themes.

3.3.1 Economic Benefits

- City centres with an improved urban realm have been associated with as much as a 40% uplift in retail takings (House of Commons Library, 2020).
- Good quality roads have been shown to encourage people to leave their homes and engage in economic activity; four out of ten people are influenced in whether they go by the condition of the roads (YouGov, 2010).
- Increased uptake in cycling; the UK market for cycling equipment and goods alone is now worth an estimated £3 billion a year, when considering direct employment and spend (House of Commons Library, 2020).
- Reduction in traffic accidents which have an overall costs to society of around £9 billion per annum (Cabinet Office, 2009).
- Reduction in costs caused by congestion and disruption in urban areas which equate to around £11 billion per annum (Cabinet Office, 2009).
- Reduction in damage to vehicles caused by potholes which were worth £1.25 billion in 2020 (Kwik Fit, 2021). In the past year local authorities paid out £22.5 million in compensation claims for damages arising because of defects in the road surface (House of Commons Transport Committee, 2019).
- Badly maintained local roads are costing SMEs £5 billion a year in wasted staff time, production delays, increased fuel consumption and vehicle damage (RAC Foundation, 2015).

3.3.2 Social Benefits

- Improved links between urban areas and rural communities leads to a reduction in the imbalances between areas and social groups across England (Herefordshire County Coucil, 2023).
- Improving community accessibility reduces isolation by removing barriers to mobility among vulnerable groups and can provide potential savings in social care (Age UK).
- Making places healthier, greener and more attractive places to live and work (National Institute for Health and Care Excellence (NICE, 2019).
- Road traffic is the major cause of local emissions in urban areas costing £5-10 billion per annum. A decline in vehicle use, due to increased modal shift to active travel, would support lower levels of air pollution which may lead to a decrease in respiratory conditions (Cabinet Office, 2009).

3.3.3 Health Benefits

- Increased levels of physical activity among the public, will lead to healthier societies, decreasing the risk of chronic health conditions including heart disease (Sustrans, 2017).
- Reduction in NHS costs of £17 billion over 20 years due to active travel replacing short motor vehicles, plus potentially additional £2 billion per annum due to reduced obesity levels. (The Lancet, 2012).
- Increased levels of physical activity among the public, physical inactivity is estimated to cost the NHS £1.06 billion per year (House of Commons Library, 2020).
- The risk of mortality reduced by almost 40% through cycling to work, reducing the risk of obesity and cardiovascular disease. The NHS recoups £4 in reduced health costs for every £1 spent on cycling provision (National Institute for Health and Care Excellence (NICE, 2019).
- Decrease in deaths associated with air pollution. Up to 40,000 early deaths are attributable to air pollution each year (Sustrans, 2017).

3.3.4 Environment and Sustainability Benefits

- A decrease in NO_2, CO_2 and particulate matter emissions. Maintaining roads in a steady state condition can lead to a net 1,415 thousand tonnes of carbon and up to 1,700 thousand tonnes with a progressive increase in the quality of the unclassified roads (NHT CQC, 2023).
- Net gains in biodiversity which not only benefit road users but also other species that inhabit in the relevant regions (Grous Control, 2024).
- Savings in electricity costs by investing in LED upgrades (Transport, 2015).

3.3.5 Safety and Security Benefits

- Situational crime prevention on the street and in other public spaces. Crime was reduced by an average of 21% in areas with improved street lighting compared to areas without. (College of Policing, 2024).
- A decrease in the number of cyclists killed due to potholes which more than tripled between 2005 and 2017 (House of Commons Transport Committee, 2019). Since 2017, 255 people cycling have been killed or seriously injured due to road defects (Cycling UK, 2023).
- Decrease in the number of pothole related breakdowns. The AA attended more than 52,000 pothole related breakdowns in April 2023, a 29% increase compared to the same time in 2022. (AA, 2023).

3.3.6 Resilience and Climate Change Adaptation

- Effective maintenance of the local roads network will contribute to reducing the amount of damage done to roads during adverse weather events. Disruptions in the network caused by severe weather can cost up to £280m per day of disruption (Resilience Shift, 2019). The cost of associated damage could increase by about 40% by the 2050s if current management approaches continue as they are (Climate Change Committee, 2018).
- A reduction in the number of 'one-off' funds provided by the government (e.g., £140 million weather damage grant in 2014) (RAC Foundation, 2015).
- Reduction in future costs from climate change, with investments in adaptation capable of delivering strong VfM in the range of £2 to £10 of benefits per pound of investment (Department for Transport, 2024).
- A reduction in regional inequality as it decreases the likelihood that people living in areas that are most at risk from extreme weather will experience higher insurance premiums and lower investment. This is because it would be known that the roads in these regions can withstand severe weather (Department for Transport, 2024).

4. Analysis and Scenarios

4.1 ESTIMATING VFM AND BCR BY ASSET OR INTERVENTION TYPE

There are multiple sources that demonstrate funding for local road maintenance provides good to very good return on investment, with much lower risk than major projects to construct new infrastructure. For every additional £1 invested, there is an absolute minimum return of £2.20, with analyses identifying typical returns of up to £9.10 at national level. BCRs for specific schemes such as critical structures/bridges may reach three figures (UKRLG, 2021). Such BCRs may at first appear unrealistic when compared to those typically generated for new-build schemes, but as has been noted above, VfM assessments of new schemes would routinely include costs of maintenance to enable full asset life. Therefore, when re-assessing the value of this maintenance in isolation the benefits will have been largely generated by the much larger initial investment, but the relatively low maintenance cost is required to enable those benefits to continue.

To demonstrate the benefits that investment into the road network generate, the holistic view of the entire network needs to be broken down into the assets that compose its foundations. By demonstrating the BCR and VfM opportunities available for different assets, local authorities will be able to explain and allow a greater visualisation of the social, environmental and economic benefits that are available within the context of their network.

4.1.1 Carriageways

The best method to calculate the BCR and VfM of carriageway maintenance is through the combination of the Highway Maintenance Appraisal Toolkit (HMAT) and Highway Maintenance Economic Assessment (HMEA) tool discussed above. Specifically assessing the inputs and outputs of the carriageway asset, which are entwined in the larger, more holistic view of the entire HMAT tool. The table below shows a series of previous challenge fund schemed bid submissions which used HMAT and HMEA to demonstrate the BCR of carriageway schemes.

TABLE 1

BCR for carriageway schemes from challenge fund bids

BCR	Qualitative benefits
▪ Range between 1.6 and 22.5. ▪ Weighted average BCR: **6.85.**	▪ Reduced traffic accidents from improved roads. ▪ Reduced need for frequent remedial patching works, therefore reducing roadworks and disruption. ▪ Wider benefits for cyclists, pedestrians and local businesses. ▪ Regeneration of town centres. ▪ Less traffic noise caused by empty lorries clattering over uneven surfaces. ▪ Promotion of quality route to new business and regeneration.

4.1.2 Structures

To assess the VfM and BCR of structures maintenance the Highways Infrastructure Resilience Modelling (HIRAM) support tool is the most appropriate method. HIRAM provides data layers from local authority information, local highways asset information, public data on the environment, Environment Agency datasets, climate change datasets, and geological datasets (LgTAG, 2020). HIRAM support tool was developed to enable local highways teams to:

- Record the locations and structures at the highest risk from severe weather across the network.
- Estimate the economic and social costs of disruption if no preventative action was taken.
- Price the intervention measures needed to decrease the risk of impact in the event of severe weather in addition to making the case for investment and preventative works to reduce social and economic impacts of severe weather incidents in the future.

TABLE 2

BCR for structures schemes from challenge fund bids

BCR	Qualitative benefits
▪ Range between 1.5 and 100+. ▪ Weighted average BCR: **6.56.** ▪ The BCR for specific schemes involving critical structures and historic bridges is estimated to be 100+, however, these were excluded when calculating the weighted average a BCR.	▪ Prevent weight restrictions being implemented on a bridge which would negatively impact alternative routes. ▪ Maintaining the longevity of the structure and preserve historic highway structures for future generations, which are of unmeasurable cultural value. ▪ Deliver fresh commercial space creating additional business opportunities that will generate additional economic activities and revenue. ▪ Avoided delays to traffic on other (secondary) roads onto which traffic would be diverted to avoid weak structure in the absence of repair works.

4.1.3 Footways and Cycleways

The most appropriate method for obtaining the BCR or VfM of footway and cycleway targeted investment is the Active Mode Appraisal Toolkit (AMAT), which measures the overall benefits and costs of proposed walking and cycling interventions. AMAT aligns with UK Government guidance on policy appraisal including the HM Treasury Green Book and DfT Transport Analysis Guidance (TAG). AMAT is able to quantify the key impacts of a proposed intervention, therefore helping provide decision-makers with as full a view as possible about impacts on transport users, the environment, society and the economy. These metrics are then quantified into a measure of the VfM of a proposed intervention, in the form of a BCR.

The table below shows a series of previous challenge fund schemed bid submissions which demonstrate the BCR of footway and cycleway schemes.

TABLE 3

BCR for footway and cycleway schemes from challenge fund bids

BCR	Qualitative benefits
▪ Weighted average BCR: **3.39** ▪ Some of the benefits from active travel schemes are currently not being quantified when using the existing appraisal tools and methodologies so it is expected that BCR for footways and cycleways is higher.	▪ Provide a safer, healthier environment for pedestrians, cyclists and vulnerable road users through environmental enhancement and reduce verge maintenance requirements. ▪ Improve the town centre and make more attractive for walking and cycling.

4.1.4 Drainage

Drainage is not taken into consideration within the HMAT, HMEA, Highway Development and Management Version 4 (HDM-4) or AMAT tools, which are the most popular and reliable methods for obtaining a BCR or VfM metric from maintenance investment. Therefore, within this section of the study considers the most appropriate and reflective methodology for deriving the BCR or VfM of drainage maintenance. The table below shows a series of previous challenge fund schemed bid submissions which demonstrate the BCR of drainage schemes.

TABLE 4

BCR for drainage schemes from challenge fund bids

BCR	Qualitative benefits
▪ Range between 6.60 and 37.00. ▪ Weighted average BCR: **9.31**.	▪ Reduce disruption and damages well as the health and safety issues associated with flood events. ▪ A reduction in disruption to the highway network caused by flooding or repair works to existing drainage. ▪ Reduced risk to the user, increased availability of the resilient network, reduced liabilities. ▪ A resilient network will also enhance economic opportunities in the region, promoting job creation and property development.

4.1.5 Street Lighting

To derive the VfM and BCR of street lighting maintenance several qualitative elements need to be considered including but not limited to an improved sense of community such as: perceived risk of crime, perception of safety and reduced risk of traumatic event.

In addition to qualitative factors the condition profile of the street lighting assets needs to be measured, using guidance provided by the Institute of Lighting Professional within their Asset Managment Toolkit: Minor Structures (ATOMS). To obtain the VfM and BCR of street lighting maintenance a comparison needs to be produce of the outcomes of a do-minimum approach against the outcomes of the proposed scheme. With the calculations including discounting across the whole life of the proposed scheme, optimisation bias being considered as well as risk allowance measures due to the quantitative benefits of the street lighting maintenance that need to be monetised. The table below shows a series of previous challenge fund schemed bid submissions which demonstrate the BCR of street lighting schemes.

TABLE 5

BCR for street lighting schemes from challenge fund bids

BCR	Qualitative benefits
▪ Range between 1.02 and 4.91. ▪ Weighted average BCR: **3.83.** ▪ The BCR for street lighting schemes include the benefits of reduction of fear of crime.	▪ Ensuring sufficient streetlight to deter crime and mitigate the fear of crime that can lead to increased isolation and anxiety. ▪ Rapid reduction in energy consumption and costs by installing LED lights. ▪ Rationalisation of the authority's requirements for spare parts for its lighting stock which will increase efficiency and standardise maintenance procedures. ▪ Encouraging uptake of Ultra Low Emissions Vehicles (ULEV).

4.1.6 Other Assets

Other assets classes include but are not limited to signage, road markings, ITS, street furniture and green estate. These assets were not considered due to data gaps and the considerable overlaps that these assets have with the key assets of the local highway network. To understand the BCRs and VfM of sub-asset class maintenance further research needs to be conducted and local authorities need to be encouraged to collect data for them more stringently.

4.2 ESTIMATING OVERALL BCR

To calculate an overall BCR for spending on local highways maintenance in England a weighted average of the BCRs for each asset type was used. Two options were considered for applying the weightings:

- Option 1: using the existing formulae provided by DfT to allocate the HMB funds.
- Option 2: using weightings based on consultation with SMEs and stakeholders to determine how funds are allocated by local authorities for different asset classes.

The table below shows the BCR, and weighting used for each asset type, as well as a summary of the assumptions and rationale for each value.

TABLE 6

Overall BCR spending on local highways maintenance in England from challenge fund bids

Asset type	BCR	Option 1	Option 2
Carriageways	6.85	82.4%	65.0%
Structures	6.56	15.4%	15.0%
Footways and cycleways	3.39		5.0%
Drainage	9.31		5.0%
Street lighting	3.83	2.2%	10.0%
Other assets	NA		
	Overall BCR:	**6.74**	**6.45**

Assumptions

- Option 1 weightings for Carriageways includes the DfT Allocation Formulae for both classified and unclassified roads.
- Option 1 weighting for Structures includes the DfT Allocation Formulae for bridges.
- No allocation based on DfT Allocation Formulae for Footways or Cycleways or Drainage.
- No BCR available for other assets as these assets are often included in BCR calculations for bigger schemes that cover more than one asset type.

4.3 ESTIMATING LONG-TERM BENEFITS

Given that investment costs are incurred upfront, but savings are realised in the future, there can be several ways to express the return realised on any investment including BCR which is the ratio of the benefits of undertaking an intervention to their costs expressed in present value terms (considers what future costs and benefits are worth today). It is normally assumed that the investment in roads is done in the current year, so the initial outlay does not need to be discounted, but the future savings in road maintenance do need to be discounted. The higher the assumed discount rate, the smaller the present value benefits and thus BCR. Likewise, the longer the time horizon (years the savings are computed for) the higher the BCR.

The CQC Efficiency Network statistical model considers the impact of road condition on costs and the trades of the cost of investment with future savings. The model shows that upfront investment in the local road network can also produce substantive future savings. When looking at a 10-year horizon, £1 in investment in road condition will yield between £4.20 and £5.70 in future cost savings expressed in present value terms. The table below shows the BCR over 10 years, over 20 years, and in perpetuity. Demonstrating that even using a high discount rate and considering only the first 10 years of savings, investing in improving the condition of the local network can provide a BCR of 4.197 which translates to savings of £4.20 per £1 of initial outlay (NHT CQC, 2019).

TABLE 7

Example of BCR over different time horizons and discount rates of undertaking an intervention

Discount rate	BCR		
	10-year time horizon	20-year time horizon	Perpetuity
3.5%	5.709	10.288	21.440
7%	4.197	5.979	10.720

5. Conclusion

- Funding for highway maintenance is provided by government to local authorities through multiple routes, however, how much money each local authority spends on highway maintenance annually or how that compares to funding allocated for that purpose is unclear. Local authorities do not formally report on actual maintenance budgets, so collating information of this nature requires significant effort. This also results in budget and spend data that is inconsistently produced and of potentially low levels of accuracy, comparability and national coverage.
- Funding streams themselves are inconsistent and currently uncertain from year to year, making long term planning near-impossible even with significant announcements like the Network North statement. Additionally, while the statement was welcomed by authorities, there is low confidence from local authorities that there will be a significant and sustained increase in investment over the next 10 years.
- As with the funding data, the availability of inventory, condition and cost data across local authorities is also inconsistent with significant regional variations. The UKRLG State of the Nation Report is the most recent source that gathers all asset types and all authorities across the country, but this is already over 5 years old. However, there was a consistent response from stakeholders regarding the level of inflationary pressure on maintenance budgets over recent years and the impact this has had on work that can be delivered.
- Overall, funding for local highways maintenance provides good to very good return on investment, with socio-economic benefits estimated to provide up to £5+ return on £1 investment. Research findings are unanimous in framing local highway maintenance as a good investment, however, there is little understanding of how to quantify and communicate many of the benefits as current tools and guidance only focus on a certain subset of monetised benefits.

- BCRs and VfM of local highways maintenance is likely to vary across different regions and different types of assets and even for different investment strategies on a single network section. Therefore, a direct assessment of a national level of VfM of maintenance may not be as informative as it would first appear. The outcome would be likely to enable only a binary decision of whether funds should be targeted at maintenance or not, but with no facility to inform a strategy of how much funding should be invested, where, or over what period of time.
- The assets that provide the foundations of the road network all need to be treated and assessed differently in relation to the inputs they require and how they influence the overall network. All the key assets of the network are inter-connected and have some level of overlap. Being able to break down the benefits and costs that are tied to each asset class is a complex task that is best represented through the comparison of schemes relative to the impacts of no intervention.
- With regards to undertaking assessments to inform preferred strategies at a local level, significant investment has been made in developing tools such as HMAT and HMEA to aid this process and continues to be made in gathering data to understand existing and changing road conditions. However, the use of these resources is somewhat limited at a local authority level due to a lack of experience or confidence in their use and concerns over budget to employ consultants. Simplified models or tools requiring less input could be beneficial but once again caution will need to be taken when observing the reliability of these outputs.

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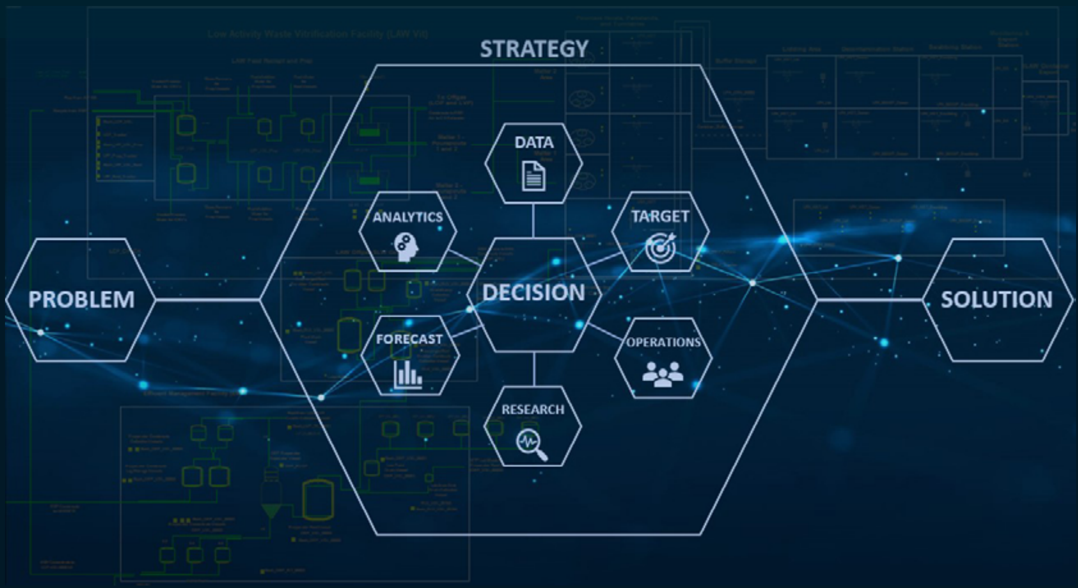
05: Planning for Success and Derisking Nuclear Plant Operations Through Predictive Simulation

Significance Statement

AtkinsRéalis is using predictive simulation to help the United States (U.S) Department of Energy (DOE) and its clients, derisk first-of-a kind nuclear facilities at Hanford. Our models are providing critical insights into the expected performance of the complex preparation, treatment, vitrification and immobilization of low activity waste. Through modeling, we can identify key issues early, such that improvements are focused to optimize throughput, availability and safely advance the Hanford mission.

Énoncé d'importance

AtkinsRéalis utilise la simulation prédictive pour aider le département de l'Énergie des États-Unis et ses clients à éliminer le risque lié à l'exploitation d'installations nucléaires uniques en leur genre à Hanford. Nos modèles fournissent des renseignements essentiels sur le rendement attendu de la préparation, du traitement, de la vitrification et de l'immobilisation complexes des déchets de faible activité. Grâce à la modélisation, nous pouvons cerner rapidement les principaux problèmes, permettant d'orienter les améliorations vers l'optimisation du débit, de la disponibilité et de la sécurité des opérations.



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Abstract

A predictive simulation of the Direct Feed Low Activity Waste (DFLAW) systems has been developed to help derisk future nuclear facility operations at the United States Department of Energy's, Hanford site. The DFLAW program includes low activity waste feed preparation and treatment in the Tank Farms and vitrification and immobilization of treated waste at the Waste Treatment Plant. A model of the DFLAW systems has been developed to assess overall throughput and availability for our clients, from a program perspective. The model provides critical insights on the expected operational performance of current and planned facilities and is used to help identify potential operational risks such that improvements are focused. A new generation of operators and engineers at the Hanford Site must re-learn the nuances of the DFLAW systems. This paper describes how predictive simulation has helped our clients derisk and optimize DFLAW operations to safely advance the Hanford mission.

KEYWORDS
Predictive simulation; Derisk; Vitrification; Hanford

1. Introduction

Companies are increasingly facing difficult and complex decisions. Markets are constantly changing, competition is fierce, and our clients are demanding innovative new experiences and consistently high service levels. Predictive simulation simplifies this complexity. A simulated model of a process generates powerful future-state data and helps demystify much of the analytical process by providing a rich interactive visualization of information. Predictive simulation, also referred to Operations Research (OR) modeling, helps clients and key decision-makers understand their processes, data and how they affect one another. For decades, AtkinsRéalis has used predictive simulation to help derisk and optimize complex nuclear facility operations. Advanced modeling techniques have been used to anticipate and mitigate potential issues before they occur. These predictive simulation techniques help in proactively managing risks, ensuring the safety and reliability of nuclear plant operations.

The Advanced Mixed Waste Treatment Project (AMWTP) in Idaho Falls, in the US, designed and built by British Nuclear Fuels Incorporated (BNFL Inc, now AtkinsRéalis), is a great example of how predictive simulation has been used during design and commissioning to optimize operations in the nuclear industry, leading to significant efficiencies and early project completion. Construction began in August 2000 and was completed in 2002. The facility became operational in 2003, using advanced technologies, including real time radiography, radioassay, robotics and automated treatment processes such as the supercompactor which significantly reduced the number of shipments required to transport waste to the Waste Isolation Plant (WIPP) in New Mexico. During the AMWTP design and construction phases, simulation modeling aided in the understanding of the impact of plant and equipment and operational strategies on the project lifetime. ‘What if’ case scenarios were also performed with a large number of variable design and operational parameters as the specifics were unknown at that particular point in time e.g. equipment performance and reliability.

As the project transitioned into the commissioning and operations phases (2002 to 2005), the model's functional requirements switched from being a design tool to a production planning tool. The primary focus was to make best use of the equipment and resources in order to successfully meet schedules within reasonable bounds of accuracy.

The AMWTP project achieved ramp-up to full design capacity within 12 months, treating over 6,000m^3 per year waste, and over 20 shipments per week to the Waste Isolation Pilot Plant (WIPP) as predicted by the model. Throughout modeling the team were able to identify risks early on and optimize AMWTP facility throughput. The AMWTP contract transitioned to Bechtel and its partners in 2005 and the project was completed in 2011, nearly three years ahead of schedule, resulting in significant cost savings. Predictive simulation is being used by AtkinsRéalis to help the United States (U.S.) Department of Energy's (DOE) Prime Contractors at Hanford, including Washington River Protection Solutions (WRPS) and Bechtel Inc. (BNI) to help derisk plant operations.

2. The Hanford Site

The U.S. Department of Energy (DOE), Office of River Protection (ORP) cleanup mission at the Hanford Site, is to retrieve waste from single-shell tanks (SST's), stage the waste in the double-shell tanks (DST's), and transport the waste to the Waste Treatment and Immobilization Plant (WTP). At the WTP, the waste will be vitrified for safe long-term storage.

The pretreatment capability for DFLAW comprises solids removal followed by cesium-137 removal via ion exchange. DFLAW pretreatment will be provided by the Tank Side Cesium Removal (TSCR) process during early stages of DFLAW and by the Advanced Modular Pretreatment System (AMPS) in the latter part of the mission.

The TSCR process provides for the early production of immobilized low activity waste (ILAW) by preparing low activity waste (LAW) that will be fed directly from Tank Farms to WTP's LAW facility. The TSCR system will receive tank supernatant waste from the DST system, filter out undissolved solids and treat the tank supernatant waste by removing radioactive Cesium (Cs) using an ion exchange sub system. Treated waste will be sent to a separate DST. The treated waste, compliant with WTP waste acceptance criteria, will be fed by Tank Farms to the WTP LAW Facility.

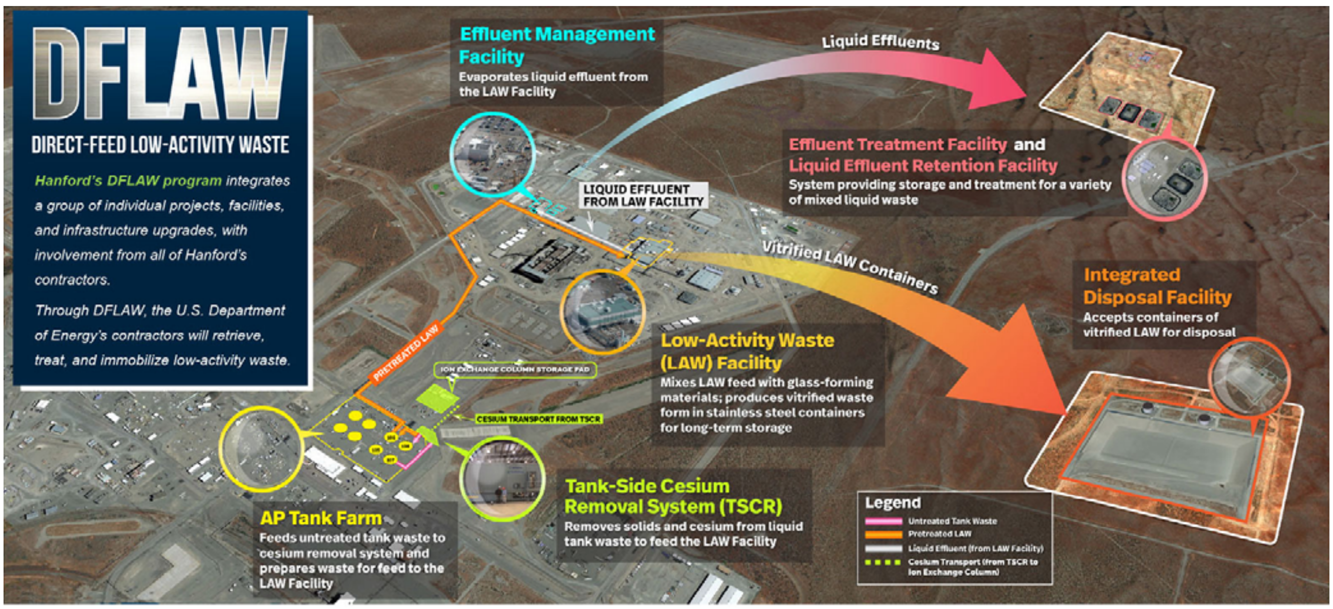
In 2022, Hanford began the first large scale treatment of radioactive waste from large underground storage tanks. Hanford is now preparing for 24/7 operations to treat waste from the Tank Farms through the Direct Feed Low Activity Waste program (Figure 1).

Under the DFLAW program, the newly operational TSCR system, removes cesium and solids from the tank waste. Over 800,000 gallons of low activity waste has been treated to date by TSCR. The treated waste will be fed directly to the Waste Treatment and Immobilization Plant (WTP) for immobilization into glass when it comes online next year. The immobilized LAW containers produced by the LAW Vitrification Facility will be transported to the Integrated Disposal Facility for final disposal and the Secondary Liquid Waste shall be treated by the Effluent Management Facility.

Crews at the WTP are continuing to commission and build operator proficiency on major systems that will immobilize tank waste in glass in two first of a kind melters in the LAW Facility. AtkinsRéalis has been involved with the vitrification project since its inception through our collaboration with the Catholic University. Today, we support subcontractor Bechtel National with engineering support, vitrification consulting and testing.

FIGURE 1

Hanford's Direct Feed Low Activity Waste Program



3. Derisking Operations at Hanford

A predictive simulation of the DFLAW systems has been developed such that overall throughput and availability can be assessed from a program perspective. Through modeling we have provided a more detailed understanding of the interactions between the various DFLAW systems and key bottleneck areas identified such that improvements are focused. The DFLAW simulation model was developed using the Witness process simulation software. The software uses discrete event simulation (DES) which works by modeling individual events that occur using a time-based engine, taking into account resources, constraints and interactions with other events. Models reflect the process rules, randomness and variability that affect the behavior of real-life systems and complex operating environments. By creating a mirror of your processes, often referred to as a Digital Twin, you can then experiment with different "what if" scenarios without the risk or expense involved with altering your real processes. Through predictive simulation, AtkinsRéalis has provided results to our clients on how to derisk future plant operations and to identify improvements that will optimize throughput, minimize downtime and advance the mission. Some examples of how modeling has helped our clients at Hanford include:

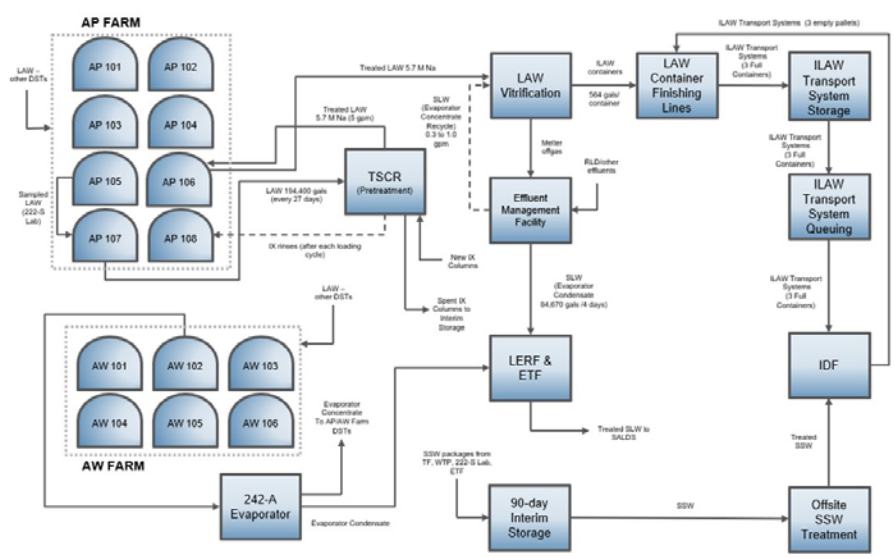
- Identification of critical spares.
- Identification of lag storage (buffer) requirements to decouple facilities.
- Sizing the ILAW container transport system fleet.
- Determining shift, resource requirements.
- Identifying the need for additional treatment capacity.

The simulated flows in the DFLAW model are provided in Figure 2 and include the following:

- Waste feed preparation and staging in the AP and AW Tank Farms, including waste volume reduction through evaporation using the 242-A evaporator, and low activity waste feed prequalification sampling.
- Tank Side Cesium Removal System, where cesium is removed from the low activity waste using ion exchange columns.
- Pretreated LAW feed receipt and preparation, where glass forming materials are mixed with the low activity waste; vitrification of mixed low activity waste using first-of-a kind LAW melters; pouring of vitrified waste into stainless steel containers and ILAW container finish handling.
- ILAW Container Export and Transportation to the Integrated Disposal Facility (IDF) for final disposition.
- Secondary Liquid Waste (SLW) generation at the Effluent Management Facility (EMF) and transfer to the Liquid Effluent Retention Facility (LERF) and Effluent Treatment Facility (ETF) for treatment and final disposal.
- Secondary Solid Waste (SSW) transportation, offsite treatment and final disposal at the Integrated Disposal Facility.

FIGURE 2

Simulated flows in the DFLAW OR model



3.1 METHODOLOGY

Data was mined from a variety of sources, across various organizations, in order to underpin the model bases and assumptions, including:

- Tank Farm transfer volumes, sequences and timings from the System Plan.
- Tank Farm transfer equipment routing diagrams.
- Tank and equipment sizing, mass balance calculations, flow rates, process flow logic, process cycle times, mechanical handling sequences and times and lag storage capacities from design.
- Equipment downtime data for over 1,000 items of equipment, including Mean Time Between Failures (MTBF) and Mean Time To Repair (MTTR), planned maintenance and other constraints based on lessons learned. Where there were gaps, data from published reliability databases including the Savannah River Site Generic Reliability Database, the Nonelectric Parts Reliability Database, failure modes and effects analyses (FMEA's) and interviews with subject matter experts from the 222-S Analytical Laboratory was also performed.
- Shift schedules and labor resource requirements from operations personnel.

All modeling activities, including configuration control, model requirements (including functionality, performance, input and outputs and hardware and software requirements), were performed in accordance with the Tank Operations Contract procedures.

To avoid garbage in, garbage out (GIGO), it was crucial to ensure the quality of model input/output data. The verification of data inputs was an iterative process, performed through a series of workshops involving engineering and operations personnel as well as subject matter experts (SME's) to ensure the model bases and assumptions were aligned with design and anticipated operation of the DFLAW facilities. Equipment reliability and maintenance data was adjusted based on lessons learned/past operating experience at Hanford and other nuclear cleanup sites (e.g. Savannah River Site).

The model was developed using the Witness process simulation software, developed by the Lanner Group. The Witness software is capable of simulating a variety of discrete (e.g. part based) and continuous (e.g. fluids and high-volume, fast-moving goods) and logical elements.

Model inputs and outputs were organized into a MS Excel interface. The model input file imports the model data at the start of the simulation and applies the data to each discrete, continuous and logical element in the model.

The model simulates several years of anticipated operations in a matter of minutes. Hundreds of simulations are performed, each with a different random number seed, such that a high confidence can be obtained in the statistical output data.

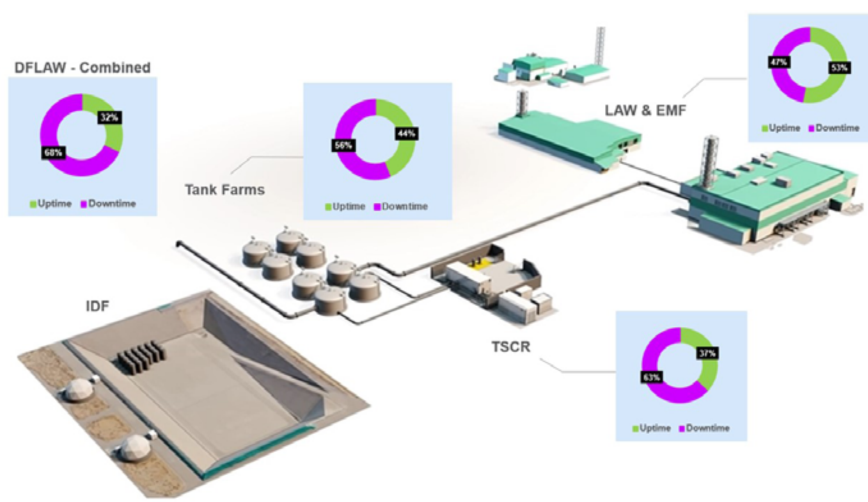
Once model development was complete, model testing, verification and validation of the inputs, code and outputs was performed to provide confidence that the model performs as intended and produces reasonable results based on the model inputs.

3.2 MODEL RESULTS AND PATH FORWARD

Throughput and system availability were measured after simulating future DFLAW operations, taking into account the losses that can occur during the day-to-day operation of each system area including equipment performance, ramp up, equipment set up/changeout, equipment failures, planned maintenance, shift patterns and labor resources. Model results indicate that a daily throughput of 1.7 ILAW containers per day can be achieved by the integrated DFLAW systems, resulting in an overall system availability of 32%. This is significantly lower than the design (theoretical) throughput capacity of 5 ILAW containers per day. Based on past nuclear operating experience in the US (i.e. the Defense Waste Processing Facility at the Savannah River Site) and the UK (e.g. the Waste Vitrification Plant at Sellafield) it is reasonable to expect an availability of 30-40%, for complex processes that have remote, mechanical handling equipment. Chemical processes tend to be more reliable where you would expect > 90% availability, which is considered world class. When we looked at the availability of each of the individual facilities that comprise the DFLAW system, the model results indicate that the AP and AW Tank Farms had an availability of 44%, TSCR had an availability of 37% and the LAW and EMF had an availability of 53% (Figure 3). Therefore, TSCR has the highest potential to impact DFLAW downtime.

FIGURE 3

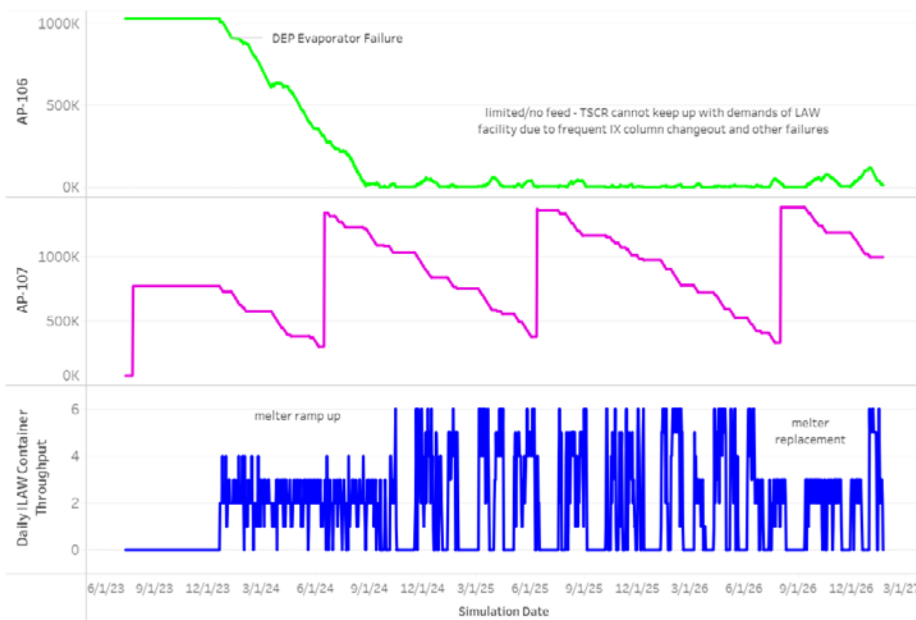
DFLAW Individual facility availability



Further analysis was performed to determine what factors impacted DFLAW throughput and performance. The utilization of both the TSCR feed tank (AP-107) and the receiver tank (AP-106) and from TSCR, which feeds the Law Facility, were assessed. Figure 4 indicates that sufficient feed is available in AP-107, therefore, equipment failures upstream of AP-107 do not have an impact on throughput. However, there is not sufficient feed available in AP-106 to supply the LAW Facility as the levels in AP-106 steadily decrease and reach very low levels during the latter part of the second operating year. This is primarily caused by the TSCR ion exchange column changeout activities and sporadic equipment failures associated with TSCR, causing a reduction in the average processing rate. There is also a melter outage in the fourth year, which slightly increases the levels in AP-106, allowing upstream TSCR operations to catch up to the LAW Facility demand. The results also show that the LAW melter replacement activities have an impact on the daily throughput of ILAW containers.

FIGURE 4

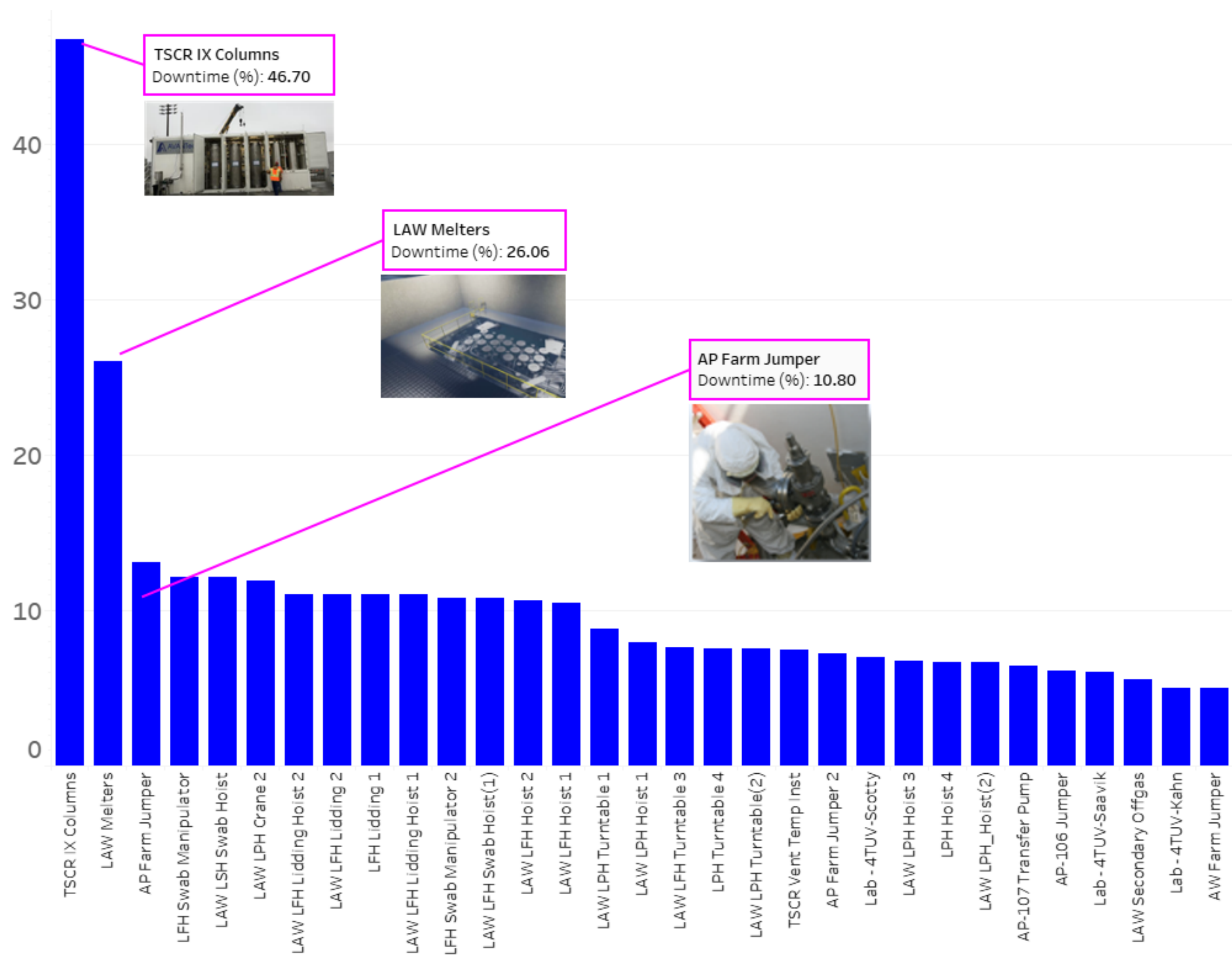
Tank utilization and ILAW container throughput



Equipment utilization and downtime statistics were used to identify any potential bottleneck areas or constraints within the DFLAW system. The TSCR ion exchange columns contribute the most to downtime (46%), followed by the LAW melters (26%) as shown in Figure 5. The results also indicate that AP transfer equipment (jumpers) and the swabbing/decontamination manipulators, hoists and cranes in the LAW facility also contribute to the downtime.

FIGURE 5

DFLAW equipment downtime summary (%)



Sensitivity analyses were performed to see how overall DFLAW availability could be improved upon. The results indicate that an additional standby TSCR unit would increase overall availability from 32% to 43%, but TSCR is still the key bottleneck and cannot keep up with LAW Facility demands. Sensitivity analyses were also performed to optimize operations and make the best use of equipment and resources. Analyses were performed to determine the impact of operating just one LAW melter as opposed to two, since one TSCR unit cannot keep up to LAW Facility demand. Results indicate that with only one operational LAW melter, TSCR can keep up with LAW facility demand, resulting in a lower throughput and availability. However, the AP-106 tank never empties, therefore, allowing for continuous operations at the LAW Facility.

As the DFLAW Program continues to evolve and the LAW Facility moves into hot commissioning and operations, the model will continue to be updated based on any upgrades/modifications and will be used as a production planning tool, making the best use of equipment and resources to optimize throughput and availability.

A new generation of operators and engineers must re-learn the nuances of the DFLAW systems. Predictive simulation is a powerful tool that will allow for proactive improvements essential for supporting the safe, continued and successful operation of the DFLAW facilities, reducing risks, downtime and enhancing overall equipment effectiveness.

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Nuclear Engineering

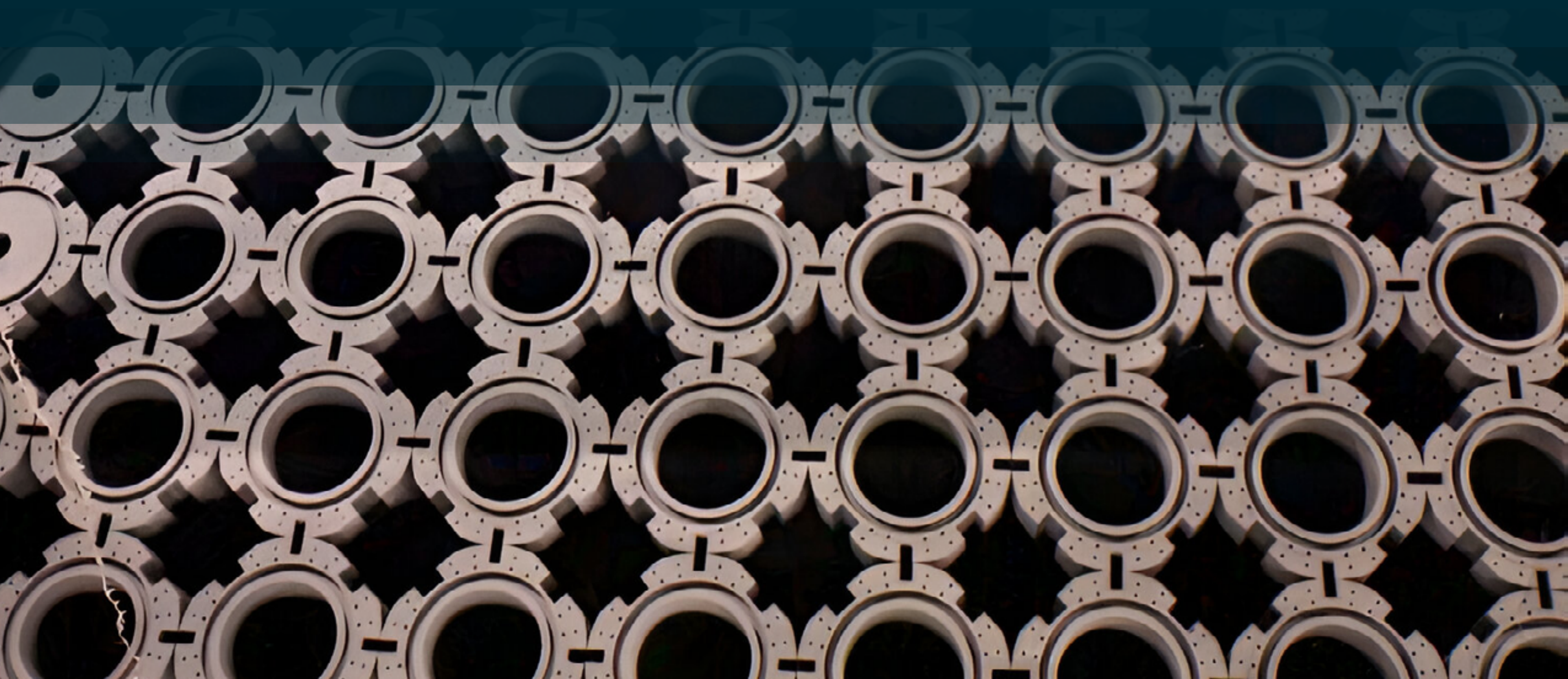
06: Digital Twin Applications for Seismic Assessment of Graphite Reactor Cores

Significance statement

Digital twins enable the study of complex infrastructure without expensive and potentially destructive testing programmes by creating a computer model of a physical asset, such as a power station or a sub-system within the power station. Experimental validation of the computer model is needed to ensure the digital twin accurately reflects physical reality. This paper provides a case study illustrating the steps required to experimentally validate a specific digital twin for a power station sub-system. Developed by AtkinsRéalis, this technology has been instrumental in supporting the ongoing operation of nuclear power stations in the UK, thereby contributing to energy security and advancing Net Zero. This work constitutes the first example of this approach.

Énoncé d'importance

Les jumeaux numériques permettent l'étude d'infrastructures complexes sans programmes de tests coûteux et potentiellement destructeurs en créant un modèle informatique d'un actif physique, tel qu'une centrale électrique ou un sous-système au sein de la centrale. La validation expérimentale du modèle informatique est indispensable pour garantir que le jumeau numérique reflète avec précision la réalité physique. Ce document présente une étude de cas illustrant les étapes nécessaires pour valider expérimentalement un jumeau numérique spécifique pour un sous-système de centrale électrique. Mise au point par AtkinsRéalis, cette technologie a joué un rôle essentiel dans le soutien de l'exploitation continue des centrales nucléaires au Royaume-Uni, contribuant ainsi à la sécurité énergétique et à l'avancement des projets nets zéro. Ce travail constitue le premier exemple de cette approche.



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Abstract

The reactor cores of the Advanced Gas-cooled Reactors (AGRs) are made up of a large, three-dimensional array of interlocking graphite bricks. To assess the seismic performance of a wider range of reactor cores in a given condition (number, type and location of cracking of individual graphite components) that would be possible with physical testing, a computational model or digital twin has been developed. Cross-comparison of numerical simulations using this model and output from testing of a quarter-scale physical model have been used to validate the computational model, which has then been used to assess the behaviour of full-sized reactor cores during a seismic event. These assessments aim to demonstrate that the reactor cores can be shut and held down and adequate cooling of the fuel maintained during and after seismic events.

KEYWORDS
Graphite; Seismic hazard; Reactor core; Digital twin; Qualification

1. Introduction

The reactor cores of the Advanced Gas-cooled Reactors (AGRs), owned and operated in the UK by EDF Energy, are made up of a large, three-dimensional array of interlocking graphite bricks which provide the reactor core structure, which houses the fuel stringers, control rods and cooling gas channels, and provide neutron moderation. A general description of the AGR cores and their safety functions is given in (1).

AGR cores experience sustained neutron irradiation over the course of their operating lives (for example Hinkley Point B operated for 32 full power reactor years) and consequently changes in material properties of the graphite. In some cases, the impact of these ageing processes has resulted in cracking of lattice bricks, potentially affecting the seismic performance of the graphite reactor core.

To understand the seismic performance of a reactor core in a given condition (number, type, location and orientation of cracking of individual graphite components), digital analysis coupled with physical modelling in a verification and validation methodology has been undertaken, using a numerical analysis technique called GCORE (2). To qualify this model, a quarter-scale physical model has been tested. Cross-comparison of the physical tests and numerical simulations have then been used to validate the computational model. This has then allowed numerical models of the full-sized reactor cores to be modelled effectively using simulations. These assessments aim to demonstrate that the reactor cores can be shut and held down, and adequate cooling of the fuel maintained. GCORE results have been successfully used to provide evidence to support the seismic safety cases for EDF's AGR reactors.

This paper sets out the experimental validation of the GCORE analysis technique used to allow virtual qualification of a computational model representing a full-sized graphite core. This permits assessment of a wider range of graphite cores than is feasible using a physical representation, making it possible to explore the graphite core's fundamental seismic performance and inform the safety assessment process.

2. Importance of Digital Twinning in Critical Infrastructure Programmes

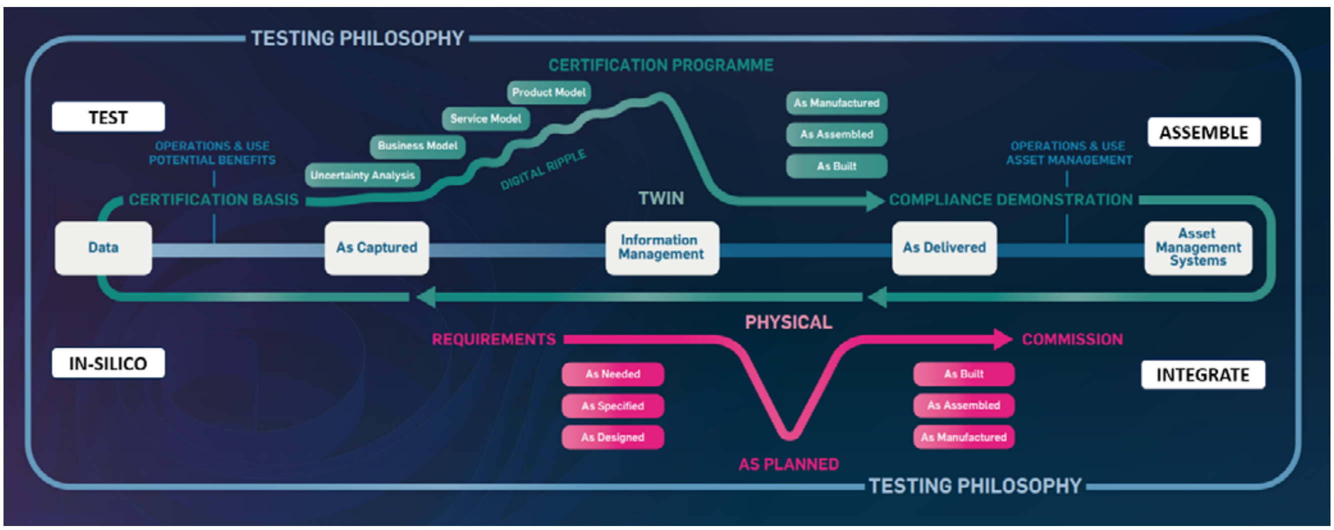
The increased complexity and uncertainty in the delivery of new fission challenges, and future fusion technology, requires new engineering methods to realise the exciting potential of these new technologies (3). Drawing on the wealth of experience in materials testing across global industries (e.g. aviation, additive manufacturing and material development) virtual product and process development through data-driven or digital processes is needed to support product knowledge (4).

Twinning in materials development has wide ranging applications in mitigation of infrastructure risks (3) with benefits that include enhanced safety and reliability, improved security engineering, reduced errors, faster information sharing, and better predictions (5). Notably, the opportunity to rapidly iterate and test conditions in low-cost, boundary controlled digital environments is very attractive in novel or First of a Kind (FOAK) applications. As shown in Figure 1, the opportunity of modelling and simulation allows for iteration and multiple stages of testing, which expands the context of the conventional Verification & Validation model. Conventional V&V approaches are now enhanced across industries due to decreasing computation costs, increased access, and growing sector capability. The benefits of a 'left-shift' in the in-silico testing and certification programme helps in product development phase through reduced uncertainty/risks which carry through to physical model development. The evolution and accessibility of digital twin approaches moves away from conventional V&V coupled in-silico representation, where testing and representation of physical systems occurred simultaneously, reducing opportunity for system optimisation or improvement. Largely driven by decreased computational costs and increased accessibility, digital twinning is globally accepted in a range of applications from complete energy network modelling (6) to reactor scale interfacing (7) and further complex materials testing (5), (8).

The UK is the only country to operate the AGR design of reactors. While other countries have experience in the seismic response of graphite cores (e.g. Japan, China, Russia), investigation into the aging and degradation of the core holds no international experience or industry codes to support assessment of graphite core distortion during seismic events. Digital twin concepts, which provide an in-silico representation of physical assets, have become increasingly available to solve such challenges. This paper provides a case study for a toolset known as GCORE, developed over the past 27 years, and illustrates the steps required to experimentally validate a digital twin concept.

FIGURE 1

Digital twin testing philosophy



3. AGRs Overview - The Graphite Core

The graphite core of each AGR (see example in Figure 2) is constructed from over 20,000 graphite bricks arranged in up to 13 rings and 15 layers, depending on the specific reactor design. The graphite core houses the fuel stringers, control rods and cooling gas channels, and provides neutron moderation.

Different types of bricks serve different functions. Lattice bricks, arranged in columns on a square lattice, provide channels for the fuel stringers. Interstitial bricks provide channels for the control rods and other instrumentation. A keying system, made up of keys and keyways cut into the graphite bricks, maintains the relative position of the bricks while permitting differential thermal expansion of the core and its surrounding structures (1) and differential brick shrinkage caused by fast neutron irradiation.

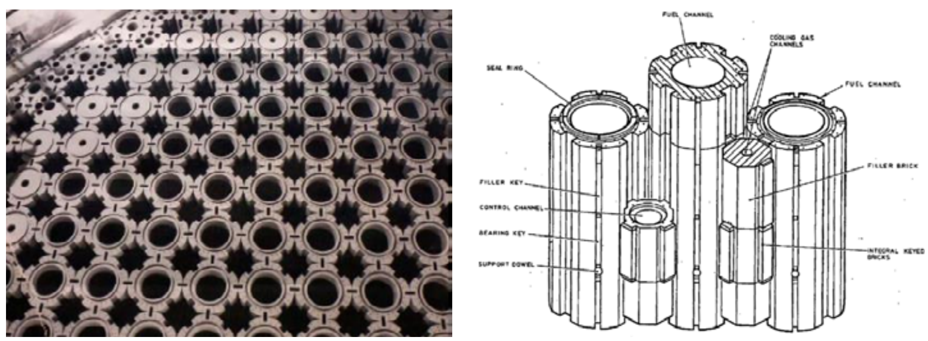


FIGURE 2

Plan view of the top layer of an AGR core (left) showing the keyways in the fuel bricks and labelled schematic of the key components of an AGR core (right)

Neutron irradiation of the graphite bricks during reactor operation results in dimensional change (1). Later in life, tensile stresses occurring at the keyways can lead to cracking at the keyway root (known as keyway root cracked bricks). Keyway root cracked bricks can affect the static and seismic distortion of the core, as it can lead to degradation of the keying system. The clearances between the keys and keyways and the strength of the graphite are also affected by prolonged neutron irradiation. Further discussion of graphite brick cracking can be found in (9).

A principal seismic performance requirement is that the graphite core does not distort sufficiently during an earthquake such that there is any delay to insertion of the control rods required to shut down the nuclear reactions. A seismic event could disturb the graphite bricks, resulting in brick displacements that could then distort the control rod channels. To assess whether or not the reactor could be shut down during a 1 in 10,000 year earthquake, it is necessary to understand whether any distortion of the control rod channels resulting from a seismic event would impede insertion of the control rods. As the graphite core ages and some bricks begin to crack, understanding how those cracked bricks affect the dynamics of the graphite core is key to understanding what level of cracking is tolerable.

The sheer physical size of a full scale reactor graphite core means that it would be impractical to conduct physical tests of a core empty of fuel to understand the dynamics of the reactor core. The number of graphite components means that it would be intractable to test a meaningful number of test cases, with differing distributions of cracked bricks. The operating temperatures of the core would mean that tests at representative conditions would be unachievable.

4. The GCORE Method and Toolset

GCORE is a computational method and toolset for seismic analysis of AGR cores, developed by AtkinsRéalis for EDF. It uses explicit time integration Finite Element Analysis (FEA), representing the graphite bricks by rigid bodies and interactions between components with discrete non-linear spring-damper pairs (Figure 3). A visualisation of a full core model (known as AGR GCORE) is shown in Figure 4. To facilitate use and interpretation, the toolset includes automated approaches for model generation and output post-processing. Simulation output includes assessment of interstitial channel distortions, fuel integrity margins, keying system loading, brick displacements and rotations and brick-to-brick separations. GCORE offers reasonable computational cost, at approximately 100 CPU hours per full-core analysis.

FIGURE 3

Plan representation of rigid bodies and spring-damper interactions

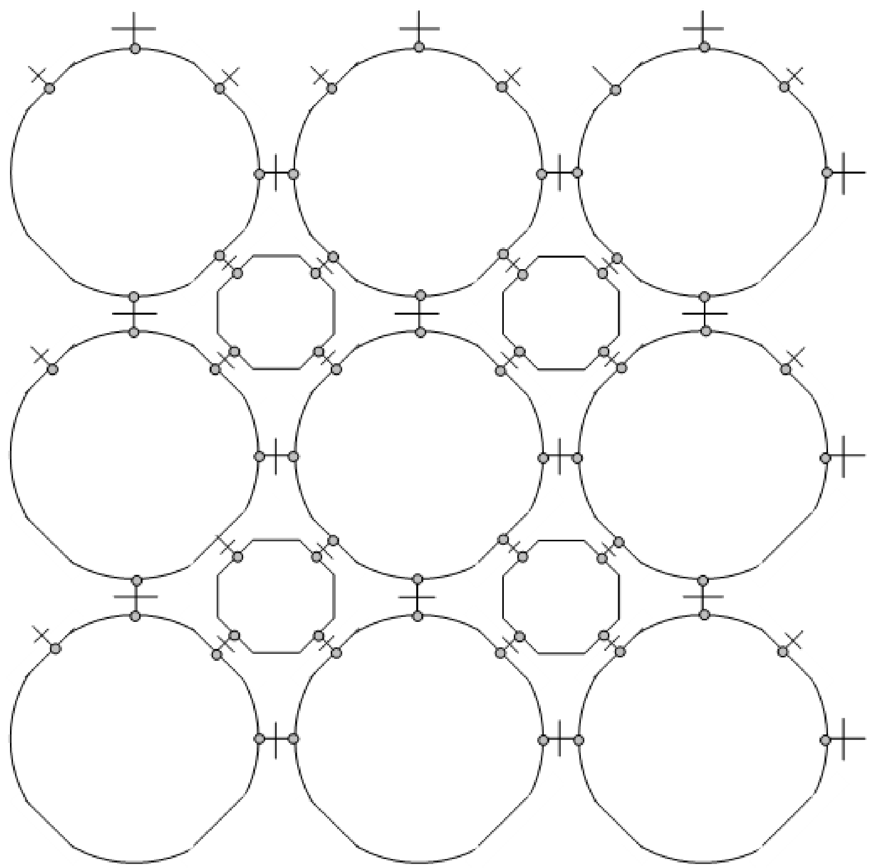


FIGURE 4

Visualisation of a full GCORE model of a graphite core

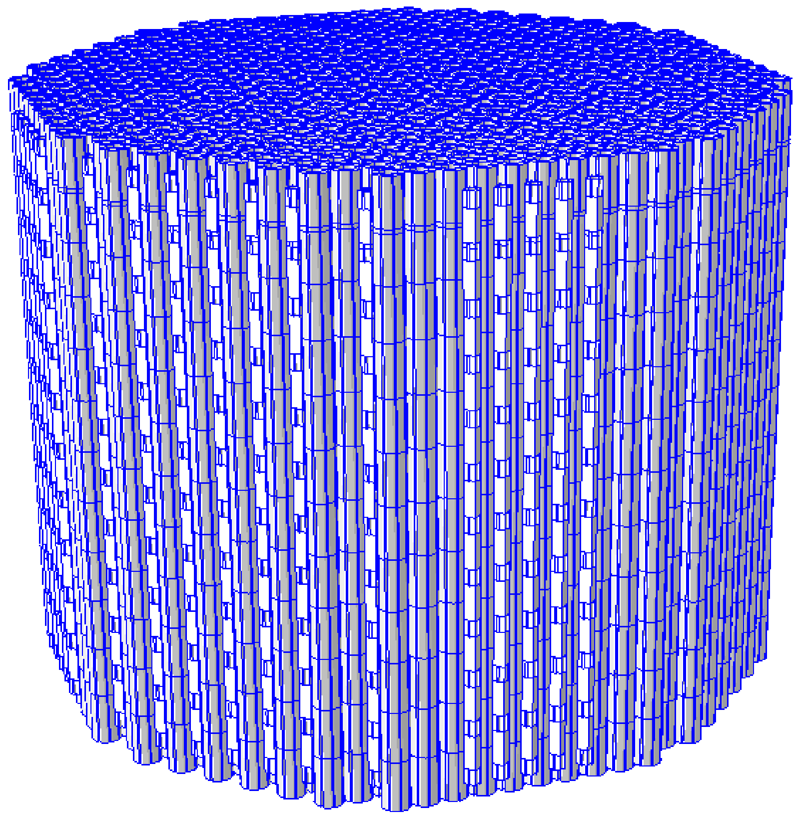
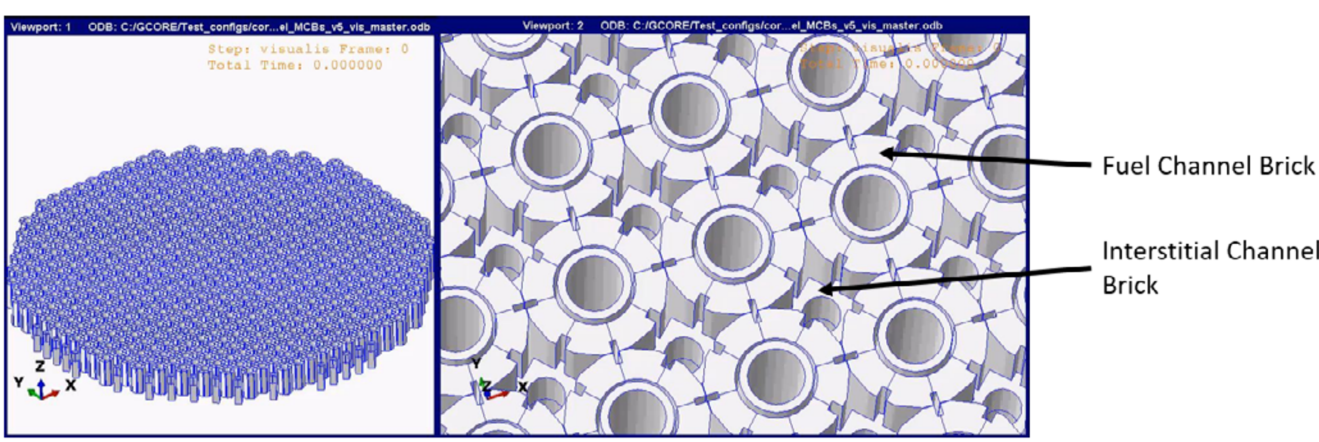


FIGURE 5

Visualisation of a single layer, with close up showing fuel and interstitial channel bricks



5. Validation of the GCORE Approach

Validation of the computational model has been provided through physical testing. A physical model was developed for use in physical testing by the University of Bristol, shown in Figure 6.

To enable cross-comparison of the results from the physical tests with the output of the GCORE model, a specific GCORE model representing the simplified components of the physical model was developed, known as the Multi-Layer Array GCORE model, or MLA GCORE. This model is analogous to the physical model, to enable validation of the computational approach (see Section 5.1).

The physical array is built at quarter scale, based on an AGR core late in life at 34 full power reactor years (1). The quarter scale rig is similar to the AGR core design, in terms of overall design and features, but is not intended to be directly representative of an AGR core. Key design differences include the brick material and brick and crack geometry simplifications.

Instead of graphite, which is brittle, difficult to manufacture, dirty to handle and subject to dust production though wear during shaking, an engineering plastic called acetal was selected for the physical model components.

To best replicate the dynamic behaviour of the AGR core using the rig, material selection was highly dependent on scaling of the density and Young's modulus of graphite, using the material scaling law:

$$S_\rho = \frac{S_E}{S_L}$$

where S_ρ is the scale factor for density, S_E is the scale factor for Young's modulus (stiffness) and S_L is the scale factor for length. S_L is ¼ for the MLA rig, such that the ratio S_ρ/S_E should be equal to 4 for an ideal model material.

In practice, it is very difficult to find a material which exhibits these ideal scaled properties and also adheres to practical requirements which make it suitable for manufacture of the rig components. The MLA rig is therefore designed to maintain 'first order' similarity, which implies that the physical parameters with significant influence on the seismic response are accurately scaled, while the 'second order' parameters can be approximately scaled. Further discussion of the scaling approach used in the design of the MLA rig can be found in (10). Acetal has a reasonable S_ρ/S_E ratio (2.79) and its high rigidity makes it suitable for precision machining, allowing for the required component dimensional accuracy (10), (11).

The MLA quarter-scale array includes simplified representations of intact bricks and bricks modified to simulate the effects of one, two, three or four keyway root cracks, with all cracks modelled as full brick height and full wall thickness vertical keyway root cracks. A number of geometrical features of the AGR graphite components have been simplified in the MLA (e.g. removal of chamfers present in as-built graphite components). These simplifications were not considered to affect the dynamic response of the model. The geometry and the dimensions of all rig and numerical model components, as well as their density and stiffness properties have been defined accounting for the effects of graphite aging under fast neutron irradiation, temperature and radiolytic oxidation.

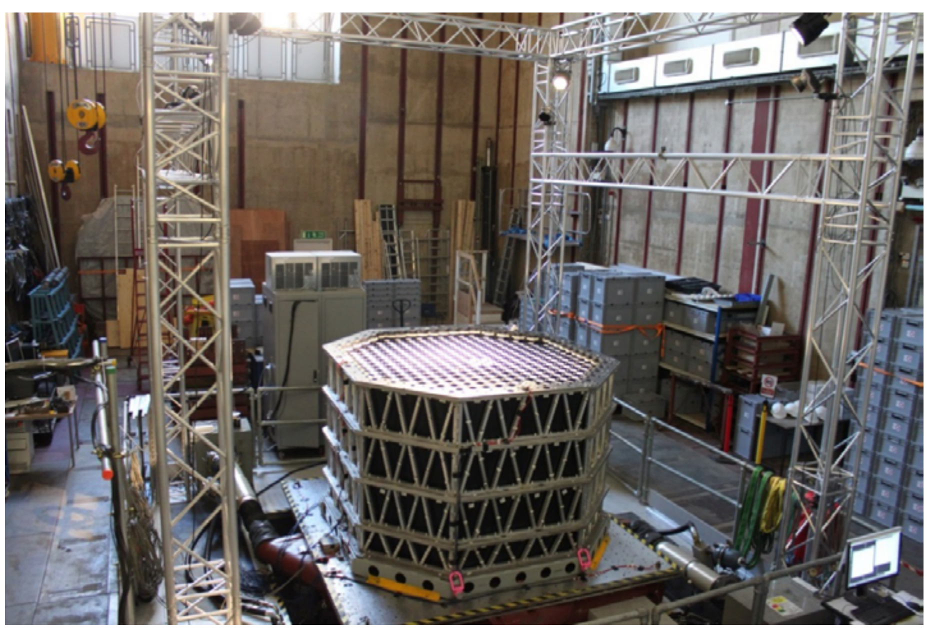


FIGURE 6

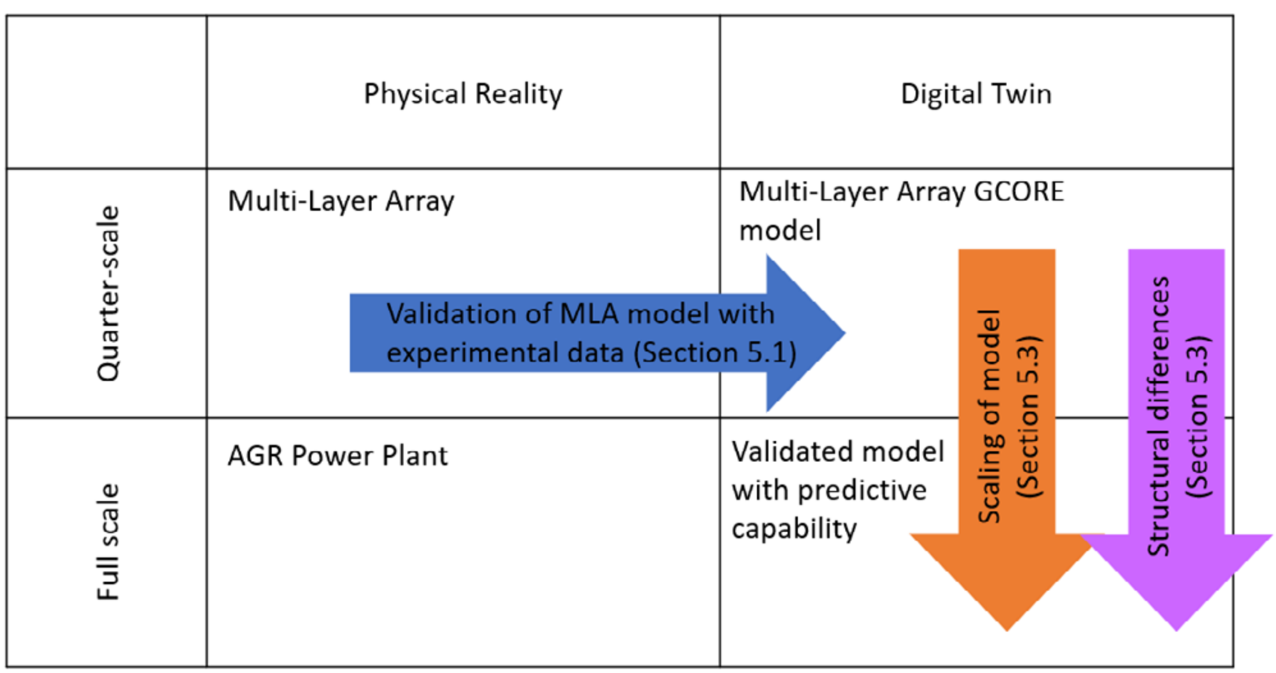
Quarter-scale MLA array on the shaking table at the University of Bristol. The shake table measures approximately 3m by 3m

Sophisticated instrumentation was included in the array to monitor displacements of the top level of bricks, profiles of columns of bricks and brick-to-brick separations. The shaking table facility at the University of Bristol is able to apply specific input motions (magnitude, direction and frequency content). A detailed presentation of the design process of the experiment is available in (11), (12).

As it is not possible to validate the GCORE approach against a full-scale AGR core, results from the MLA GCORE model were compared with experimental measurements from the quarter scale rig to validate the GCORE approach. By validating the GCORE approach at quarter scale for similar geometry to a full scale core using similar material properties to graphite, the GCORE approach can be extended to predict the behaviour of a real AGR core. Figure 7 shows the route to take the GCORE model from quarter-scale representation to predictive capability for full-scale reactor cores.

FIGURE 7

Map showing route from Multi-layer Array to validated GCORE model with predictive capability for a full scale AGR core

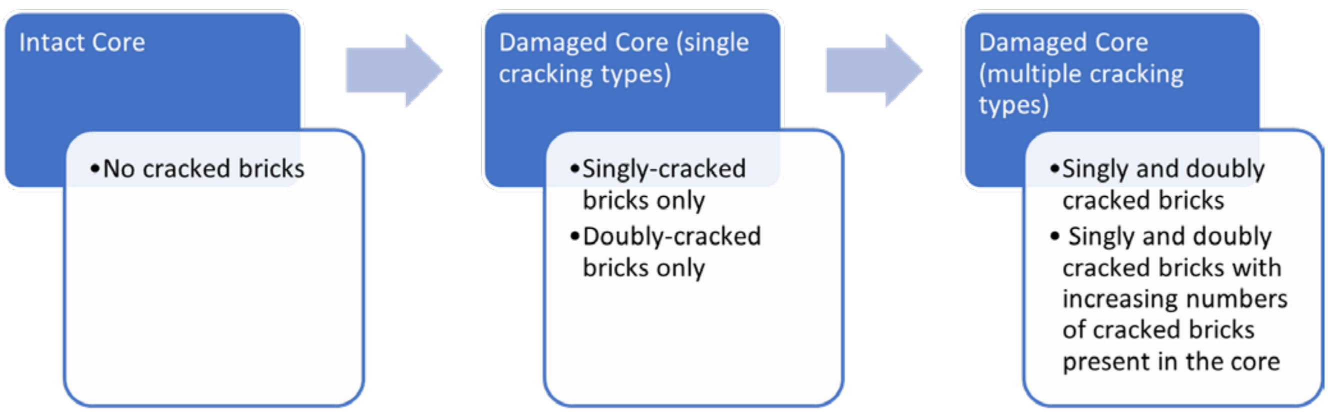


5.1 CROSS-COMPARISON

To validate the MLA GCORE model using experimental data from the MLA rig, an iterative series of comparisons between data obtained from the instrumented physical MLA rig and the MLA GCORE model output was carried out, as shown in Figure 8. By bringing in separate types of damage (i.e. including different cracking features step-by-step), the effects of including different features on the dynamics of the experimental rig (e.g. singly and doubly cracked bricks) could be studied in isolation.

FIGURE 8

Steps in including features for iterative comparison between the MLA GCORE model and MLA rig



Damaged arrays included varying amounts of cracked bricks and keying system damage, positioned in different locations to create different core configurations. Comparisons of displacement, frequency and phase were performed for column distortions, top layer displacements and local brick displacements.

Column profiles at the times of maximum positive and negative relative displacements for a lattice brick column in an intact array, and the displacement time history for a particular top layer brick, are shown in Figure 9. This shows that while the MLA GCORE model predictions are very similar in terms of overall shape to the rig results, there is some over-prediction of magnitude for this core case.

Figure 10 shows column profiles at the times of maximum positive and negative relative displacements for a lattice brick column in an intact array, and the displacement time history for a particular top layer brick in an array containing 70% intact bricks and 30% doubly cracked bricks (DCBs). Again, the MLA GCORE model predictions in terms of overall shape are similar to the rig results, with some under-prediction of magnitude for this core case.

Finally, Figure 11 compares kinetic energy time histories for experimental data and model output for a core containing 50% intact bricks and 50% doubly cracked bricks.

The model results are generally aligned with the experimental data, but there are noticeable deviations in scale for most parameters and some deviations in the response frequency and phase. The measured displacements in the MLA rig are typically over-predicted by the GCORE methodology with the measured column profile shapes being consistently bounded by the prediction, indicating that the GCORE approach is conservative.

To further understand the differences between the MLA GCORE model results and experimental results, sensitivities and uncertainties in the MLA GCORE model were investigated (Section 5.2) and the key contributors identified. By identifying the key effects, appropriate parameters could be selected and the GCORE approach then mapped from the quarter-scale MLA to the full-scale AGR (Section 5.3).

FIGURE 9

Column profiles for a specific lattice column at the time of maximum relative x-displacements and the corresponding top layer time history for an intact core

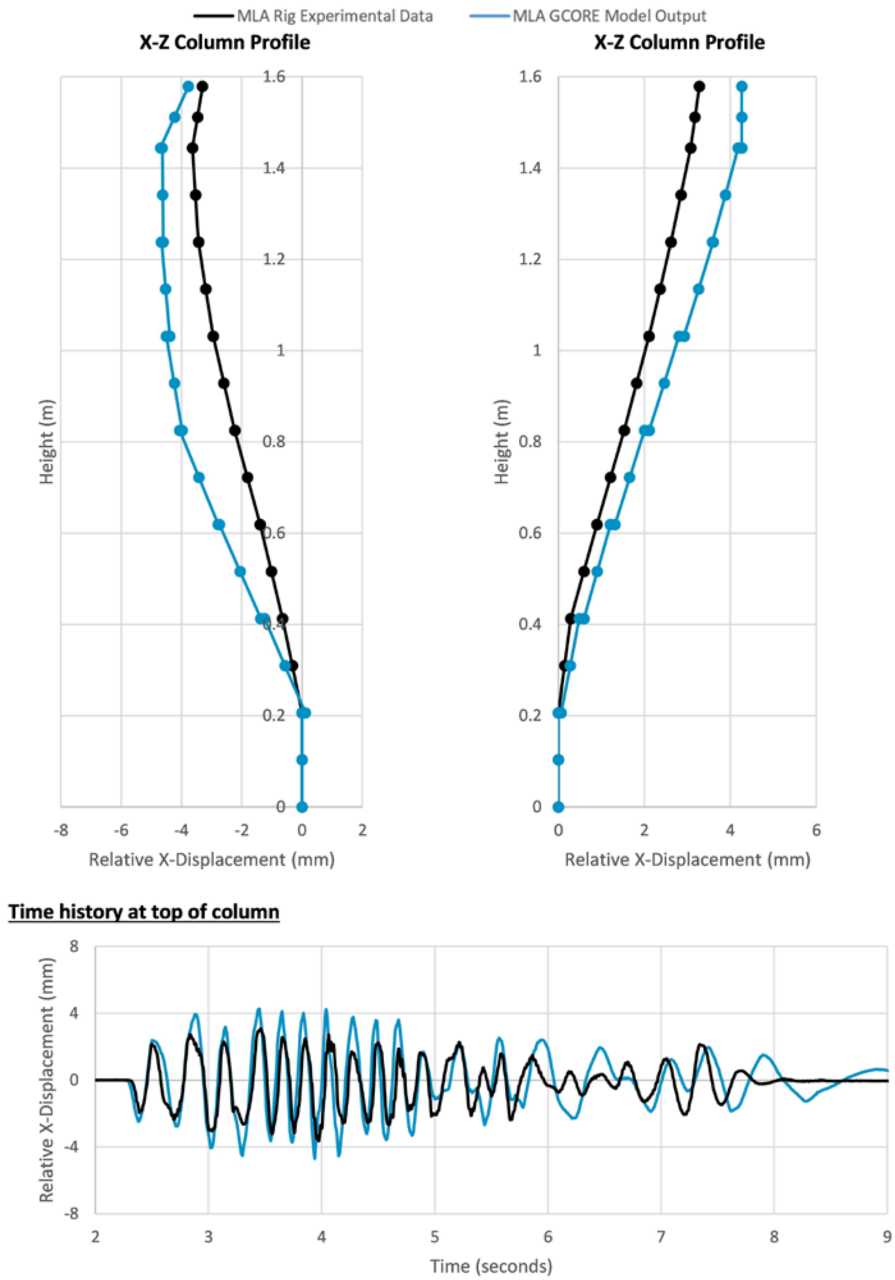


FIGURE 10

Column profile for a specific lattice column at the time of maximum relative x-displacements and the corresponding top layer time history for a core containing 70% intact bricks and 30% DCBs

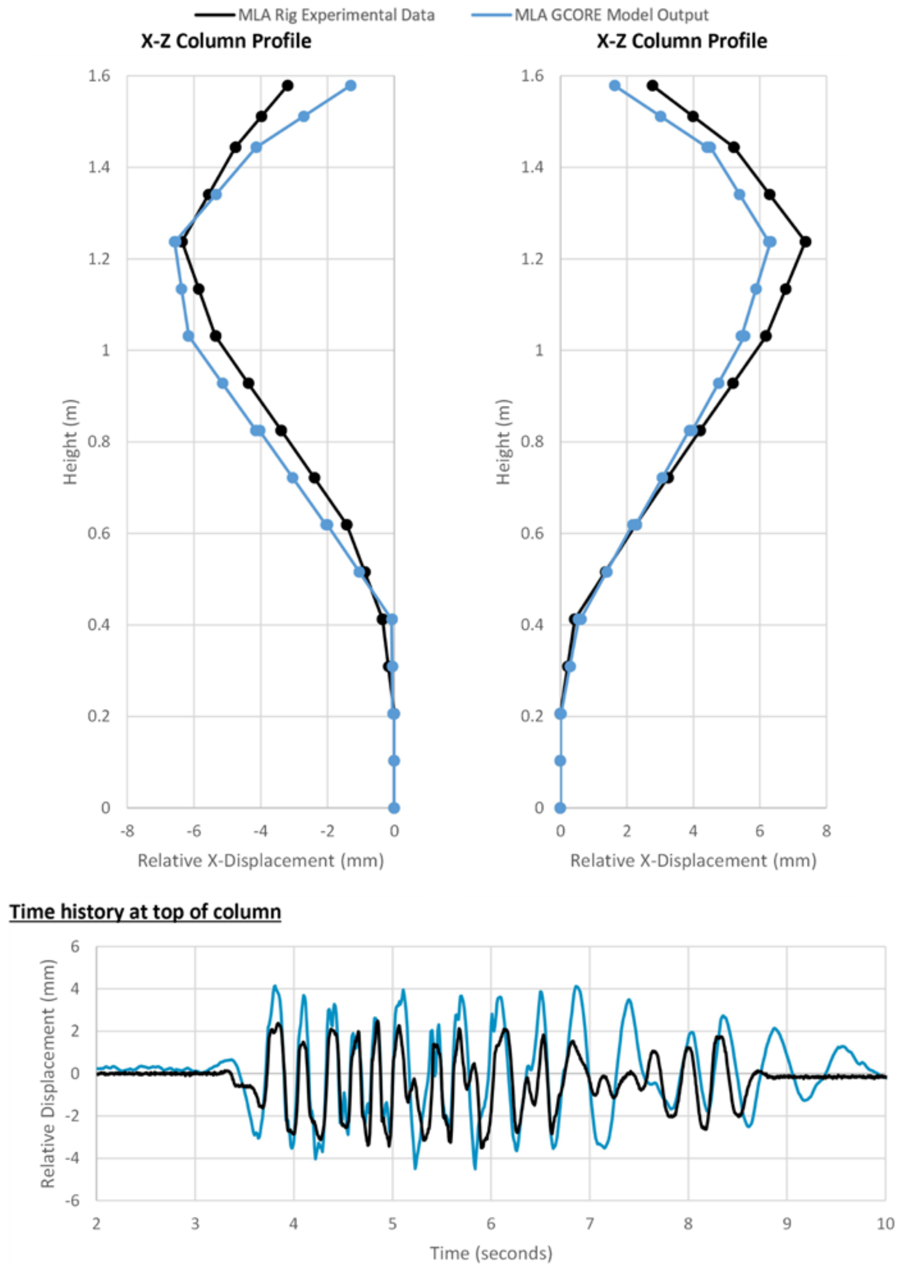
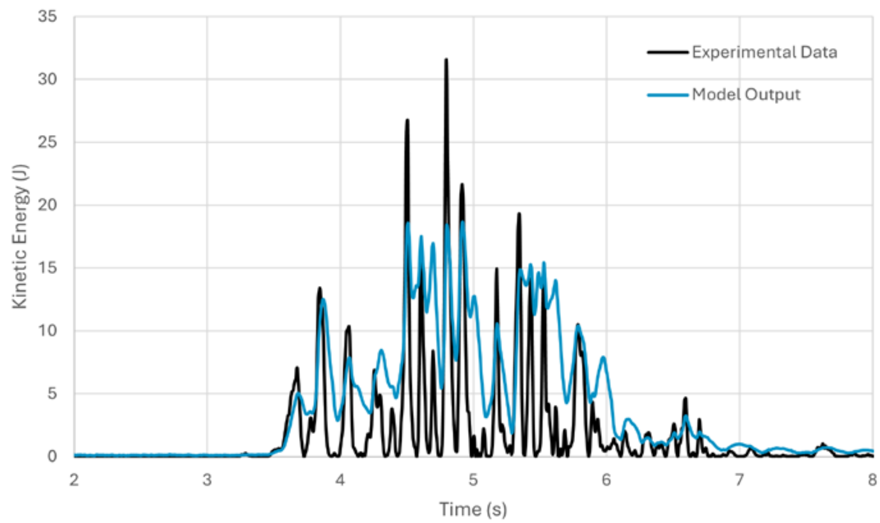


FIGURE 11

Kinetic energy time histories for experimental data and model output for a core containing 50% intact bricks and 50% doubly cracked bricks



5.2 ASSESSMENT OF SENSITIVITIES AND UNCERTAINTIES

During validation experiments, a number of key modelling features of the GCORE model representation of the rig were identified which could significantly affect the prediction of the array response. Through a series of sensitivity studies, the inclusion of friction and refinement of the keying system clearances were shown to significantly improve the MLA GCORE model's representation of the MLA rig. The effects of including friction and adjusting keying system tolerances are discussed in the following sections and are also addressed in (13).

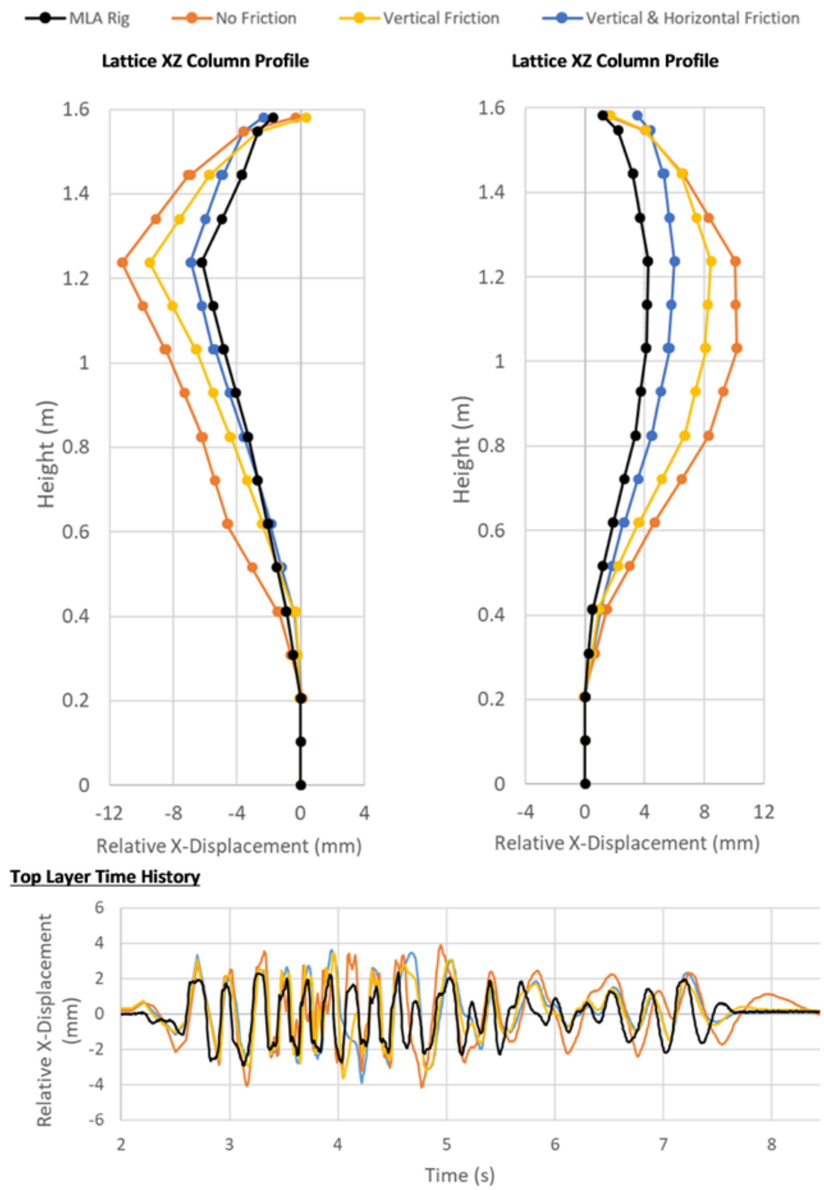
5.2.1 Simulating Friction Between Horizontal and Vertical Interactions

The inclusion of friction effects to the MLA GCORE model significantly improved the prediction of the measured shape and the magnitude of the peak column distortions compared to the rig. The best prediction of channel distortions occurs when both horizontal and vertical surface friction is applied to the MLA GCORE model (Figure 12).

Applying horizontal and vertical friction improved the predicted column profile shapes and displacement magnitude predictions of the MLA GCORE model, particularly at the top of the array. The phase and frequency of the response is also improved, most noticeably after the strong motion (after 5 seconds). The predictions from the MLA GCORE model due to altering the value of the coefficient of friction for acetal between 0.15 to 0.3 (14), (15) showed that altering the coefficient of friction over this range had a small effect on the predictions.

FIGURE 12

Column profile for a specific lattice column at the time of maximum relative x-displacements and the corresponding top layer time history for a friction sensitivity study for a core containing 70% intact bricks and 30% DCBs



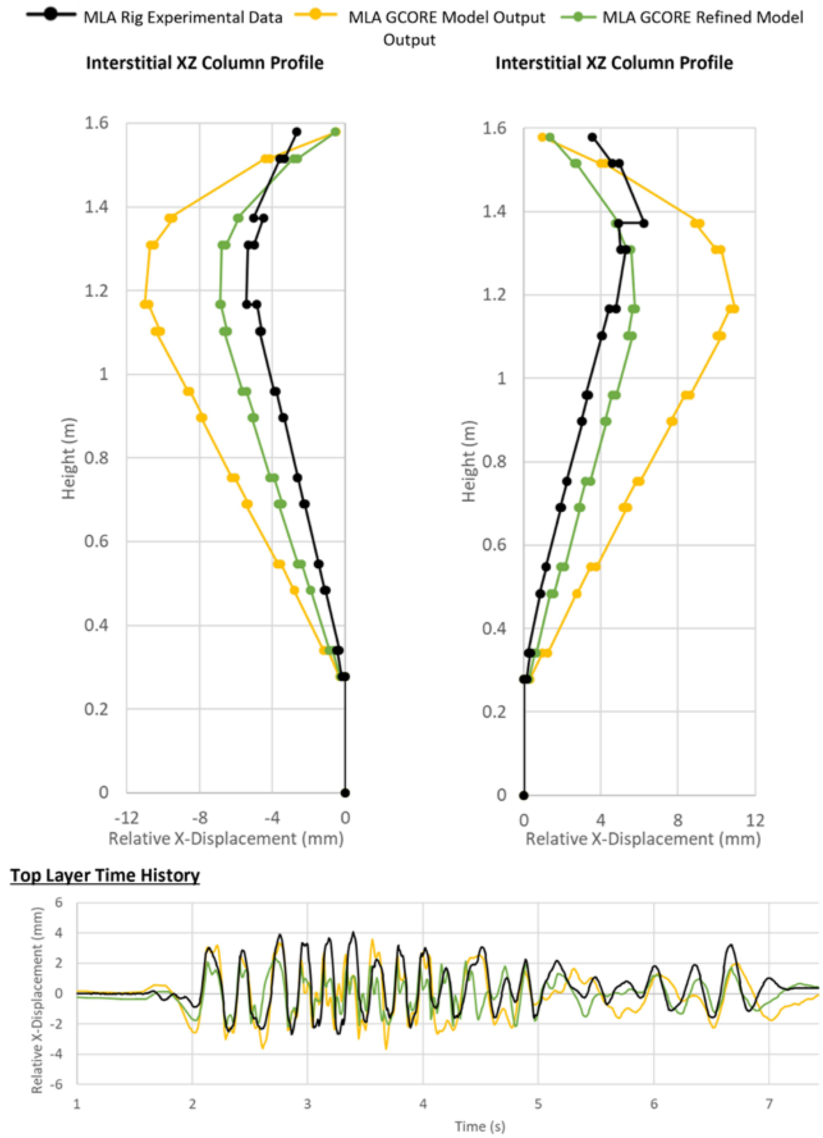
5.2.2 Effect of Altering Tolerances of the Keys and Keyways

Adjusting the direct contact and key/keyway clearances within the design tolerance range for components within the MLA rig also significantly changes the predictions of the MLA GCORE model, (Figure 13). Tighter clearances in the MLA GCORE model provide predictions closer to the MLA rig but the shapes of the most distorted channel profiles are not as well predicted as when friction is applied. Additionally, altering the clearances causes small offsets in the phase of the response. The same tolerance adjustment has been applied to every brick within the array.

The minimum tolerance range that is achievable by the manufacturer in the production of the Acetal standard array components is 0.1mm due to the relief of manufacturing stresses inherent in the Acetal during machining. The as-built Acetal brick clearances were measured to establish the true clearances in the manufactured components, and the refined MLA GCORE model clearances reflect these. The full-scale AGR model uses clearances informed by dedicated graphite brick analysis and modelling, with sensitivity studies performed to bound the behaviour that may be expected through any deviation from the assumed position.

FIGURE 13

Column profiles for a specific lattice column at the time of maximum relative x-displacements and the corresponding top layer time history for tolerance sensitivity study for a core containing 30% SCBs. This figure presents data from a different experimental core configuration in terms of the distribution and orientations of cracked bricks to that presented in Figure 12 and is not therefore directly comparable



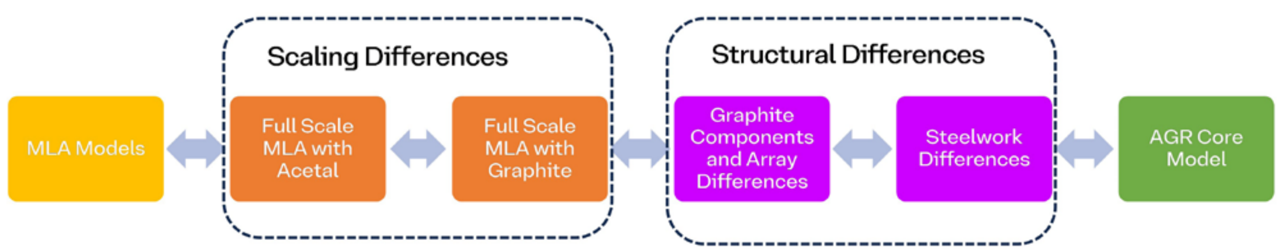
5.3 MAPPING FROM MLA TO AGR

To extend the validation of the GCORE approach from the quarter-scale model and physical array, four modelling aspects were read across to the AGR GCORE model using a model mapping approach, where model output for models incorporating additional modelling aspects was sequentially compared. These four aspects were steelwork structural differences, graphite components and array differences, and scaling differences for both graphite and acetal (see Figure 14). By assessing the effect of each aspect in isolation it was possible to demonstrate the key characteristics of dynamic behaviour at AGR scale are adequately captured.

The steps in the model mapping process were carried out to understand the delta caused by each change, to underwrite the engineering judgement that the step does not have a significant effect on the model predictions, or show that the magnitude of the change is in line with expectation. In this way, these intermediate steps support the engineering judgement that the findings from the MLA analytical model can be used to validate AGR cores.

FIGURE 14

Mapping process between the MLA Model and the AGR Core Model, showing the intermediate steps grouped into scaling differences and structural differences



5.3.1 AGR-Scale Acetal MLA

This step modifies the material properties from acetal (i.e. the physical quarter-scale MLA) to scaled acetal (a representation of a full-scale acetal rig; this full-scale rig does not exist physically). This affects the stiffness of the keying system interactions, as well as the density of the components. To achieve scaling equivalence for the change in size, the material density has been factored. The AGR-Scale Acetal model is part-way between an MLA-Scale Acetal model and an AGR-Scale Graphite model. Changing the scale and the material simultaneously would not allow the effects of each change to be understood.

As the MLA rig is a quarter-scale model, it would be expected that the displacements experienced by the bricks would be approximately one quarter of the size of the displacements in the AGR-scale model, with equal frequency and phase, when the time axis scaling is accounted for.

This is demonstrated in Figure 15, which shows the mean peak relative displacements respectively for both the AGR-scale and rig-scale MLA GCORE models. The rig scale model peak relative displacements are approximately four times smaller than the peak relative displacements in the AGR-scale model in each layer. Figure 16 shows these modifications introduced a small phase shift (less than 0.1 seconds) in the later stages of the seismic input motion, however the overall effect on frequency and phase of these modifications was small.

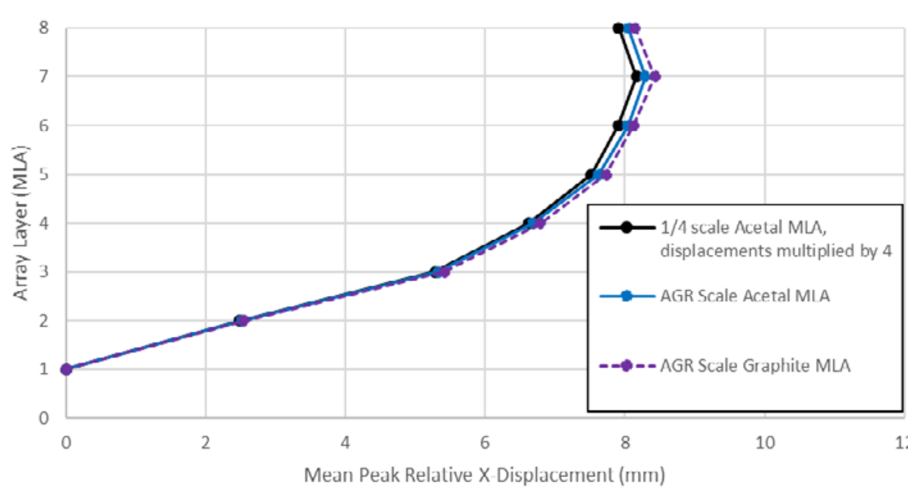
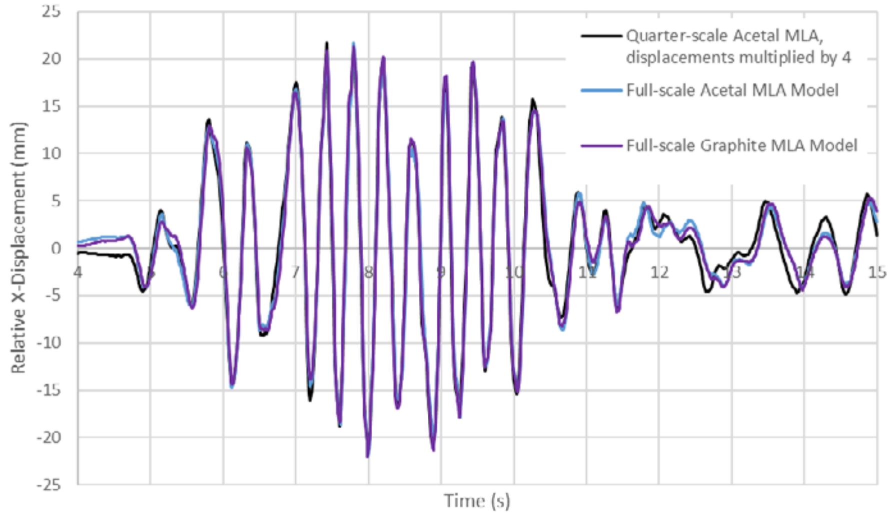


FIGURE 15

Comparison of the mean peak relative displacement in the direction of the seismic input motion for an eight-layer AGR-scale Acetal and Graphite MLA model and the mean peak relative displacement, multiplied by a factor of 4, in the direction of the seismic input motion for the quarter-scale acetal MLA model

FIGURE 16

Time history comparison for the relative displacement of a specific brick in the direction of the seismic input motion. The quarter-scale model relative displacement has been multiplied by a factor of 4 and the time axis scaled appropriately



5.3.2 AGR-Scale Graphite MLA

This step in the model mapping process modifies the material properties from scaled acetal to graphite, including a significant change in keying system clearances, due to differences in manufacturing tolerances for graphite and Acetal (see Section 5.2).

Figure 15 indicates an increase in displacements across the array when moving from acetal to graphite; this change is small. Figure 16 shows no change in frequency, phase or magnitude between acetal and graphite.

5.3.3 Graphite Structural Differences

This step considered the structural differences in the graphite array, including moving between:

- Uniform brick properties in the MLA array and zoned brick properties that vary across the core.
- The shape of the array from eight sides for the MLA array to 16 sides for the AGR core, which accounts for additional outer reflector bricks in the AGR model.
- Number of layers in the MLA representation (eight layers) and the number of layers in the AGR core (for this comparison, 12).

The MLA array is based on a late in life (34 full power reactor years) core. For uniform brick properties, all the bricks in a given layer are assumed to have the same properties (key/keyway clearances, brick-to-brick gaps, stiffness, damping) those in the centre of the core. This is a modelling simplification as graphite property change effects, including dimensional change, are greater in the centre of the graphite core than the outer regions. As the clearances in the centre of the core are larger than those in the outer regions, and are applied throughout the MLA array, this simplification increases peak relative displacements throughout the array, but does not affect the frequency or phase of the response, as seen in Figure 17 and Figure 18. The AGR GCORE models account for these differences using zoned properties which vary by layer and by region, informed by stress analyses of graphite bricks under irradiation. Of the changes in brick properties caused by irradiation, the dimensional changes which affect the key/keyway clearances have been found to be most significant for the dynamic behaviour of the array. The model's sensitivity to changes in different parameters is discussed in Section 5.2.

Moving from an eight-sided array to a 16-sided array increases the peak relative displacements as the cumulative total clearance between the bricks increases, permitting greater displacement, as shown in Figure 17. The frequency and phase of the response is largely unchanged (Figure 18).

Changing the number of layers in the model, i.e. including additional graphite brick layers at the top of the AGR core does not significantly change the peak relative displacements in the corresponding layers (Figure 17). Brick-specific displacements decrease (Figure 18) and the phase shifts by ~0.1 s to the left throughout the motion. This small phase shift is reasonable when considering the significant change in magnitude. In addition to this, the higher frequency components of the motion are more pronounced once the additional layers are added.

FIGURE 17

Comparison of the mean peak relative displacement in the direction of the seismic input motion for increments in the model mapping process showing the progression from an eight-sided array with uniform properties, an eight-sided array with zoned properties, a 16-sided array with zoned properties and eight layers and a 16-sided array with zoned properties and 12 layers (full core AGR model)

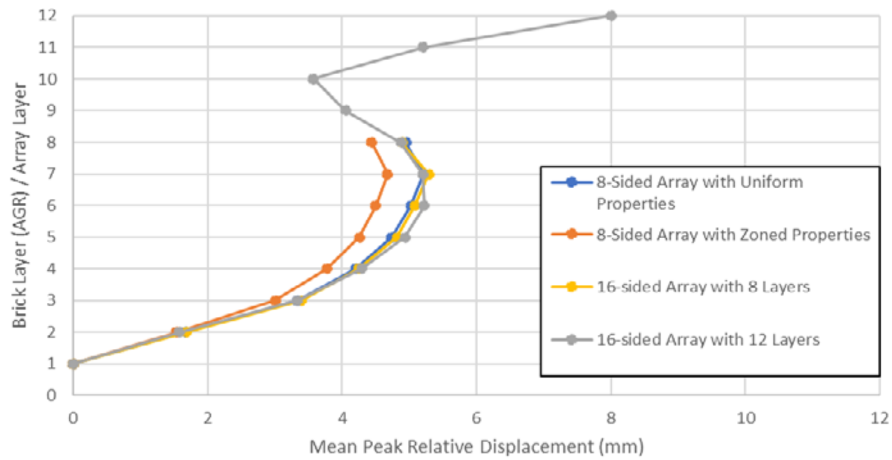
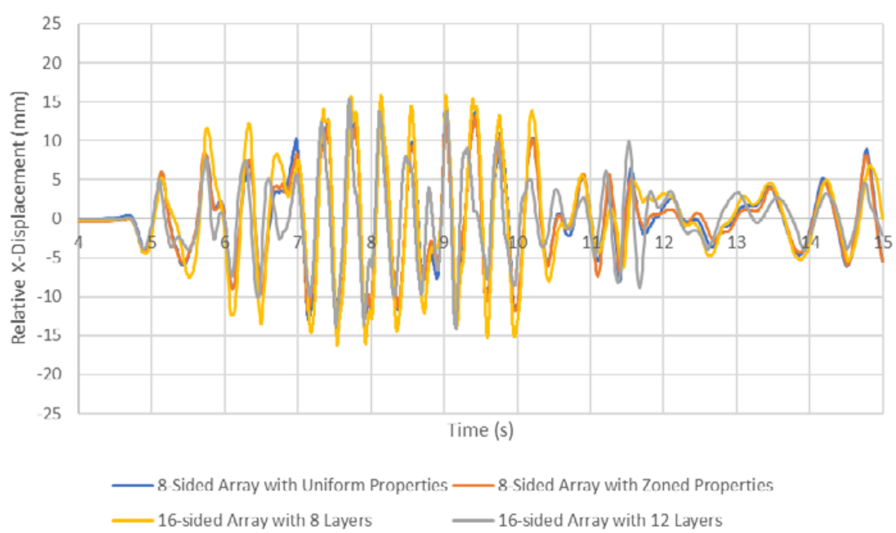


FIGURE 18

Time history for the relative displacement in the direction of the seismic input motion for increments in the model mapping process, showing the progression from an eight-sided array with uniform properties, an eight-sided properties, an eight-sided array with zoned properties, a 16-sided array with zoned properties and eight layers and a 16-sided array with zoned properties and 12 layers (full core AGR model)



5.3.4 Restraining Structures

This step investigated the role of the restraining structures on the accuracy of the model, by sequential inclusion of the upper neutron shield (UNS), guide tubes, restraint structure and fuel stringers.

The purpose of the MLA validation programme is to enable the GCORE modelling methodology for arrays of keyed bricks to be applied to degraded graphite cores by showing that the array behaviour is appropriately represented. The steel restraint structures of the AGRs are not subject to significant in-service degradation and are simple to model in a manner which aligns with industry norms. Similarly, the fuel stringers are not subject to in-service degradation which would affect the seismic performance of the system, as they are replaced regularly. The structural properties of these aspects are well understood and are modelled in a simple manner accordingly, with validation through comparison to hand calculations and engineering judgement.

FIGURE 19

Comparison of the mean peak relative displacement in the direction of the seismic input motion for increments in the model mapping process for an intact core.properties and eight layers and a 16-sided array with zoned properties and 12 layers (full core AGR model)

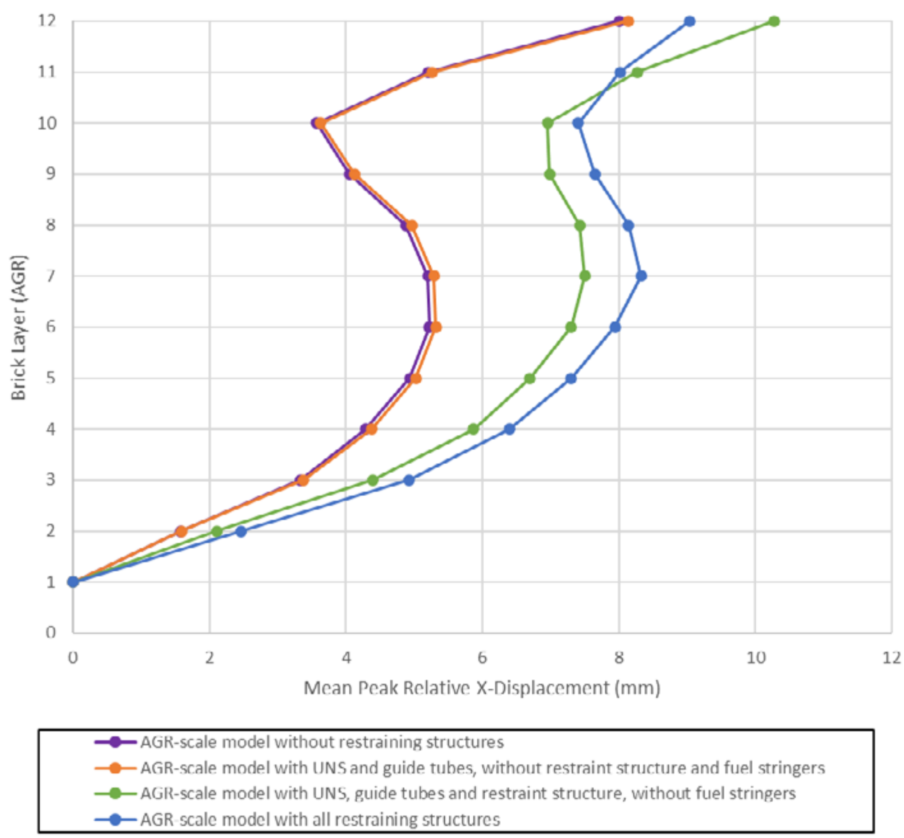
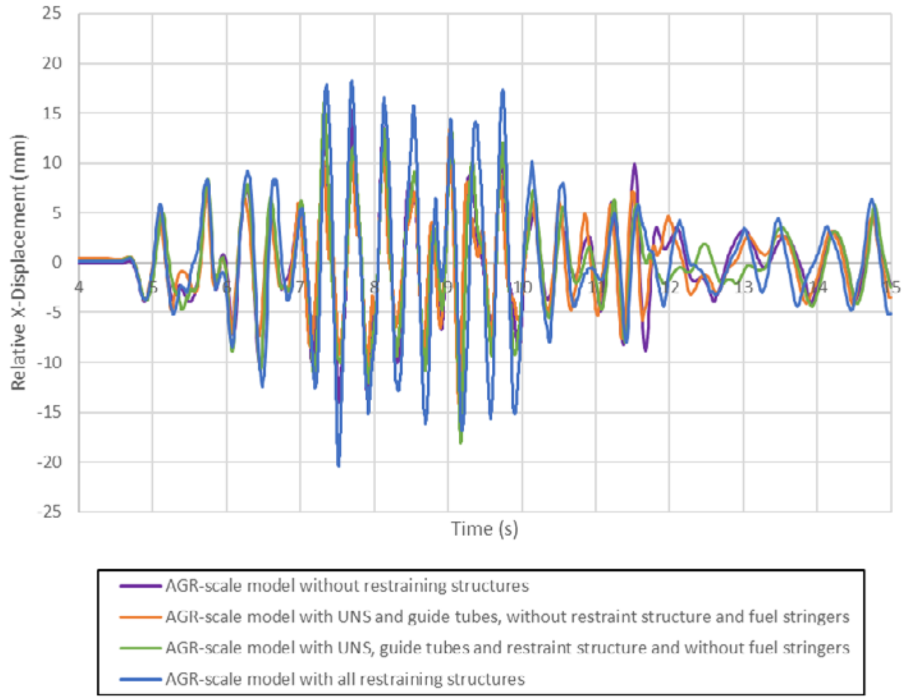


FIGURE 20

Time history for the relative displacement in the direction of the seismic input motion for increments in the model mapping process for an intact core



The biggest change was seen for the inclusion of a representation of the AGR restraint structure, which alters the constraints applied to the outer bricks (Figure 19) from a fixed boundary (as in the MLA, which has a near-rigid restraint frame and is modelled as such), to one that can displace in a simple linear elastic manner as expected of steelwork. The magnitude of this change is in line with expectations.

The final step, to include a representation of the fuel stringers, increases the total mass of the core and the corresponding increase in peak displacements through the mid-height of the core is therefore as expected. The upper layer displacements reduce due to the additional constraint provided by the fuel plug units.

No significant change in the frequency or phase of the response was found for the different representations of upper neutron shield, guide tubes, restraint structure and fuel stringers (Figure 20).

5.3.5 Summary

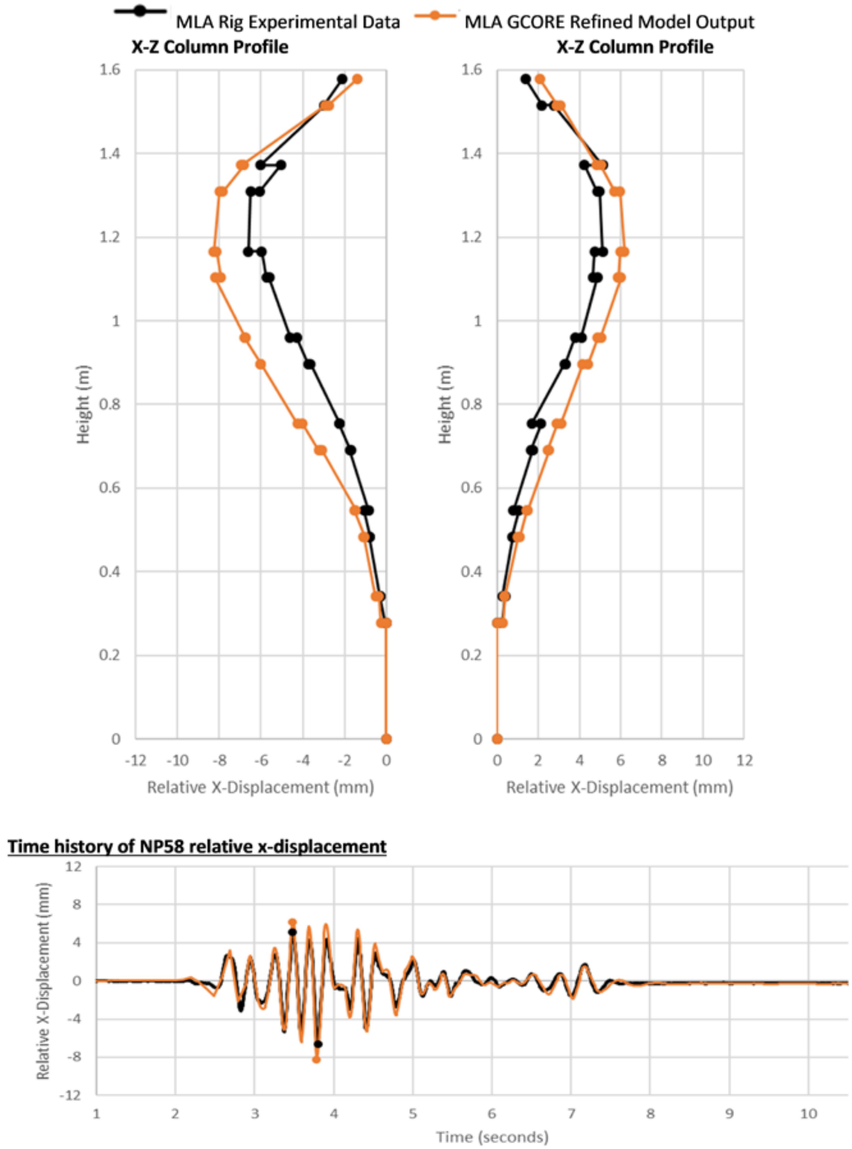
This step-by-step mapping approach has shown that the physical differences between the quarter-scale acetal MLA model and full-scale graphite AGR model can be accounted for in the GCORE modelling approach, validating the full-scale digital twin of the AGR core.

5.4 MODEL REFINEMENT

To further improve model performance, additional physical behaviours (modelling of friction between horizontal and vertical interfaces) and refinement of key parameters (geometric tolerances), as addressed in Section 5.2, were implemented to better align with the physical rig. This was shown to improve prediction accuracy. The inclusion of an appropriate representation of friction in the model was found to be of more significance than the coefficient of friction that was used, however a coefficient of friction for acetal of 0.15 was finally selected. This value is broadly in line with the range quoted in the literature (14), (15), but is biased towards the lower end of the range to maintain a conservative prediction of array behaviour. Geometric tolerances were modelled halfway between mid-tolerance and the tightest tolerance (Figure 21), in line with measurements from a sample of the as-manufactured lattice bricks. This step is important to ensure the digital twin provides the best predictive capability.

FIGURE 21

Column profiles for a specific lattice column at the time of maximum relative x-displacements and the corresponding top layer time history for for the MLA rig and refined MLA GCORE model (i.e. with tolerances updated in line with measurements from a sample of the as-manufactured lattice bricks) for a core with 50% intact bricks, 20% SCBs and 30% DCBs



5.5 VERIFICATION

Model checking activities were required for validation simulations and for those used in assessment of the graphite cores. These checks included unit and assembly tests, independent checks of the model results through hand calculations and alternative FEA methods. Code review, detail checking, comparison with previous work and independent peer review provided further verification of the computational approach.

5.6 SUMMARY

The cross-comparison between the initial MLA GCORE model and MLA experimental data demonstrated that the key characteristics of the dynamics of an array of quarter-sized acetal bricks could be modelled using the GCORE approach (Section 5.1).

The mapping process between the MLA GCORE model and the AGR GCORE model (Section 5.3) demonstrated that the key characteristics of an array of graphite bricks in an AGR should be adequately captured by the array of quarter-sized acetal bricks in the MLA.

Sensitivity studies (Section 5.2) have identified the following as significantly improving the MLA GCORE model predictions:

- Simulation of friction between horizontal and vertical interactions.
- Adjusting the key and keyway clearances based on the manufacturing tolerances of the MLA rig components.

The predictions of the MLA GCORE model have been shown to improve through refining the modelling approach (Section 5.4).

These findings validate the ability of the GCORE model to predict array distortion and demonstrates that GCORE can accurately model the displacements of keyed arrays of bricks.

6. Use of AGR GCORE Model for Continued Operation of Nuclear Power Plants

Following validation and verification of the scaled digital twin, virtual qualification of specific station graphite cores was carried out using a full sized GCORE representation. Core-specific input data has been used for the GCORE assessments to demonstrate the damage tolerance to seismic hazards of the graphite cores. The specification of the site-specific seismic input motions, component material properties, distributions and configurations of cracked bricks used in these analyses is outside the scope of this paper.

Taken with other safety case arguments, these analysis results have been a key part of the graphite structural integrity safety cases for the majority of the UK's AGR nuclear power stations.

7. Conclusion

Experimental validation of a scaled digital twin has been used to allow virtual qualification of a computational model representing a full-sized graphite core.

GCORE results have been successfully used to provide evidence to support the seismic safety cases for EDF's AGR reactors. The models have been robustly substantiated using a combination of validation, verification and assessment of uncertainty, and have demonstrated how virtual qualification can be used to give confidence in the fidelity of a digital twin of a complex physical asset.

This paper has shown how experimental validation of a digital twin, combined with verification and assessment of uncertainties, was used to allow virtual qualification of a system it would otherwise be impossible to assess. This computational tool allowed assessment of a wider range of graphite cores than would have been possible using a physical representation, making it possible to explore the graphite core's fundamental seismic performance and inform the safety assessment process.

The continued operation of the AGR fleet of power stations has contributed to energy security for the UK and prevented emission of CO2. The output from GCORE, an experimentally validated digital twin, has been an important contribution to this continued operation.

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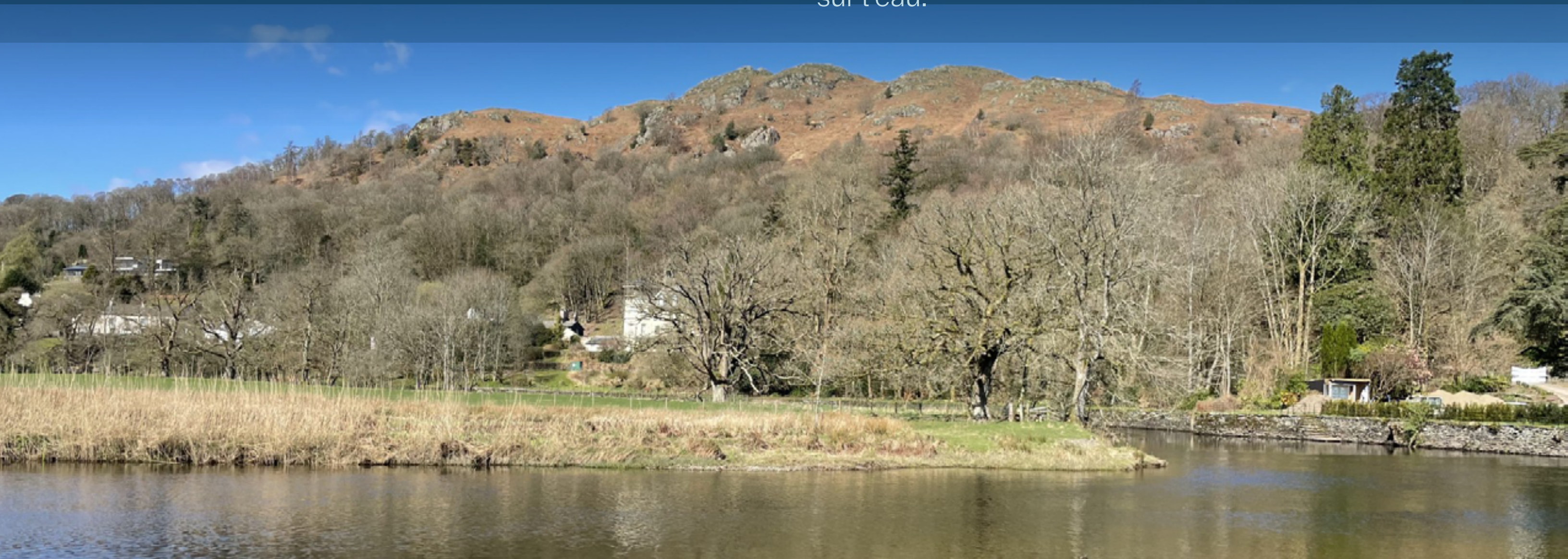
07: Responding to the Challenge of Trace Contaminants Entering our Water Environment

Significance Statement

AtkinsRéalis has played a pivotal role in supporting the UK water industry in meeting Water Industry National Environment Programme (WINEP) obligations for chemicals. This was achieved through a collaborative research program coordinated by UK Water Industry Research (UKWIR). This work addresses the pressing challenges posed by trace contaminants in wastewater treatment works (WwTW) and emphasizes the need for continuous innovation and a deeper understanding of environmental impacts. By investigating chemical trends and focusing on compliance risks, the research provides essential evidence for optimizing investments, informing regulatory decision-making, and enhancing treatment strategies. Ultimately, this initiative aims to drive improvements in water quality across England and Wales, aligning with the objectives of the Water Framework Directive.

Énoncé d’importance

AtkinsRéalis a joué un rôle essentiel en soutenant l’industrie de l’eau au Royaume-Uni dans le respect des obligations du Water Industry National Environment Programme (WINEP) pour les produits chimiques. Cet objectif a été atteint grâce à un programme de recherche concertée coordonné par UK Water Industry Research (UKWIR). Ces travaux portent sur les défis pressants posés par les contaminants à l’état de traces dans les installations de traitement des eaux usées et mettent l’accent sur la nécessité d’une innovation continue et d’une meilleure compréhension des impacts environnementaux. En examinant les tendances chimiques et en se concentrant sur les risques liés à la conformité, la recherche fournit des données probantes essentielles pour optimiser les investissements, éclairer la prise de décisions réglementaires et améliorer les stratégies de traitement. À terme, cette initiative vise à améliorer la qualité de l’eau en Angleterre et au pays de Galles, conformément aux objectifs de la directive-cadre sur l’eau.



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Abstract

The water industry in England and Wales has responded to the challenge of increasing diversity in chemical inputs by undertaking a programme of collaborative research coordinated by UK Water Industry Research (UKWIR). An investigation into chemical trends has focussed on substances with use restrictions as a result of European Union (EU) regulations such as the Regulation on the registration, evaluation, authorisation and restriction of chemicals (REACH) and the Stockholm Convention on Persistent Organic Pollutants (POP). This research has investigated chemical concentrations in wastewater treatment works (WwTW) influent and effluent and projected concentrations to 2027, aligning with the Water Framework Directive requirement to achieve good status in all bodies of surface water and groundwater. It has gathered the evidence base to avoid misplaced investment and to ensure the focus of research aligns with the chemicals at greatest risk of non-compliance.

KEYWORDS
Chemicals; Water quality; Wastewater; Regulation

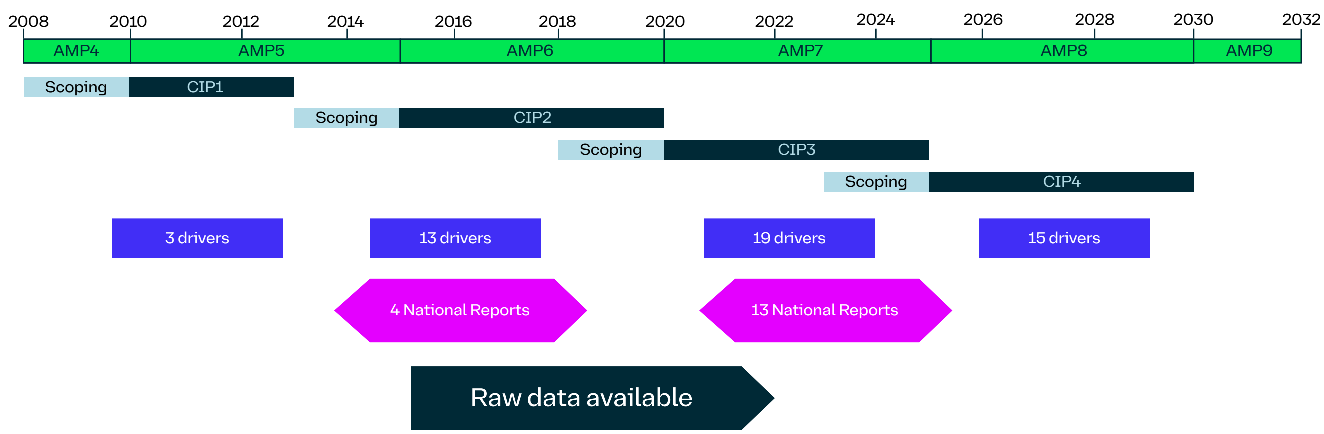
1. Introduction

The magnitude of the challenge facing our water environment from chemicals is encapsulated in the number of Chemical Abstracts Service (CAS) registrations per year which has increased exponentially in the last ten years (Arp et al., 2023). Numbers are in the region of 10-20 million registrations each year; therefore, the scale of the challenge regarding chemicals entering our water environment is constantly evolving. The Environmental Audit Committee warns that water companies and agriculture are the biggest contributors to the chemical cocktail that is entering England's rivers (House of Commons Environmental Audit Committee, 2022). The stresses of synthetic chemical pollution along with plastics are creating multiple pressures on these key ecosystems.

The water industry has been investing in understanding the role they play in the transfer of chemicals to the environment. The Chemical Investigation Programme (referred to henceforth as CIP) is a collaborative programme of research by water companies in England and Wales and the respective national regulators, coordinated by UK Water Industry Research (UKWIR). It is intended as a means of gaining a better understanding of the occurrence, behaviour, and management of trace chemicals in the environment. CIP was initiated to ensure the proper management of chemicals and support the water industry in effectively treating the contents of sewers under the Water Industry Act 1991. The programme was orignally developed to give confidence in how wastewater treatment works (WwTW) are contributing to Environmental Quality Standard (EQS) failures and understand available treatment options. The challenge for each programme of research, aligned with the water industry funding cycles known as Asset Management Plans (AMP) is set out in the Water Industry National Environment Programme (WINEP) and the findings are publicly available in a series of reports and raw data (Figure 1).

FIGURE 1

Overview of UKWIR Chemical Investigations Programme

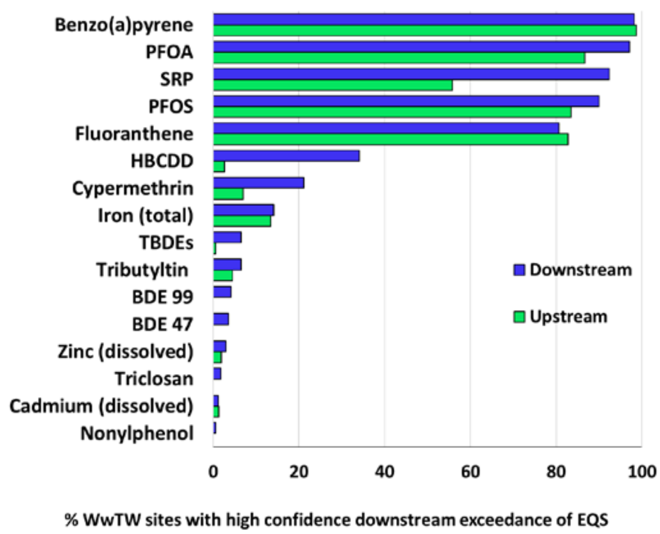


Three phases have now been completed, with the first phase (CIP1) having the objective to understand and manage the risks from water company assets in meeting chemical EQSs, making it possible to prioritise substances for which regulation had been introduced. In the second phase (CIP2), the investigations were designed to investigate site-specific compliance status at over 600 WwTWs as well as to demonstrate a clearly justifiable need for investment. Amongst other investigations, it assessed the potential improvements in effluent quality offered by novel treatment processes. The third phase (CIP3) was much more varied in scope with over 19 chemical drivers investigating sources of chemicals, emerging substances, microplastics and anti-microbial resistance (AMR) as well as a wide range of receptors. This programme of national research at an unprecedented scale and complexity across England and Wales has led to a massive advancement in our understanding of the role of the water industry in chemicals entering the water environment. Therefore, providing an important evidence base to inform regulation and policy decisions.

One of the key findings in CIP2 was related to the ranking of contaminants (UKWIR, 2020). Figure 2 shows the risk prioritisation of substances (expressed as the percentage of WwTW sites) with a high confidence of downstream exceedance of EQS based on the mean concentration. This is presented for the first and largest tranche of the 600 CIP2 sites, with similar observations in the subsequent three tranches. Non-compliances with EQS values were relatively infrequent, except in the case of a small number of substances, many of which align with those identified in the effluent trend analysis presented in this paper. The risk ranking made it possible to prioritise trace contaminants and identified compliance risk downstream of discharges for substances such as poly aromatic hydrocarbons (PAHs) and poly and perfluorinated alkyl substances (PFAS). The difference between the upstream and downstream concentrations is indicative of the overall impact of the WwTW effluents on non-compliance and supports the importance of understanding in-river concentrations.

FIGURE 2

CIP2 Tranche 1 contaminant risk ranking (high confidence of non-compliance (UKWIR, 2020



For this paper, the focus is on investigating effluent trends in substances that show a reduction in use and emissions as this evidence has the potential to remove the need for their treatment which can require costly modifications. This provides key evidence for regulatory decision makers in terms of assessing regulatory controls for the Water Framework Directive as well as wider catchment management, prioritising investments in wastewater treatment to where they are really needed.

2. Methodology

2.1 SAMPLING METHODOLOGY

The investigation into chemical trends assessed substances that are common to all CIP phases. This paper focuses on the seven determinants with effluent concentrations that exceed the environmental standards in CIP3 and are likely to be of greatest interest to regulators as they have the highest percentage of samples exceeding standards. The trend investigation as a whole monitored a total of 20 substances and the assessment of the other 13 substances can be found in the full report (UKWIR, 2023a).

Monitoring was undertaken within CIP3 for a duration of 18 months from September 2020 to March 2022. This was a partial dataset as the monitoring is ongoing until Spring 2025 when the full results will be assessed. Monitoring for many of the parameters will continue during the fourth phase of the Chemical Investigations Programme (CIP4) from 2025 to 2030. Monthly samples were collected and analysed to align with the same frequency as operator self-monitoring at 50 WwTW across England and Wales. The 10 participating water companies each monitored 5 effluent discharges including sites that were previously monitored during either CIP1 (UKWIR, 2014) and/or CIP2 (UKWIR, 2020) and one discharging into a transitional and coastal water body. To assess the trend, CIP3 data were compared to data from CIP1 and CIP2 (split into 4 tranches) (Table 1).

The analytical requirements in terms of target maximum limits of detection (LoD) and target maximum tolerable error were outlined in the CIP3 Technical Specification (UKWIR, 2021).

TABLE 1

Number of WwTWs sampled to enable trend analysis

Dataset		Number of WwTWs
CIP1 (2010 – 2013)		185
CIP2 (2015 – 2020)	Tranche 1	182
	Tranche 2	164
	Tranche 3	141
	Tranche 4	154
CIP3 (2020 – 2021)		50

2.2 QUALITY CONTROL AND PROFICIENCY TESTING

Quality control (QC) across the CIP programme was expected to follow basic features such as a periodic assessment of the LoD achieved and determination of QC samples in each batch of analysis (Gardner, 1989). Performance test information was submitted by participating laboratories to evidence meeting analytical performance targets. In addition, there was a programme of interlaboratory proficiency tests (PT) including routine and bespoke exercises as part of the wider programme. No clear instances of continued or consistent patterns of error were identified.

Rejection of statistical outliers was undertaken using the median absolute deviation z-score method for CIP1 and 2 (Iglewicz & Hoaglin, 1993) with CIP3 using the approach of 1.5 times the interquartile range on a WwTW-by-WwTW basis.

2.3 ENVIRONMENTAL STANDARDS

Data from the monitoring of 7 substances are presented and compared against EQS's (Table 2). The EQS may be expressed as an annual average value (AA-EQS) or a maximum allowable concentration (MAC-EQS) which is the maximum for any single measurement.

TABLE 2

EQS for selected determinants

			Surface water EQS		TraC EQS	
Determinant	**Abbreviation**	**Unit**	**Annual Average (AA-EQS)**	**Maximum Allowable Concentration (MAC-EQS)**	**Annual Average (AA-EQS)**	**Maximum Allowable Concentration (MAC-EQS)**
Benzo(a)pyrene	BAP	µg/l	0.00017	0.27	0.00017	0.027
Perfluorooctane sulfonic acid	PFOS	µg/l	0.00065	36	0.00013	7.2
Hexabromo cyclododecane	HBCDD	µg/l	0.0016	0.5	0.0008	0.05
Fluoranthene	FLU	µg/l	0.0063	0.12	0.0063	0.12
Tributyltin	TBT	µg/l	0.0002	0.0015	0.0002	0.0015
Lead (dissolved)	PbD	µg/l	1.2	14	1.3	14
Mercury (dissolved)	HgD	µg/l	-	0.07	-	0.07

2.4 CALCULATION OF CHEMICAL DIE AWAY

The projected outcomes of current trends are presented in the results with plots of the 3 substances with the greatest percentage of samples exceeding the EQS and explained in the context of the dataset containing 20 substances. They assess the concentrations of determinants over the entire CIP programme and predict concentrations in 2027 when the third and final cycle of the current Water Framework Directive River Basin Management Plan Cycle ends. The approach plots the overall mean effluent concentration as determined in the three phases of the Chemical Investigations Programme. An exponential curve was fitted to the measured mean values and projected to 2027. To estimate the worst-case mean concentrations that might occur, the 75th percentile concentrations were applied.

3. Results and Discussion

3.1 COMPARISON AGAINST ENVIRONMENTAL QUALITY STANDARDS

Table 3 shows the average and maximum concentrations of the 7 determinants in effluent over the 18-month period were found to be above their respective EQS values. The determinants are ranked from most exceedances to the least. Six of these were above the AA-EQS and 3 above the MAC-EQS. Benzo(a)pyrene and PFOS had the highest percentage of samples exceeding an EQS, both exceeding the EQS in more than 99% of samples detected above the LoD.

TABLE 3

Percentage of effluent samples above AA-EQS or MAC-EQS (where available)

Determinant	Total samples above LoD	Total samples above AA-EQS	Total samples above MAC-EQS	Percentage of samples above AA-EQS	Percentage of samples above MAC-EQS
Benzo(a) pyrene	832	830	9	99.8%	1.1%
PFOS	870	867	0	99.7%	0%
HBCDD	609	419	0	68.8%	0%
Fluoranthene	606	287	6	47.4%	1%
TBT	298	35	0	11.7%	0%
Lead (dissolved)	778	37	0	4.8%	0%
Mercury (dissolved)	469	-	7	-	1.5%

As EQSs are set for surface water concentrations, rather than effluent, a degree of dilution would be expected to occur in the receiving waterbody. Table 4 shows the appropriate dilution factor required downstream for the determinant to be measured below the AA-EQS. A dilution of over 10 times the AA-EQS would be required for Benzo(a)pyrene and PFOS. Mercury (dissolved) has been assessed against the MAC-EQS and the average ratio of exceedance in effluent is 34.9 (standard deviation 33).

TABLE 4

Summary of ratios of AA-EQS exceedance in effluent

Determinant	Average ratio of AA-EQS exceedance in effluent	Standard deviation of AA-EQS exceedance in effluent
Benzo(a)pyrene	18.8	22
PFOS	10.5	19.1
HBCDD	2.7	1.5
Fluoranthene	3.0	2.9
TBT	1.3	0
Lead (dissolved)	1.1	0.1

All WwTW's effluent exceeded the AA-EQS for Benzo(a)pyrene and PFOS (Table 3) and would require a large dilution to remain below the EQS in the receiving water (Table 4). For HBCDD and Fluoranthene, fewer mean concentrations were found above the AA-EQS and to avoid downstream exceedance lower dilutions were found to be required. Only two WwTW exceeded the AA-EQS for TBT and for Lead (dissolved) the ratio of exceedance was much lower <2%.

3.2 TREND ANALYSIS

To assess changes in concentrations across the entire CIP programme, overall mean effluent concentrations are presented for the 3 determinants with the highest percentage of samples above AA-EQS. These are shown in Figures 3 to 5 for Benzo(a)pyrene, PFOS and HBCDD, respectively. The number of wastewater treatment works represented by the mean concentration for each blue circle is given in Table 1. The calculation of chemical die away is set out in Section 2.4. An exponential curve is given by a blue dotted line, the solid purple line represents the AA-EQS, and an estimate of the worst-case mean concentrations predicted for 2027 is illustrated using a yellow circle. The exception is PFOS due to the high PFOS measured during CIP2 Tranche 1, an exponential decay curve has not been fitted.

FIGURE 3

Predicted trends in Benzo(a) pyrene concentrations (AA-EQS = 0.00017 µg/l (purple line))

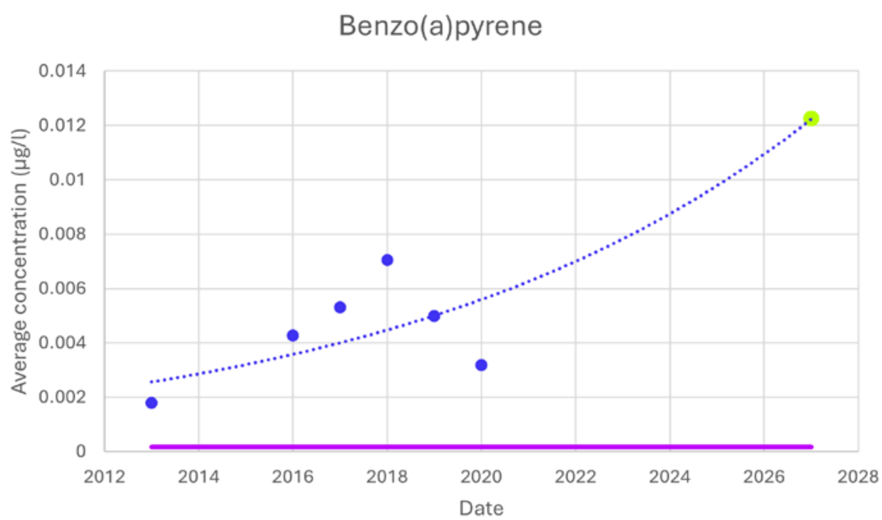


FIGURE 4

Predicted trends in PFOS concentrations (AA-EQS = 0.00065 µg/l (purple line))

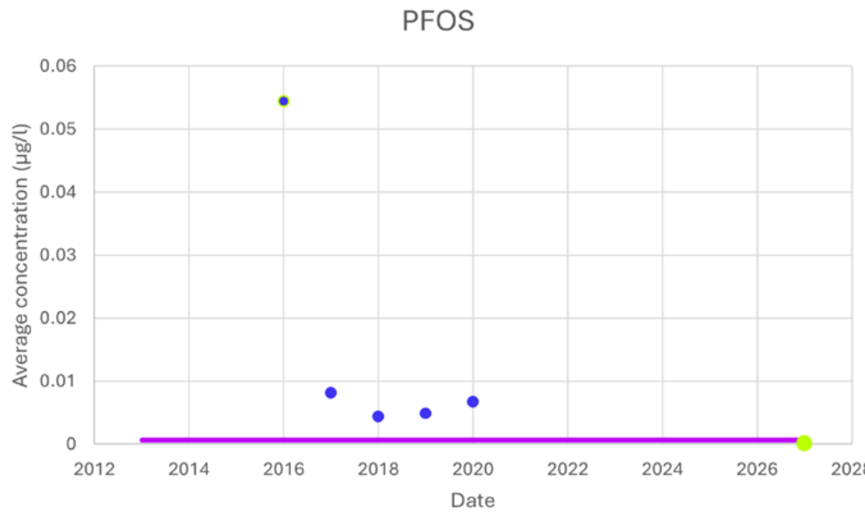
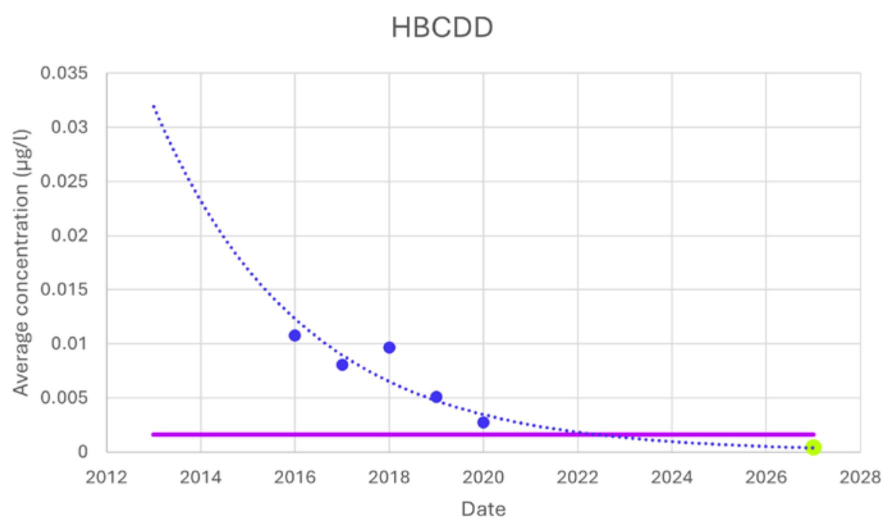


FIGURE 5

Predicted trends in HBCDD concentrations (AA-EQS = 0.0016 µg/l (purple line))



The trend analysis showed a downward trend for HBCDD (Figure 5) which aligned with the majority of the determinants in the wider dataset of 20 substances reported in UKWIR (2023a). The mean concentration of these determinants are likely to be below the AA-EQS in 2027 even using the 75% data for worst-case "mean" scenario by 2027. The trend for PFOS (Figure 4) was also downwards, although has been projected that the across all the WwTW's the worst-case "mean" scenario effluent would require a dilution of 8.48 times to meet the EQS in 2027. This was not the case for Benzo(a)pyrene (Figure 3) (or the other PAH, Fluoranthene) for which an upward trend was observed with mean concentrations expected to increase in the future.

3.3 CONCENTRATION CHANGE ACROSS THE WASTEWATER TREATMENT WORKS

Mean removal (or potential addition) of each determinant was calculated from influent to effluent for each wastewater treatment works. All 7 determinants showed removal across the works with the highest removal for Fluoranthene and the lowest for PFOS. It should be noted that the percentage change data was highly variable with the standard deviation for PFOS, Lead (dissolved) and Mercury (dissolved) exceeding the mean removal.

TABLE 5

Mean removal of determinant across the WwTW

Determinant	Mean removal (%)	Standard deviation between WwTWs (%)
Benzo(a)pyrene	87%	10%
PFOS	10%	36%
HBCDD	87%	12%
Fluoranthene	92%	5%
TBT	77%	34%
Lead (dissolved)	50%	66%
Mercury (dissolved)	27%	77%

Removal of determinants across the WwTW from influent to effluent was illustrated by the 7 determinants that form the focus of this paper. However, the wider study had a number of determinants with higher concentrations in the effluent compared to the influent. It should be noted that the errors have not been calculated around these removals and there was a large variation in removals across the WwTWs. The greatest confidence in removal was for Benzo(a)pyrene and Fluoranthene. In contrast, there was a very low confidence of removal for Lead (dissolved) and Mercury.

4. Conclusion

The 18 months of monitoring during the CIP3 investigation into chemical trends has identified 7 determinants with a mean or maximum concentration in WwTW effluent above the EQS. These chemicals have a range of uses including flame retardants, anti-foulants, and fire retardants as well as metals and incomplete combustion products. The assessment of chemical die away illustrates that concentrations in effluent (with the exception of Benzo(a)pyrene) have a downward trend suggesting that regulatory restrictions are having an impact.

The CIP3 catchment investigations have evidenced that the HBCDD signal is linked to domestic sources due to the use as a flame retardant (UKWIR, 2023b). However, the downward trend suggests a reduction in use has resulted from the listing of HBCDD in REACH regulations as well as the Stockholm Convention on POPs.

Although a die away curve was not fitted to PFOS, a clear downward trend is apparent. Though the use of PFOS and PFOS-related substances are restricted in the EU the CIP3 catchment investigations and identified sewer sources including landfill leachate, trade effluent from manufacturing and metal plating as well as domestic effluent. River sources included sites with historic contamination from fire-fighting foams as well as high concentrations upstream of obvious point sources supporting ubiquitous nature of PFOS. Illustrating that despite the restrictions, old products will continue to act as a source for a number of years (Environment Agency, 2021a). PFOS is the only PFAS with an EQS. The trend of declining PFOS supports evidence for a move away from legacy PFAS with the potential increase in substitutes from the PFAS group (Environment Agency, 2021b).

Benzo(a)pyrene concentrations in effluent have continued the upward trend observed in CIP2. The ubiquitous nature of this PAH which is a POP, listed under REACH as well as a priority hazardous substance under the Water Framework will exceed the EQS in 2027.

The trend investigation has illustrated that existing source control measures are contributing to downward trends for some substances, however, there are exceptions including Benzo(a)pyrene and Mercury. Although this investigation has focussed on influent and effluent policy, the in-river quality, flow, and potential dilution remain important factors for the assessment of permitting. The monitoring programme for CIP3 will continue to 2025 then within CIP4 to continue to assess over longer timeframe. The implications of confirming these trends are to ensure investment in WwTWs is aligned with removal of chemicals that are of greatest risk of non-compliance. Decision makers will be able to apply these findings to prioritise removal of those substances that will make a difference to compliance rather than those that will die-away under the current regime.

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08: Improvement of the Stability of Tailings Storage Facilities by Buttressing

Significance Statement

Tailings are a by-product of mining operations after extracting and recovering valuable minerals from ore. A tailings dam is typically an earth-fill or rock-fill embankment dam to store the tailings. In the past 100 years, a number of tailings dams failed for various reasons and released substantial quantities of tailings into the natural environment, causing severe casualties, including loss of life and deterioration of environmental and cultural values, infrastructure, and economy. This paper demonstrates how constructing a buttress can help stabilize an existing tailings dam and outlines how to design a buttress which could benefit professionals in the mining industry.

Énoncé d'importance

Les résidus miniers sont un sous-produit de l'exploitation minière après l'extraction et la récupération de minéraux précieux du minerai. Une digue à résidus miniers est habituellement une digue de remblai en terre ou en roche visant à stocker les résidus. Au cours des 100 dernières années, un certain nombre de digues à résidus miniers se sont effondrées pour diverses raisons et ont rejeté des quantités importantes de résidus dans le milieu naturel, causant plusieurs morts et provoquant des pertes environnementales et culturelles, ainsi que des dommages à l'infrastructure et à l'économie. Ce document montre comment la construction d'un contrefort peut aider à stabiliser une digue à résidus miniers existante et décrit comment concevoir un contrefort qui pourrait profiter aux spécialistes de l'industrie minière.

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Abstract

Tailings dams, which store the tailings (usually in the form of slurry), a byproduct of mining operations, have a global impact. With over 18,000 such dams worldwide (the actual number may be higher) and about 3,500 currently active, the potential for catastrophic failure is not just a concern but a looming threat. The past few decades have seen numerous such failures, releasing significant quantities of tailings into the natural environment. The resulting damage, including loss of life, environmental degradation, and economic disruption, underscores the urgent need for effective solutions. The instability of many existing tailing dams has become a significant concern in the mining industry. Mining companies are taking different measures to address the instability issues of existing tailings dams in collaboration with engineering consulting companies to avoid any casualties. Constructing buttresses at the dam toe is one practical solution, as it can effectively provide a resisting moment against slope failure by providing enough dead load near the toe of the dam. Buttresses are being designed and constructed to stabilize the existing tailings dams worldwide, including in high seismic areas. Adherence to international standards and guidelines is critical to their success and reliability. However, authors have found that the buttressing of the tailings dam has yet to be independently reviewed with emphasis on fundamentals and design considerations. This paper presents how the buttresses reinforce unstable tailings dams. Two case studies have also been summarized and discussed, where buttresses stabilize the tailings dam by increasing the Factor of Safety (FoS) to safeguard and mitigate dam failures.

KEYWORDS

Mining; Tailings dams; Buttress; Stability

1. Introduction

Tailings are a by-product of mining operations after extracting and recovering valuable minerals from ore. A tailings dam is typically an earth-fill or rock-fill embankment dam used to create Tailings Storage Facilities (TSF) that store the tailings. The process of transporting these tailings involves using a pipeline to transport the tailings as a slurry to the TSF. This slurry, a mixture of water and soil particles, including medium sand, silt, and clay, is then discharged in the TSF using different techniques, including sub-aerial discharge, sub-aqueous discharge, and thickened discharge (Jewell, 1998). The coarse particles of tailings (i.e., sand) settle close to discharging points while the fine particles (i.e., silt and clay) move down the beach into the tailings pond (Vick, 1990). Tailings dams are generally constructed by upstream, downstream, or center-line methods (Vick, 1990). Upstream tailings dams often show slope stability problems when the dam raising rate is too fast, generates excess pore water pressure, and tailings with low hydraulic conductivity undergo slow consolidation (Zardari, 2011). Slope instability occurs when overturning moments exceed resisting moments, resulting in a slip failure.

On a global scale, the issue of tailings dam failure is not just a concern but a significant and pressing problem. There are more than 18,000 tailings dams, of which about 3,500 are active. Zongjie Lyu et al. (2019) reported that in the past 100 years, about 1.2% of the total tailings dam failed or breached compared to the 0.01% failure rate of the traditional water storage dam. This alarming statistic, underscoring the global magnitude of the problem, should serve as a wake-up call to readers. For instance, the 2019 Brumadinho dam disaster in Brazil resulted in the release of 12 million cubic meters of tailings, causing the loss of 270 lives and significant environmental damage.

There are numerous causes for tailings dam's failure, including dam slope instability, inadequate foundation support, improper design without following any international guideline or standard, overtopping of tailings, seepage, erosion, earthquake, lack of monitoring and surveillance, etc. (Lyu et al., 2019; Rico et al., 2008). Failure of tailings dams releases substantial quantities of tailings into the natural environment, causing severe casualties, including loss of life and deterioration of environmental and cultural values, infrastructure, and economy.

Mining companies are collaborating with engineering consulting companies to address the instability issues of existing tailings dams and prevent potential casualties. This collaborative approach is a testament to the industry's commitment to safety and environmental responsibility. Buttresses, a proven method, are being designed and constructed to stabilize existing tailings dams worldwide, even in high seismic areas. It is important to note that the buttressing of the tailings dam has yet to be independently reviewed with emphasis on fundamentals and design considerations. This paper aims to fill that gap by presenting how buttresses reinforce unstable tailings dams. Two case studies have also been summarized and discussed, where buttresses have not just increased the Factor of Safety (FoS) but have done so effectively, instilling confidence in their ability to safeguard and mitigate dam failures.

2. Factors Affecting the Stability of Tailings Dam

The open literature has extensively cataloged a comprehensive list (e.g., Lyu et al., 2019) of dam failures. These failures, primarily attributed to earthquakes, seepage, foundation failure, and over-topping, are not just incidents but reminders of the critical need for robust design and maintenance of tailings dam construction. The following subsections present an overview of those factors affecting dam stabilization:

2.1 SEEPAGE/LIQUEFACTION

Many historical tailings dams were breached due to the rise in water level. Reasons for raising the water level (phreatic surface) in the TSF include rains, floods, and the tailings dam's limited drainage capacity. The tailings below the phreatic surface have a slow consolidation process; saturated tailings increase the weight and reduce the shear strength and modulus of deformation, initiating piping effects, liquefaction of granular materials or strain softening of the cohesive materials and ending up with tailings dam failure. Lyu et al. (2019) reported that about 21.6% of the total dam failures are due to seepage. Each dam failure has a unique story. For example, the Huangmeishan tailings dam failed in 1986 after continuous rain for several days (Davies et al., 2000). The Omai Dam failed in 1994 due to the tailings dam's limited filtration capacity, poor drainage performance, and high phreatic surface (Davies et al., 2000). In Aurul tailings dam, the phreatic line rose in 2000 due to heavy snow and snowmelt, which affected the stability of the tailings dam (Lyu et al., 2019).

2.2 EARTHQUAKES

Lyu et al. (2019) reported that a significant portion, about 17.0%, of dam failures can be attributed to the destructive force of earthquakes. The consequences of these failures are stark, as evidenced by the El Cobre Copper Mine in Chile, which collapsed in 1965 due to earthquake liquefaction, releasing 2.3 million m^3 of tailings and causing the loss of more than 200 lives (Dobry & Alvarez, 1967). Similarly, the Kayakari dam at the Ohya mine in Japan failed by liquefaction in 2011, leading to significant damage to the downstream environment following an earthquake (Lyu et al., 2019).

2.3 FOUNDATION FAILURE

Lyu et al. (2019) reported that about 17.3% of dam failures were caused by foundation failure. A notable instance of such a failure is the Mount Polley tailings dam failure in 2014, which released about 25 million m^3 of tailings and tailings water into the downstream lake basin (Petticrew et al., 2015). Lyu et al. (2019) explained that the load from the dam was more than the bearing capacity of the dam foundation material, resulting in shear damage to the dam foundation material. This technical detail is crucial for understanding the root cause of such failures.

2.4 OVERTOPPING

Overtopping is one of the major causes of tailings dam failure. Lyu et al. (2019) reported that about 20.6% of dam failures were caused by overtopping. Many tailings ponds are located close to the dam crest. During heavy rainfall events, the water level rises in the TSF quickly. In addition, if the dam's permeability is poor, rainwater is discharged at a prolonged rate, resulting in the overtopping phenomenon, drastically affecting the dam's stability. Lyu et al. (2019) stated three steps of a dam failure by overtopping: destabilization under adverse conditions (e.g., flooding) followed by the interaction of tailings sand with water, forming a debris flow with high energy, and ending up with debris flow with high potential energy moving downstream. Merriespruit tailings dam with less free board and less reservoir area released 600,000 m^3 of tailings after a few hours of thundershowers in 1994 (Blight, 1997). Zijin tailings pond dam in Guangdong, China, also failed by overtopping after heavy rain killed 22 people and destroyed 6,370 houses (Lyu et al., 2019).

2.5 OTHERS

Lyu et al. (2019) reported that about 23.5% of dam failures are caused by other reasons or combinations of two or more causes. One of the most devastating tailings dam failures in recent years happened in Córrego do Feijão Iron Ore Mine ("Dam I"), located 9 km northeast of Brumadinho, in Minas Gerais, Brazil. It suffered a sudden failure, resulting in a catastrophic mudflow that travelled rapidly downstream. The experts found several reasons behind this catastrophe (Peter et al., 2019): a) tailing pond closer to the crest resulted weak tailings near the crest; b) poor design; c) insufficient internal drainage resulted in high water levels in the dam, particularly in the toe region; d) high iron content, that is susceptible to brittle to undrained condition and e) high and intense regional rainfall reduced the strength in the unsaturated materials above the water level.

Based on the above discussion, it is evident that addressing the instability issues of existing tailings dams is one of the top priorities of the mining companies to avoid any casualties. The following section has outlined different options for stabilizing tailings dams, providing a roadmap for a safer and more sustainable future.

3. Stabilization of Tailings Dam

There are many ways to improve the stabilization of a tailings dam, such as ground improvement and creating unsaturated conditions in tailings to prohibit liquefaction and flowability. In the context of tailings dams, unsaturated conditions refer to a state where the voids in the tailings are not entirely filled with water, which can help prevent the tailings from behaving like a liquid. Other methods include treating dam materials to increase their shear strength, using geogrids, constructing a buttress at the toe of a tailings dam, etc.

Several specific methods have been investigated for ground improvement to enhance slope stability and allow an existing dam to rise. For instance, Poulos (1995) found that installing piles on unstable slopes can effectively counteract driving forces and stabilize existing dams, a testament to the success of this method. Samuel and Jordan (2018) presented a case study on the nickel tailings dam in Thompson, Manitoba, where they found that Rapid Impact Compaction of existing dam materials was a solution by densifying the loose state of dam material and improving its overall stability. Jet grouting, another ground improvement technique, has also been documented to stabilize the dam slope (e.g., Nikbakhtan et al., 2007), further reinforcing the effectiveness of these methods.

It is well established that the sensitivity of the dam stability depends on the increase in pore water pressure along a potential failure surface. Dewatering, a process of removing water from the tailings, might be an effective way of stabilizing the tailings dam where the phreatic level is high. Fourie and McPhail (1993) have shown that pumping and vertical de-watering wells successfully improved stability by lowering the phreatic surface and decommissioning the tailings dam in the Transvaal province of South Africa. After successful dewatering, Fourie and McPhail (1993) noticed no surface sloughing on the outer slope. Electrokinetic (Shang and Xu, 2019) and other dewatering techniques can also be considered for stabilizing tailings dams where excess pore water is an issue for stability.

Chemical treatment can be another solution for the tailings dam stabilization by increasing the shear strength of the dam materials. Alsharedah (2023) simulated the treated tailings as construction materials for Sweden's Aitik upstream mine tailings dam. They used emulsified polymer, a Cement Kiln Dust (CKD) mixture, and recycled Gypsum (B) as the chemical agents. They concluded that the Factor of Safety (FoS) with the treated tailings was 20% and 25% higher than that of untreated tailings. Their proposed treatment also reduced the maximum settlement by 40%. Other mixing techniques, such as mixing with biopolymer (Chen et al., 2013), have also been documented to increase the dam's stability.

The slope stabilization of the tailings dam can also be achieved using geogrids due to their high tensile strength and resistance to chemical degradation (Mudenge and Kalumba, 2023). Geogrid reinforcement is a technique where a geogrid, a geosynthetic material with a grid-like structure, is introduced to provide additional strength to the dam structure. This reinforcement introduces a second resisting moment to the conventional moment equilibrium, enhancing the dam's stability. In the study by Mudenge and Kalumba (2023), the geogrid reinforcement system approximately doubled the FoS. However, they pointed out that the efficiency of geogrid reinforcement will vary depending on the geogrid type and other factors, including the tailings' geochemical and geotechnical characteristics and the dam geometry.

Adding a toe buttress is one of the most common and widely used practices in dam retrofitting. A toe buttress is a structure that provides enough dead load near the dam's toe and effectively provides a resisting moment against slope failure. In other words, it counterbalances the driving forces that could cause the dam to fail. Ormann et al. (2013) investigated that the Aitik tailings dam in northern Sweden is stable up to the eleventh raising if the rockfill buttress was constructed at the downstream toe. Guilherme et al. (2023) concluded that the construction of a reinforcement buttress was needed to stabilize a tailings dam in Brazil. More details on buttressing, including fundamentals, design basis and case studies, are discussed in the following sections.

4. Fundamentals of Stabilizing Tailings Dam with Buttress

Among the various options, as discussed in the previous section, this paper underscores the effectiveness of stabilizing tailings dams through buttress construction. Adding a buttress at the downstream toe proves to be a robust measure in resisting a tailings dam's slope failure. Figure 1 illustrates a typical circular slope failure, which can be more complex. However, for the sake of clarity, a circular failure surface is considered in this explanation. On a dam slope, two moments typically act on the failure mass: the resisting moment stabilizing the slope and the driving moment destabilizing it. Introducing a buttress at the dam toe significantly reduces the driving moment while simultaneously increasing the resisting moment, effectively stabilizing the dam. The resisting moment and driving moments are defined as follows:

$$\text{Resisting Moment} = T * R \tag{1}$$

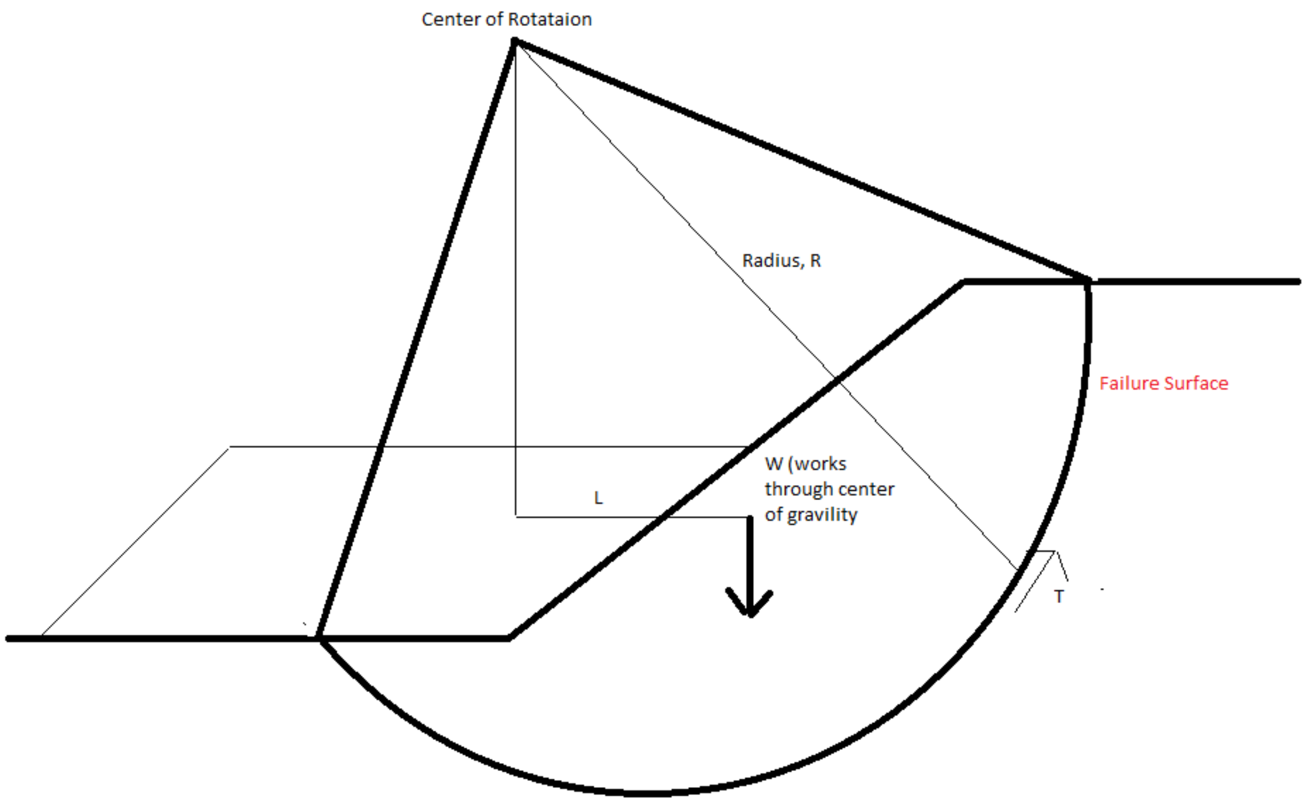
$$\text{Driving moment} = W * L \tag{2}$$

Where T = Shear Force; R= Radius (also the moment arm of the shear force); W= weight of the soil (in failure mass), and L= moment arm of the weight

Adding a toe buttress modifies the dam's centre of gravity (CG). In most cases, it lowers the moment arms, L. As a result, it increases the overall slope stability by reducing the driving moment, as shown in Eq. (2). Adding a buttress extends the failure surface through the buttress materials. Shear Force, T, is intricately linked to the soil's cohesion and friction. Therefore, the use of high-strength buttress materials (with higher cohesion and friction angle) plays a pivotal role in enhancing the resisting moment (Eq. (1)), thereby bolstering the overall strength and stability of the dam. However, it is crucial to note that optimizing buttress materials is a critical step. While it can increase the weight, W, and the driving moment, as shown in Eq. (2), careful planning can prevent these issues. The buttress volume/quantity needs to be optimized to avoid a scenario where the overweight of the rockfill buttress may increase the sliding force and reduce the stability. The optimum design of buttressing ensures slope stability and reduces the construction cost by utilizing the minimum volume of a rockfill, a key consideration in any project.

FIGURE 1

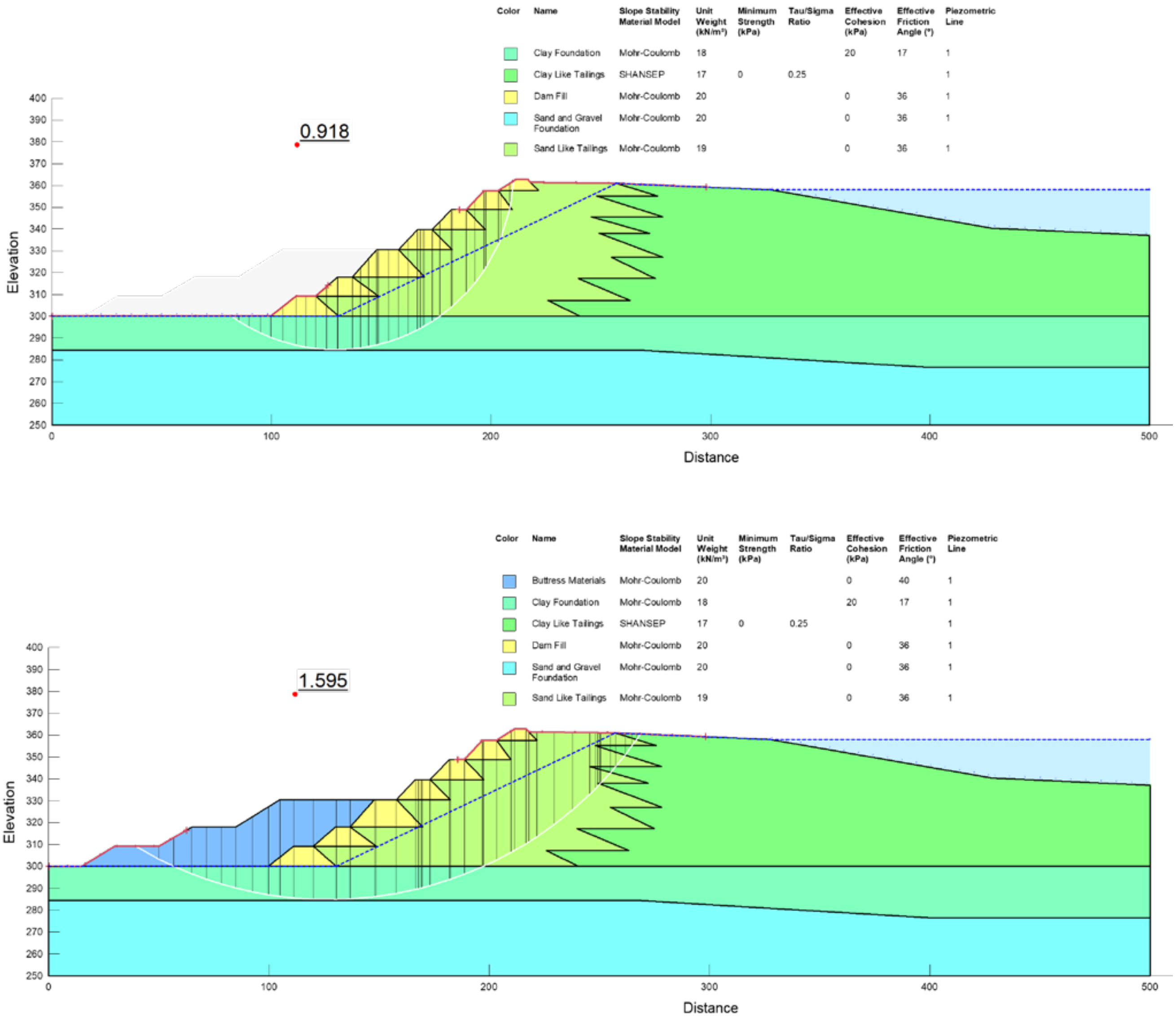
Failure Surface on the slope without buttress



The authors have designed a typical tailings storage facility using GeoStudio 2021.4 (Slope/W) for demonstration purposes unrelated to specific projects, which is likely less complicated than an actual tailings storage facility. The strength of the materials used in this design is that they are typical values and are not based on any field or lab data. To evaluate the FoS, the authors used the Limit Equilibrium Method (LEM). As seen in Figure 2, the FoS is only 0.918 without the buttress, whereas after adding the buttress, the FoS increases to 1.595. As shown in the figures, the buttress extends the failure surface through the buttress materials, which is a typical scenario. However, the failure surface might change based on material properties, geometry, etc. This typical design not only showcases the potential of a buttress to enhance the stability of an existing upstream tailings dam but also opens up a world of possibilities for further research and innovation in the field.

FIGURE 2

Slope Stability Analysis results before (Upper) and After (Lower) Buttress construction



5. The Design Basis of Buttressing

There is no unique way of designing tailings dam buttresses, as every dam is unique in terms of tailings properties (such as particle size distribution, density, and chemical composition), mine site conditions (including topography, soil type, and climate), the storage capacity of the dam, and the available construction materials (such as rockfill, or compacted soil). There are national, state, or local governmental statutes, laws, regulations, ordinances, or other government directives for tailings dams and buttresses design, operation, and safety. The Global Industry Standard on Tailings Management (GISTM), a comprehensive framework developed by a coalition of industry leaders, is crucial in providing a safe tailings facility management framework. It sets clear standards when designing dams and buttresses, ensuring that all aspects of design and construction are considered. The Canadian Dam Association (CDA), the Australian National Committee on Large Dams (ANCOLD), and the International Commission on Large Dams (ICOLD) can be used as guidelines. Many mining companies, such as Glencore, have developed standards and guidelines for their mining sites, reflecting each site's unique challenges and conditions.

The initial step in tailings dam or buttress design is the crucial process of dam classification, which involves assessing factors like population at risk and incremental losses. The details of the dam classification, which can be found in references like CDA (2019), ANCOLD (2019), or GISTM (2020), provide a comprehensive understanding of the dam's potential risks and vulnerabilities. The dam classification, determined through a dam break analysis and compared with the guidelines and standards mentioned above, guides the selection of earthquake loading and Inflow Design Flood (IDF) loading conditions for the design analysis. For example, Table 1 presents the recommended earthquake loading for designing based on dam classification. The authors refer to the CDA (2019) and ANCOLD (2019) for IDF loading, the most severe inflow flood to be considered in the design. Conducting a site-specific seismic hazard assessment is crucial for adapting the peak ground acceleration (PGA) corresponding to the Annual Exceedance probability (AEP) for liquefaction potential and stability analysis.

Buttress is a pivotal step in the design process, significantly enhancing the safety of an existing tailings dam. The primary objective is to directly increase the dam's FoS, a critical ratio representing the available shear resistance along the potential failure plane, to the activating shear forces along the same plane. This understanding of FoS is vital in the design process, as it ensures that the dam is strong enough to withstand potential stress. CDA (2019) and ANCOLD (2019) have recommended that the FoS values be considered under different loading conditions, as shown in Table 2.

Stability analysis, a complex process that involves assessing the dam's ability to resist sliding and overturning under various conditions, is a crucial stage in buttress design. The goal is to find a buttress geometry that requires the lowest material volume and simultaneously provides the target FoS under different loading conditions to stabilize the dam. The loading condition will depend on several factors, including liquefaction potential, phase of operation, etc. The input data for slope stability analysis can be adopted from Geotechnical Investigations, laboratory analysis and instrumentation data. Different commercial software, such as GeoStudio (geo slope), is available for performing stability analysis. Numerical Analysis (using Flac or Plexis) can also be performed for deformation analysis under earthquake loading to support the design if needed. The Engineer of Record (EoR) should verify the design, and any comments from the Independent Technical Review Board (ITRB) should be incorporated.

TABLE 1

Recommended Design Earthquake Loading

Dam Category	CDA (2019)	ANCOLD (2019)		GISTM (2020)	
	Annual Exceedance Probability (AEP)	Operating Basis Earthquake (OBE)	Safety Evaluation Earthquake (SEE)	Operations and Closure (Active care)	Passive-Closure (Passive Care)
Low	1/100 AEP	Commonly 1 in 475 AEP	Probabilistic ground motion: 1 in 1,000 AEP	1/200	1/10,000
Significant	Between 1/100 and 1/1000	Commonly 1 in 475 AEP	Probabilistic ground motion: 1 in 1,000 AEP	1/1,000	1/10,000
High	1/2475	High A,B,C: Commonly 1 in 475 AEP up to 1 in 1,000 AEP	Probabilistic ground motion: High A: 1 in 10,000 AEP High B: 1 in 5,000 AEP High C: 1 in 2,000 AEP	1/2,475	1/10,000
Very high	Between 1/2475 and 1/10,000 or MCE	NA	NA	1/5,000	1/10,000
Extreme	1/10,000 or MCE	Commonly 1 in 475 AEP up to 1 in 1,000 AEP	The greater of: Ground Motion from the MCE on known active faults or probabilistic ground motion Extreme: 1 in 10,000 AEP	1/10,000	1/10,000
High/Extreme	NA	NA	NA		

TABLE 2

Recommended factors of safety

CDA (2019)			ANCOLD (2019)		
Loading Condition	**Minimum factor of safety**	**Slope**	**Loading Condition**	**Minimum for Tailings Dams**	**Shear strength to be used for evaluation**
During or at the end of construction	>1.3 Depending on risk assessment during construction	Typically, downstream	Long-term drained	1.5	Effective Strength
Long-term	1.5	Downstream	short-term undrained (potential loss containment	1.5	Consolidated Undrained Strength
Full or partial rapid drawdown	1.2-1.3	Upstream	short-term undrained (no potential loss of containment)	1.3	Consolidated Undrained Strength
Pseudo-static	1.0		Post-seismic	1.0 -1.2	Post Seismic Shear Strength
Post-earthquake	1.2				

6. Designing a Buttress

The first and most crucial step in designing a buttress is to develop the geometry for the existing tailings storage facilities. The meticulous capture of the tailings and foundation stratigraphy, based on geotechnical investigations such as drilling Bore Holes (BHs), Cone penetration tests (CPT), and survey data of the existing topography, is a testament to the crucial role of geotechnical engineers. The number of BHs and CPTs should be sufficient to capture the right profile, as a higher number of these investigations can provide a more accurate and detailed understanding of the site's conditions. Considering the highest historical water level, the water level should be assigned based on the most up-to-date Vibrating Wire Piezometers (VWP) or any other piezometer readings. The most critical section should be selected for the analysis based on height, slope, and other necessary conditions. Depending on the dam length and other conditions, more than one critical section might be needed for the stability analysis.

The second most critical part of designing a buttress is estimating the accurate geotechnical properties of the existing dam, tailings, and foundations. Most materials models used in slope stability analysis are Mohr-Coulomb, SHANSEP, Undrained (Phi=0), and Normal-shear strength function (nonlinear Mohr-Coulomb). The choice of materials model depends on the types of materials (granular or cohesive), conditions (saturated or unsaturated) and other properties (e.g., susceptibility to the liquefaction). The most crucial parameters of the materials are unit weight, friction angle, cohesion, undrained shear strength, and residual strength. In most cases, the material properties are derived from empirical relationships based on in-situ testing, including Standard Penetration Test (SPT), Cone Penetration Test (CPT), Vane Shear Test (VST), etc., and later verified from laboratory testing such as Direct Shear test, Monotonic Cyclic and Post-Cyclic Direct Simple Shear & Triaxial tests and Consolidation (Odometer) tests.

Unit weight is one of the basic parameters used in slope stability analysis for all material models. The laboratory can determine it using a density test on the undisturbed samples. The cohesion and friction angle, the critical parameters in determining the stability of the structure for the Mohr-Coulomb materials model, can be estimated from the triaxial testing based on the Mohr-Coulomb failure criteria and Mohr's circle using Eq. (3) where τ is the shear strength, C is the cohesion, σ is the normal stress, and Φ is the friction angle:

$$\tau = C + \sigma \tan\Phi \qquad (3)$$

The SPT method is a proven and reliable technique that records the hammer blow count or SPT-N values. These values can be used to estimate the friction angle for granular soils in the absence of the undisturbed soil sample. The estimation is done using an empirical relationship as suggested by Wolf (1989) (Eq. 4) or Khulhawy and Mayne (1990) (Eq. 5) or other accepted relationships which can also be checked as suggested by Peck (1974) (Table 3) Where $(N_1)_{60}$ or $(N)_{60}$ are the corrected SPT-N values. Direct shear tests are recommended if undisturbed samples are available for lab testing.

$$\Phi' = 27.1+0.3 * (N_1)_{60} - 0.00054 * [(N_1)_{60}]^2 \qquad (4)$$

$$\Phi' = \tan^{1}\left[\frac{N_{60}}{12.2+20.3\frac{\sigma'}{P_a}}\right]^{0.34} \qquad (5)$$

TABLE 3

SPT -Standard Penetration Number and Frictional Angle for Granular Soils (Peck 1974)

SPT-N value	Density of Sand	Φ(degree)
<4	Very loose	<29
4-10	loose	29-30
10-30	Medium	30-36
30-50	Dense	36-41
>50	Very Dense	>41

For cohesive soils, the undrained shear strength (S_u) can be measured directly by field VSTs and supported by the laboratory Unconsolidated Undrained (UU) test. The undrained shear strength values are also estimated from SPT-N values as suggested by Terzaghi and Peck (1967) when the soil consistency is too stiff to perform the VSTs and challenging to collect undisturbed samples for advanced testing (Table 4):

TABLE 4

Consistency and Undrained Shear Strength of cohesive soil (Terzaghi and Peck, 1967)

SPT-N value	Consistency	Undrained Shear Strength, kPa
<2	Very Soft	<12
2-4	Soft	12-25
4-8	Firm	25-50
8-15	Stiff	50-100
15-30	Very Stiff	100-200
>30	Hard	>200

The residual undrained shear strength, a crucial parameter in stability analysis, can be determined from laboratory results of the post-cyclic direct simple shear test or triaxial test. Peak Undrained Shear Strength Ratio (Sand-like Tailings), τ/σ can also be estimated based on the CPT tests as suggested by Olson & Stark, 2003 by using Eq (6) and the Peak Undrained Shear Strength (Clay-like Tailings), τ can be estimated by widely used Eq. (7):

$$\frac{\tau_{yield}}{\sigma'_{vo}} = 0.205+0.0143\ (q_{c,1}) \pm 0.04\ (\text{where } q_{c,1} < 6.5\text{MPa}) \quad (6)$$

$$\tau = (S_u)_{CPT} = \frac{q_t - \sigma_{v0}}{N_k} \quad (7)$$

Where q_t is the corrected tip resistance from CPT, σ_{vo} is the total overburden pressure, and N_K is the cone factor.

Robertson (2022) suggested the relationship to determine the post-liq shear strength ratio for sand-like tailings (When Ic <3, $Q_{tn,cs}$ < 80; Limitation: σ'_{vo} <300kPa) by Eq. (8) and clay-like tailings by Eq. (9) based on the CPT tests. It should be noted that the values determined from CPT correlations should be verified with lab testing results from Post-Cyclic Direct Simple Shear or Triaxial tests:

$$\frac{S_{u\,(liq)}}{\sigma'_{v0}} = 0.0007\exp(0.084Q_{tn,cs}) + 0.3/Q_{tn,cs} \quad (8)$$

$$\frac{S_{u\,(liq)}}{\sigma'_{v0}} = \frac{f_s}{\sigma'_{v0}} \text{ When Ic} > 3 \quad (9)$$

Where S_u is the undrained shear strength, f_s is the sleeve friction, Ic is the soil behaviour type index, and $Q_{tn,cs}$ normalized cone resistance.

Static and seismic liquefaction potential evaluations on the foundation overburden soils should be carried out based on the CPT and SPT data. The seismic liquefaction assessment can be completed based on the simplified procedure recommended by Idriss and Boulanger (2014), while the static liquefaction assessment can be completed based on the state parameter criteria recommended by Jefferies and Been (2016). If the dam foundation is considered liquefiable statically or seismically, a post-liquefaction analysis is recommended. This analysis is crucial as it assesses the dam's stability after a potential liquefaction event, providing a comprehensive understanding of its safety. Otherwise, a pseudo-static analysis should be used to assess the dynamic dam stability as a screening. This type of analysis is used to simulate the effects of seismic forces on the dam, providing a preliminary assessment of its stability under dynamic conditions. A numerical analysis model such as Plaxis or Flac can be used for dynamic analysis to conform to the dynamic effect on the dam.

When the existing tailings dam's critical sections are generated, material properties are estimated, and liquefaction analysis is performed, the stability analysis using different software such as GeoStudio / Slide or other recognized tools is paramount. According to the guidelines, the FoS must meet the minimum requirement, as an unstable dam can lead to catastrophic consequences. If it doesn't, a buttress can be added at the toe of the dam and optimized by changing the width and height of the buttress until the target FoS is achieved. This stability analysis is not just a step but a critical task ensuring the entire structure's safety and reliability, and the potential consequences of an unstable dam underscore its importance.

7. Case studies

In the following sub-sections, two case studies have been selected from two different continents, where designing phases show that buttress at the downstream toe of the dams can effectively solve the stability issue of the tailings dam.

7.1 CASE STUDY #1

The Aitik tailings dam, primarily constructed using the upstream method, is near Gällivare in northern Sweden. The dam experienced a significant failure in 2000, spanning over 120 m of its length. This event, which underscored the importance of dam stability, prompted numerous subsequent studies on the Aitik tailings dam (e.g., Ormann et al., 2013; Alsharedah, 2023). One such study by Ormann et al. (2013) focused on fortifying the dam's slope by incorporating rockfill berms on the downstream toe. This approach was deemed effective as a substantial volume of rockfill was readily available at a short distance from the TSF. The study also detailed the optimization of the buttress design, with a typical section featuring a rockfill buttress shown in Figure 3.

The authors undertook a meticulous finite element analysis using PLAXIS 2D to model the dam's staged construction and optimize the buttress's volume. The model parameters were derived from either lab testing or the available literature, ensuring a comprehensive and reliable foundation for the analysis. The phreatic level of the dam was determined using data obtained from piezometers installed at the dam. The dam was assumed to be constructed in eleven stages (from level 376 m to 410 m), with each stage thoroughly accounted for in the analysis. The consolidation analyses were performed for staged construction to determine strength gain due to the dissipation of excess pore pressures. The Mohr-Coulomb (MC) model was chosen for all the dam's materials (tailings, rockfill and filter), ensuring a comprehensive and accurate representation of the dam's materials. A rockfill buttress was strategically placed on the downstream side, a key factor in improving the slope stability. The volume of the rockfill bank P (Figure 4) was optimized by changing the width and height of the buttress until a FoS of 1.5 was achieved according to the Swedish safety guidelines. Following a similar procedure, the rockfill buttress Q, R, S, T, U, V, and W were assessed and designed for the fourth to tenth raisings, respectively (Figure 4).

The slope stability was sufficient during the eleventh raising, so no rockfill buttress was added from this raise. This careful study demonstrated that the dam is stable up to the eleventh raising (level 410 m) only if the rockfill buttress was deliberately added to the downstream slope.

FIGURE 3

Cross section of dam E-F (Ormann et al., 2013)

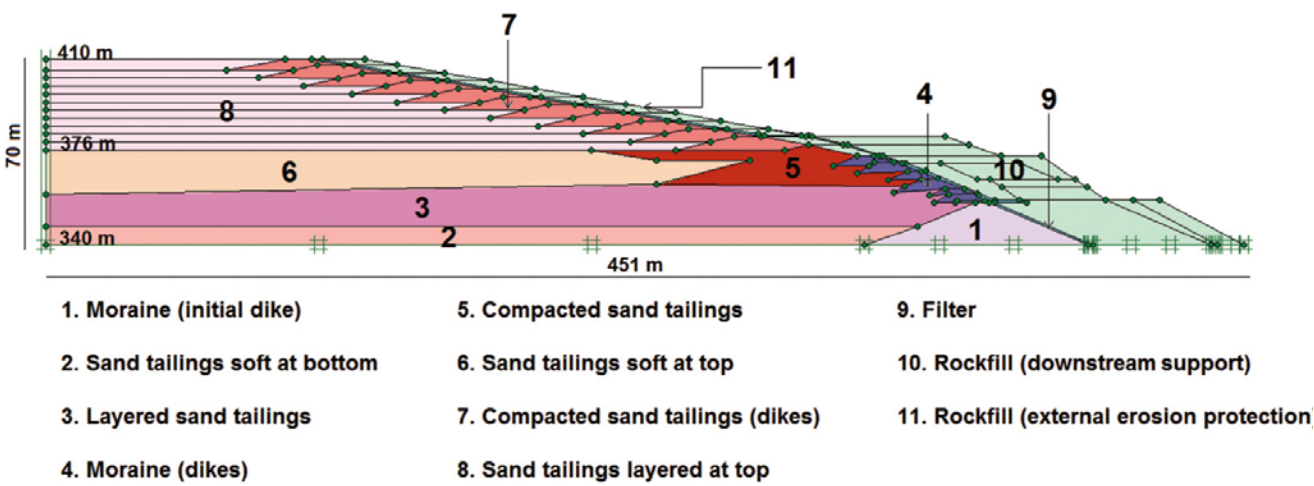
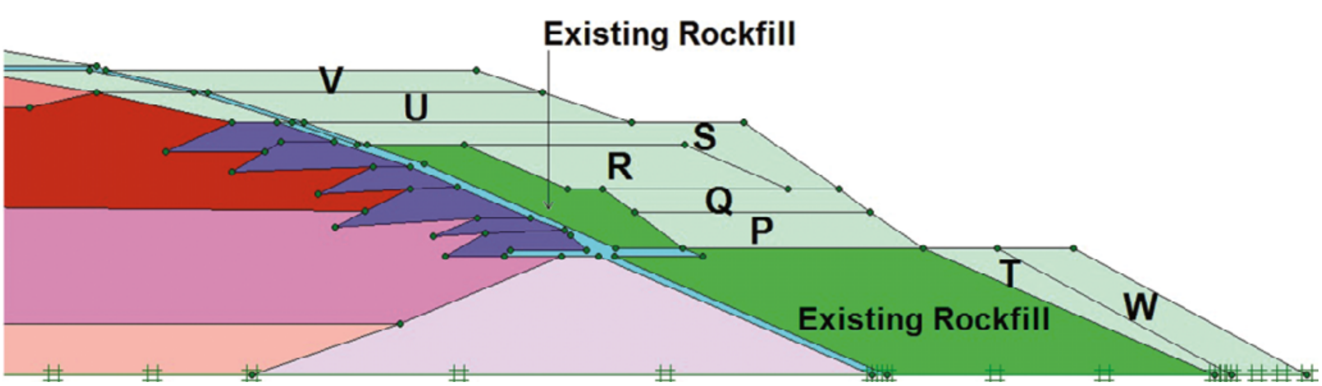


FIGURE 4

Placement of the rockfill banks on the downstream side to increase slope stability during construction (Ormann et al. 2013)



7.2 CASE STUDY #2

Guilherme et al. (2023) presented a study to simulate the stability of a dam in Brazil after reinforcement with a buttress at the downstream toe. The starter dike was designed with a 1H:2V slope. The dam was raised with a 1H:4V slope and constructed with tailings underflow. All the overflow was deposited on the TSF, creating a tailings beach. The structure has a 1 m thick drainage system of sand and gravel. The authors assessed the stability of the dam in two stages. Firstly, they evaluated the FoS under the dam's current condition, using different failure surfaces, and compared it with CDA and Brazilian regulators' recommendations. Secondly, they assessed the buttress construction at the downstream toe to reinforce the structure, analyzing the excess porewater pressure generated and the deformation in the foundation soil during and after construction. To evaluate the FoS, they used the Limit Equilibrium Method (LEM) in the initial condition (without buttress); a coupled analysis was performed using SLOPE/W and SEEP/W. The Morgenstern – Price method was applied. SIGMA/W was used to simulate the buttress construction, considering linear elastic parameters. Figure 5 shows a typical section of the dam and buttress used in their study.

The authors found the structure did not meet the minimum FoS without a buttress at the downstream toe under non-circular, optimized circular, and non-circular surface failure. However, after reinforcing with buttress, the dam met the requirements of CDA and Brazilian regulators' recommendations (by ABNT NBR 13028), achieving an FoS higher than 1.50 as the criterion adopted in their study. The excess pore water pressure generation during and after the construction was evaluated using SIGMA/W. Figure 7 shows the variation of $\bar{B}$ over at a single point, tagged as a "monitoring point" in the figure. The highest $\bar{B}$ found at the beginning of the buttress construction was 0.67, which decreases over time and becomes zero after approximately 60 days of construction. $\bar{B}$ equals 0, indicating the final dissipation of the generated pore pressure. Figure 6 shows that the calculated FoS (F.S) is lower than 1.50 at the beginning of the construction due to the high generation of porewater pressure. At the end of the construction, on the fourteenth day, the porewater pressure dissipates. The calculated FoS (F.S) becomes higher than 1.50 and reaches the maximum of around 1.65 after 55 days. The study concludes that the construction of a reinforcement buttress was needed to stabilize the dam. However, it might take some time to dissipate the pore water pressure and achieve the target FoS.

FIGURE 5

Dam cross-section with the preliminary buttress (in dark red) (Guilherme et al.,2023)

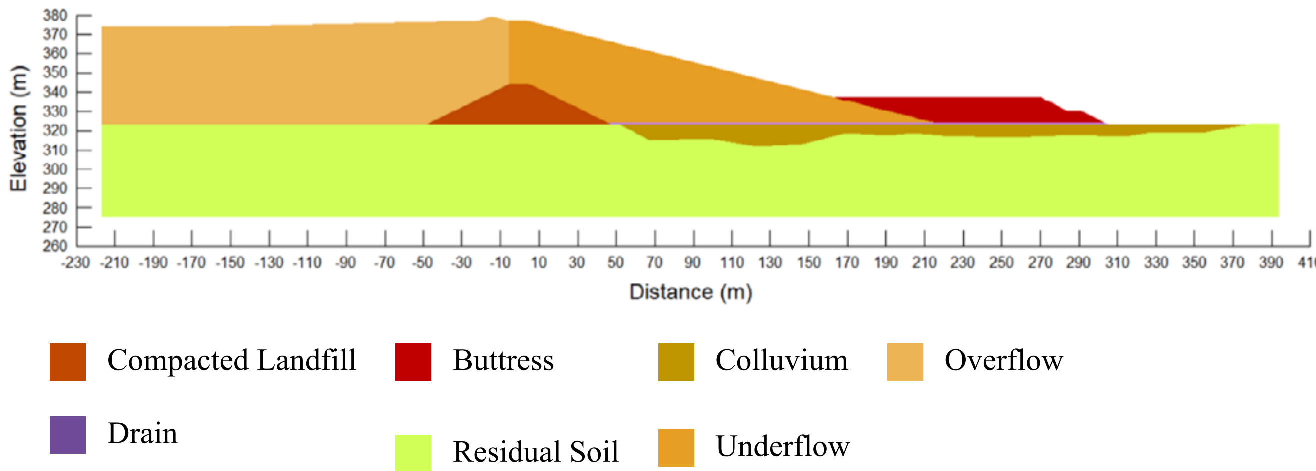


FIGURE 6

FoS over time (Guilherme et al., 2023)

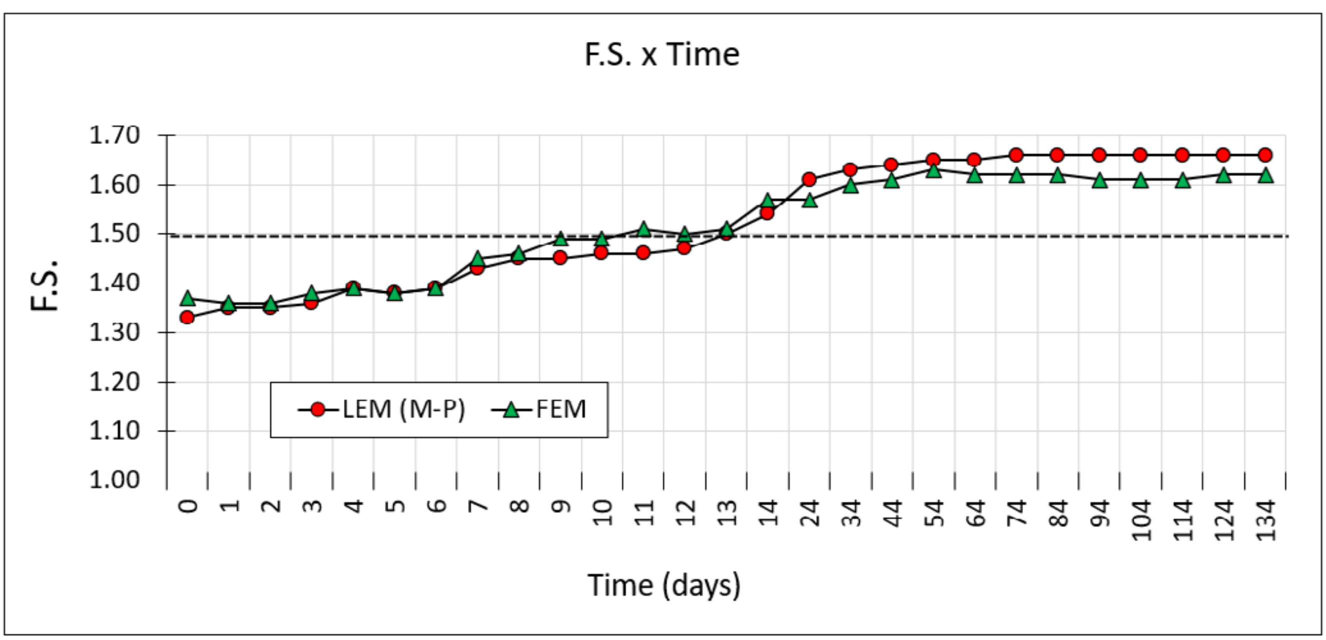
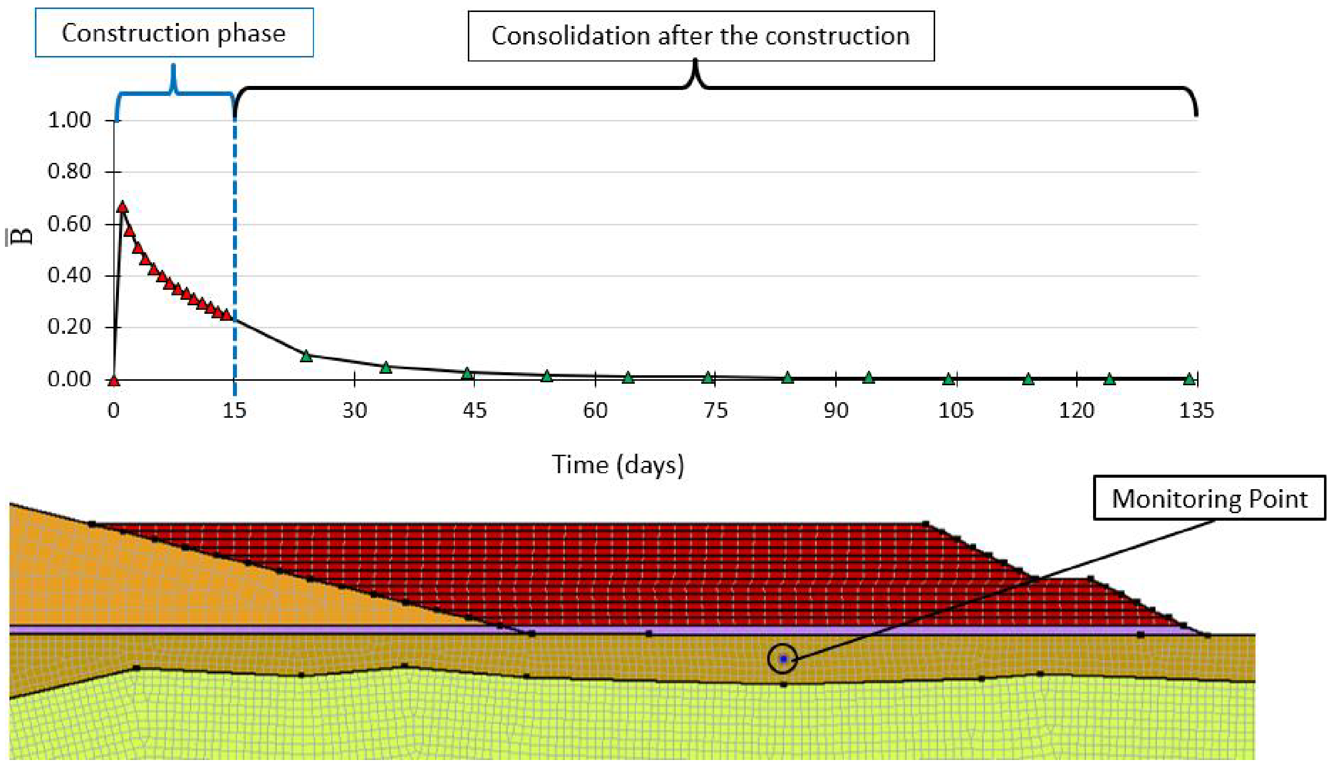


FIGURE 7

$\bar{B}$ summary over time
(Guilherme et al.,2023)



8. Conclusions

This paper focuses on fundamentals, design basis, and three case studies in which buttressing has been demonstrated as a viable option for stabilizing tailing dams. The following conclusions can be drawn from the discussion:

- The tailings dam can fail for different reasons, including but not limited to earthquakes, seepage, foundation failure, and over-topping, underscoring the critical need for robust design and maintenance in dam construction.
- There are many options to stabilize the tailings dam, including ground improvement, treating dam materials, buttressing at the downstream toe, dewatering, geogrid application, etc.
- Buttressing is one of the effective solutions for stabilizing tailings dams. The optimum buttress configuration increases the overall slope stability by reducing the driving moment and improving the resisting moment.
- Appropriate guidelines or standard requirements must be followed while designing the buttress without conflicting with local laws and regulations.
- The paper presents two compelling case studies from open literature. Case study 1 showcases the successful optimization of buttress geometry to stabilize a tailings dam. Case study 2, despite the time it took to achieve the target FoS, illustrates the effectiveness of buttressing in stabilizing a tailings dam once the pore water pressure has disappeared. These successes should instill confidence in the potential of buttressing as a solution.

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