AtkinsRéalis

TECHNICAL JOURNAL

Engineering excellence around the globe

Volume 5 | Issue 2 | 2023

Foreword

Welcome to the tenth edition of our AtkinsRéalis Technical Journal, established to showcase the fantastic depth and breadth of our engineering expertise and technical excellence across a wide range of disciplines and domains. This edition highlights the work we have been doing to improve efficiency and safety of designs, the focus we have on extending the life of existing assets whilst maximising the life of new assets and the procedures we have introduced to optimise risk and quality management for our clients. Examples of these come from our teams engaged in structural engineering, fire engineering, systems engineering, materials and water management.

In improving design efficiency and safety, we have created design rules for stainless steel angle section members under compression and bending to offer substantially more accurate and consistent resistance predictions compared to existing codified design rules. We have reviewed recent developments in sprayed concrete tunnel lining design and evaluated the challenges these pose for efficient design and construction. And we have evaluated optimum ventilation strategies for tunnel safety during the self-evacuation phase using a series of hot smoke demonstrations.

In extending the life of existing and new assets, we have proposed an extension to the life of graphite-moderated advanced gas-cooled nuclear reactors by assessing the timing and extent of cracking of fuel bricks under irradiation. We have developed predictive models for bursts of sewage rising mains to enable proactive planning for investment, replacement, and rehabilitation strategies before bursts occur. And we have developed a new more durable surface course specification for the M25 London orbital motorway in collaboration with National Highways, Connect Plus Services and its supply chain.

To optimise risk and quality management for the UK Ministry of Defence, we have applied systems engineering principles to develop a pragmatic Systemic Risk Management approach together with an approach aligned to ISO 15288 for assuring delivery, based on applying an Integrated Test, Evaluation and Acceptance (ITEA) planning process.

The above examples provide only a small insight into the wealth of innovation that AtkinsRéalis creates day to day.

I hope you enjoy the selection of technical papers included in this edition as much as we have enjoyed compiling them.

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About the Cover

*T*he Torness Nuclear Power Station, East Lothian, Scotland. Work was carried out to extend the life of graphite-moderated advanced gas-cooled nuclear reactors by assessing the timing and extent of cracking of fuel bricks.

Photo credit: EDF Energy

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01 Structural Engineering

Design of Pin-Ended Stainless Steel Equal-Leg Angle Section Columns and Beam-Columns

Abstract

The behaviour and design of pin-ended stainless steel equal-leg angle section members under compression and compression plus minor-axis bending are investigated herein. The studied members are cylindrically pinned about the minor axis. An experimental investigation on hot-rolled stainless steel equal-leg angle section members is first presented. Numerical models are developed and validated against the new experimental data. A numerical parametric study is then presented considering both hot-rolled and cold-formed stainless steel angle section columns alongside beam-columns with a wide range of slenderness values. Finally, new design proposals for pin-ended stainless steel equal-leg angle section members under compression and combined compression and minor-axis bending are developed and verified against the results of the existing and new physical experiments and numerical simulations. The proposed design rules are shown to offer substantially more accurate and consistent resistance predictions compared to existing codified design rules.

Keywords

Equal-leg angles; EC3 design procedures; Pin-ended angles; Angle section beam-columns

1. Introduction

Angle section members are used in a range of structures such as towers and trusses alongside the bracing systems in buildings and bridges. Even though studies on angles can be traced back to the 1920s, their behaviour continues to pose challenges with current structural design provisions in international standards being shown to have significant limitations. New resistance functions for steel angle section members recently developed for the US [1,2,3] and European [4,5,6,7] design frameworks have led to substantial improvements in the consistency and accuracy of their load-carrying capacity predictions. However, little attention has been paid to pin-ended angle section columns under compression within the scope of Eurocode 3. In addition, angles are often loaded eccentrically (e.g., when connected through one leg) such that the point of action does not coincide with the cross-section centroid (see Figure 1), resulting in the member experiencing combined compression and bending. It is therefore crucial to study their behaviour under combined loading.

Recently, Behzadi-Sofiani et al. [4, 5] developed new design procedures for fixed-ended steel and stainless steel angle section columns. However, the proposed method cannot be applied to pin-ended angles. This is primarily owing to the shift of the effective centroid $e_{N,v}$ along the major *u-u* axis in slender angle section columns as a result of redistribution of axial stresses caused by local buckling, which induces additional eccentricity (see Figure 2) and implies that pin-ended angle section columns should be treated as beam-columns. For equal-leg angles that are initially eccentrically loaded with respect to the minor axis, depending on the direction of the initial eccentricity, the resulting bending moments may be either exacerbated (i.e., the shift in effective centroid further increases the eccentricity) or relieved (i.e., the shift in effective centroid reduces the eccentricity). Consequently, the resistance of the member will either be reduced or increased. The influence of the shift of the effective centroid on the total eccentricity e_T is presented in Figure 3, where the shift of the effective centroid increases and reduces the total eccentricity when the initial eccentricity is applied towards the tips (positive direction - see Figure 3a) and the corner (negative direction - see Figure 3b), respectively.

FIGURE 1

Dimensions and principal axes of equal-leg angles

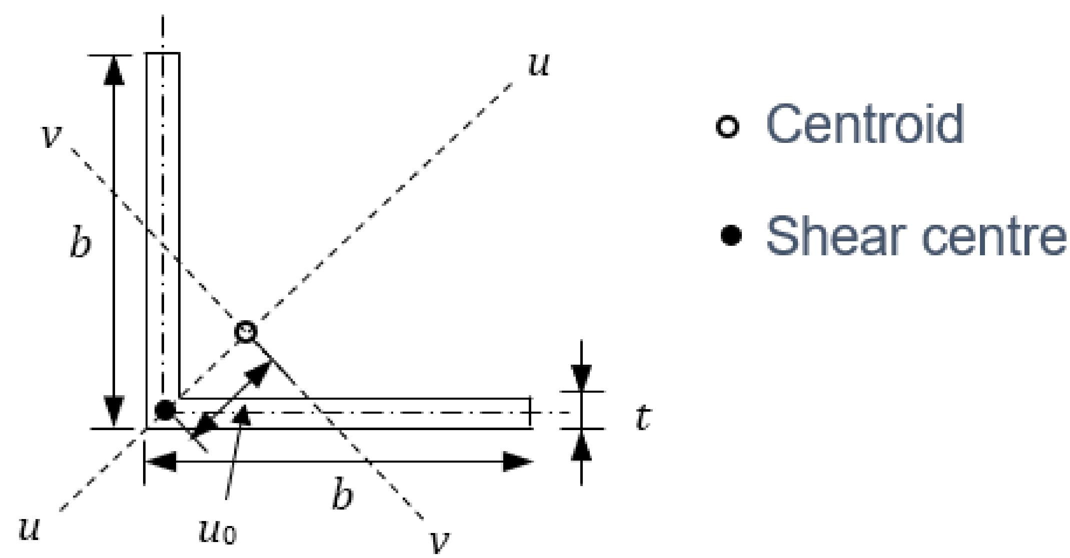


FIGURE 2

Axial stress distribution and geometric and effective centroid positions of equal-leg angle section under compression (a) prior to and (b) after local buckling

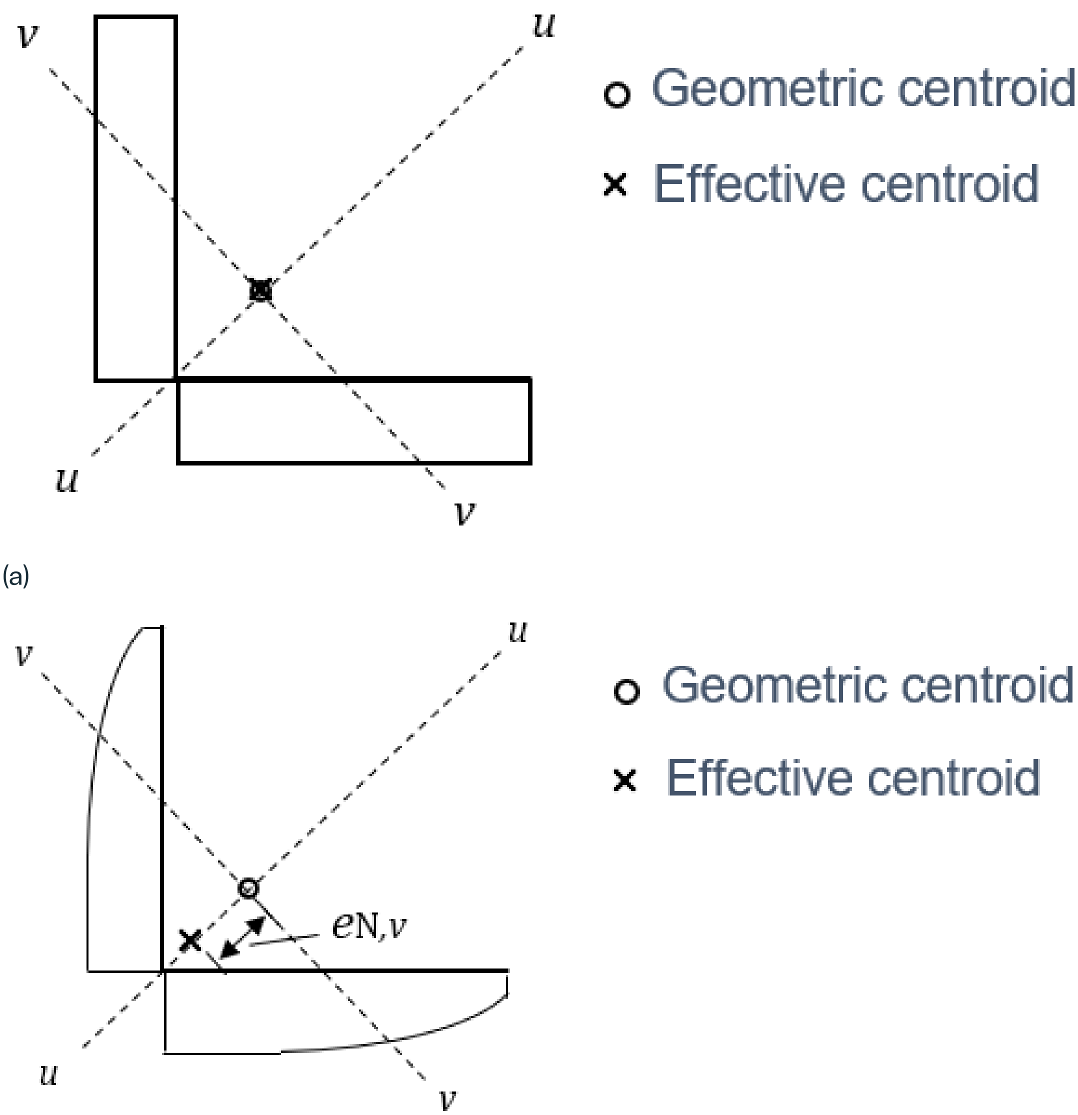
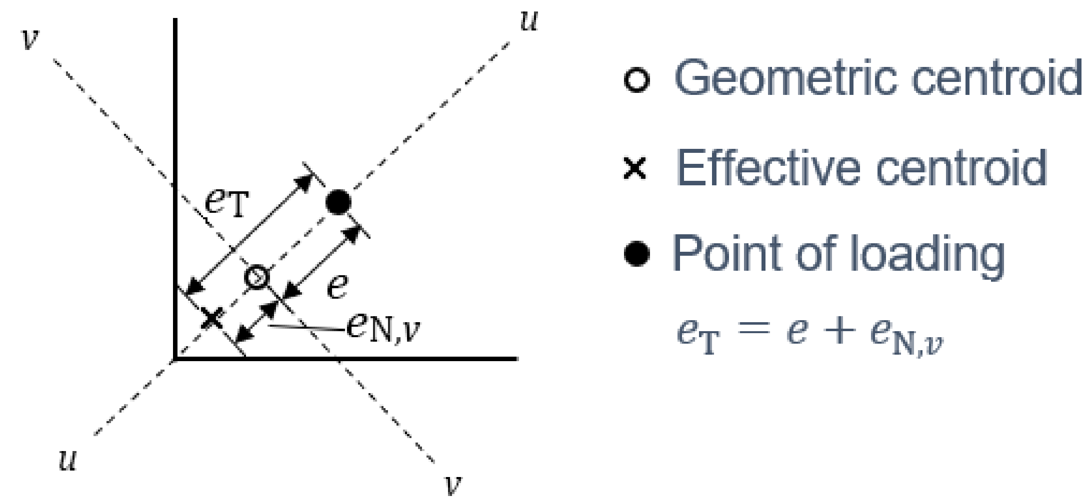
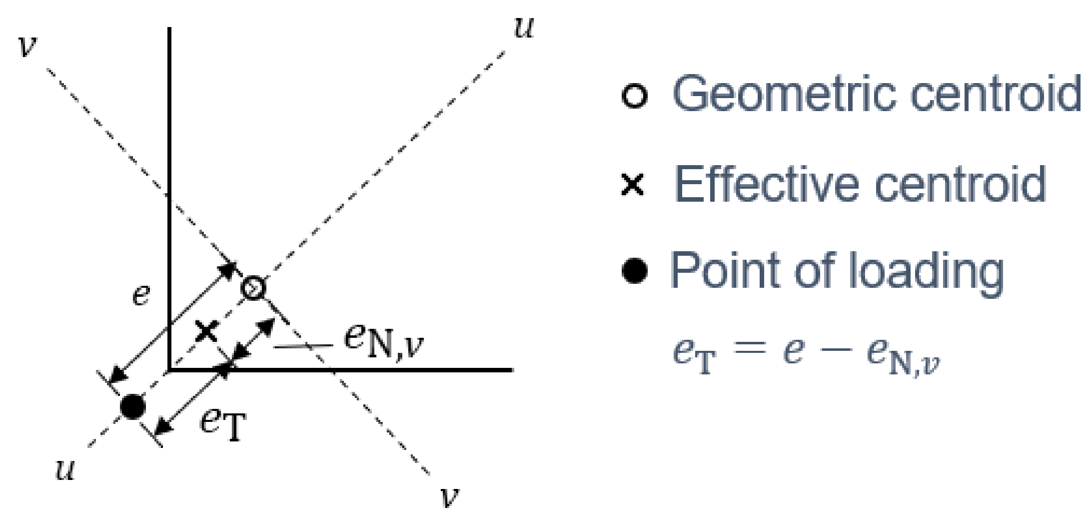


FIGURE 3

Influence of the shift of the effective centroid for cases where the initial eccentricity is towards the (a) tips and (b) corner of the cross-section



(a)



(b)

Building on previous work on fixed-ended angle section columns [4,5] and angle section beams [6,7] along with an expression developed to predict the shift of the effective centroid [8], the current aim is to establish a new approach for designing pin-ended stainless steel equal-leg angle section members subjected to compression and combined compression and minor-axis bending suitable for incorporation into EN 1993-1-4 [9].

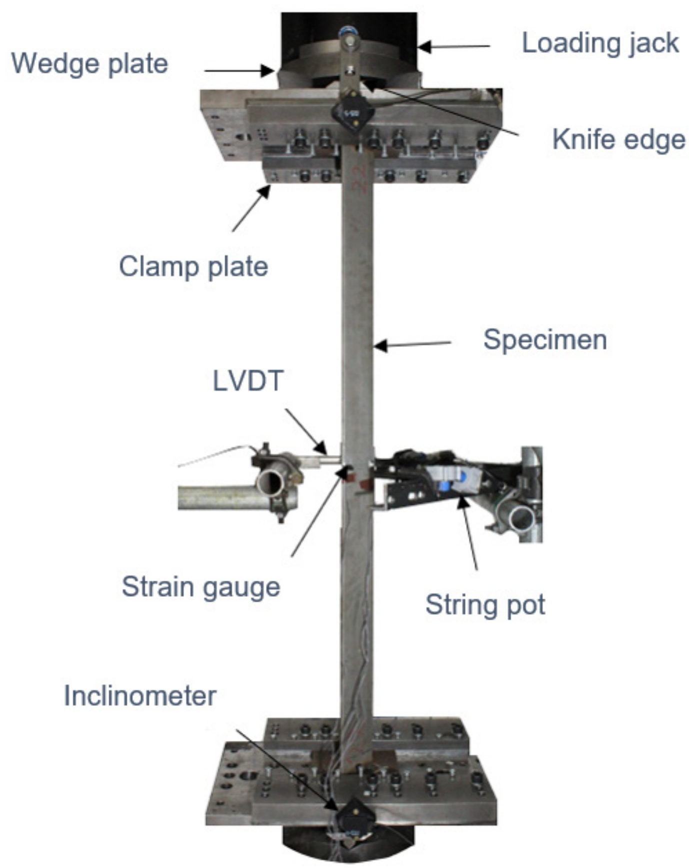
2. Experimental Investigation

Tests on 19 hot-rolled Grade 1.4307 austenitic stainless steel equal-leg angle section members – 5 columns and 14 beam-columns – were performed to study their buckling response and load-carrying capacity. The members were cylindrically pinned about the minor axis. For the column tests, the member lengths L were varied to cover a range of member slenderness $\bar{\lambda}$ values, where minor-axis flexural buckling was critical for all members. Two member lengths were chosen for beam-column tests, where torsional-flexural buckling was critical for one and minor-axis flexural buckling was critical for the other. The initial loading eccentricities were varied in size and direction to study the ultimate strength of stainless steel equal-leg angles subjected to a range of combinations of axial compression and bending.

The buckling tests were conducted using an Instron 2000 kN hydraulic testing machine under displacement control. Knife edges were used at both ends of the members to allow rotation about the minor axis and prevent rotation about the longitudinal and major axes, which created cylindrically pin-ended boundary conditions. End plates were welded to both ends of each specimen, which were inserted into special clamps connected to the knife edges. The specimens were then adjusted to achieve the required initial loading eccentricity before tightening the bolts on the clamps. Two LVDTs were used to measure the end-shortening and minor-axis lateral deflection of the specimens at mid-height. Four string pots, attached to the corner and the tips of both legs of the angle section members, were employed to measure the twist at mid-height. Six electrical resistance strain gauges were affixed to the specimens at mid-height to measure the longitudinal strains at the corner and the tips of the angles. The test set-up is presented in Figure 4.

FIGURE 4

Photographic representation of column and beam-column buckling test set-up



A comparison of the column buckling test data with the flexural buckling curve (with limiting slenderness $\bar{\lambda}_0$= 0.2 and imperfection factor α = 0.76) for angle section members set out in prEN 1993-1-4 [10] is presented in Figure 5a, where $\chi = N_u / Af_y$ is the buckling reduction factor with N_u being the ultimate load reached during the test. Note that this curve can be used because the predicted shift of the effective centroid is zero. Comparisons of the beam-column test data with the interaction curve for I-sections, set out in prEN 1993-1-4 [10], are presented in Figures 5b and 5c for specimens with L=400 mm and L=1400 mm, respectively, where the ultimate load N_u and moment M_u are normalised against the compression $N_{(b,prop)}$ and bending moment $M_{(b,prop)}$ buckling resistance proposed in [5,7]. Both the column and beam column test results generally follow the trend of the buckling curve and interaction curves, respectively, and lie consistently on the safe side.

3. Numerical Modelling

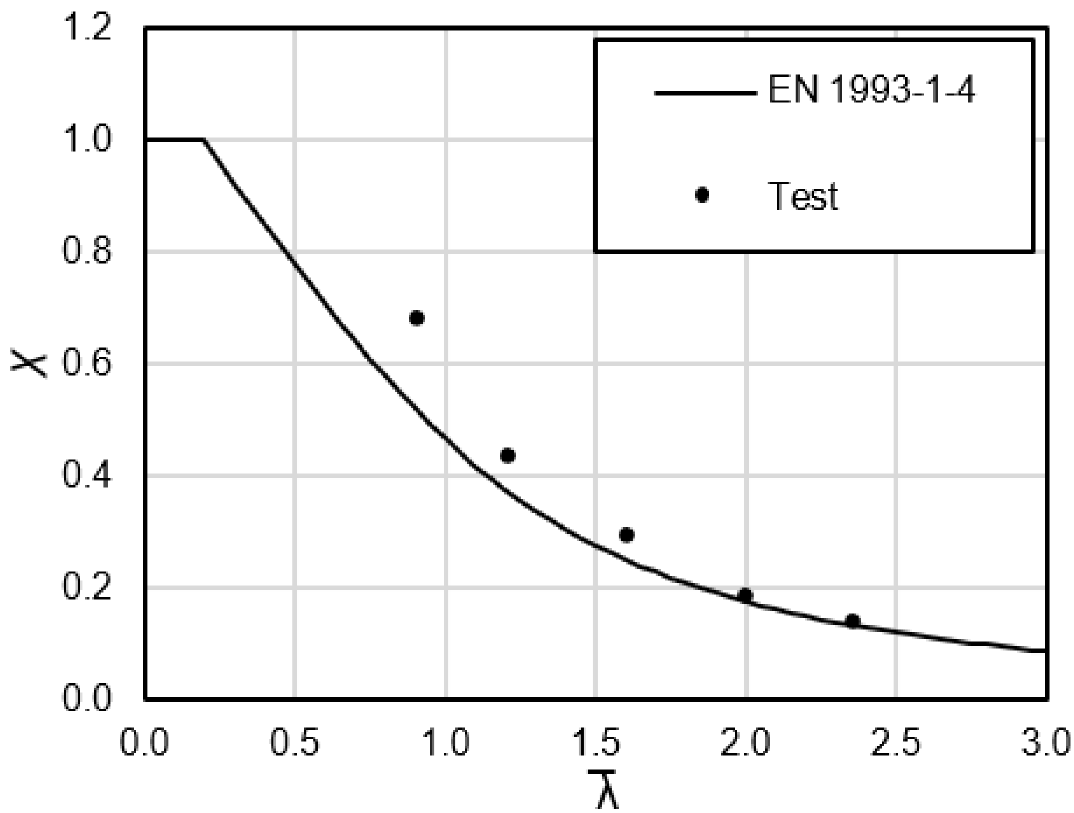
The commercial Finite Element (FE) software ABAQUS was used herein to create numerical models to simulate the mechanical behaviour of pin-ended stainless steel equal-leg angle section members under compression and combined compression and bending. The FE models are first validated by comparing against the existing and newly generated experimental data on pin-ended stainless steel equal-leg angles. A parametric study is presented to investigate the behaviour of both hot-rolled and cold-formed stainless steel equal-leg angle section members free to rotate about the minor axis and subjected to compression and combined loading; a range of cross-section geometries, member lengths and load combinations are studied.

3.1 Validation

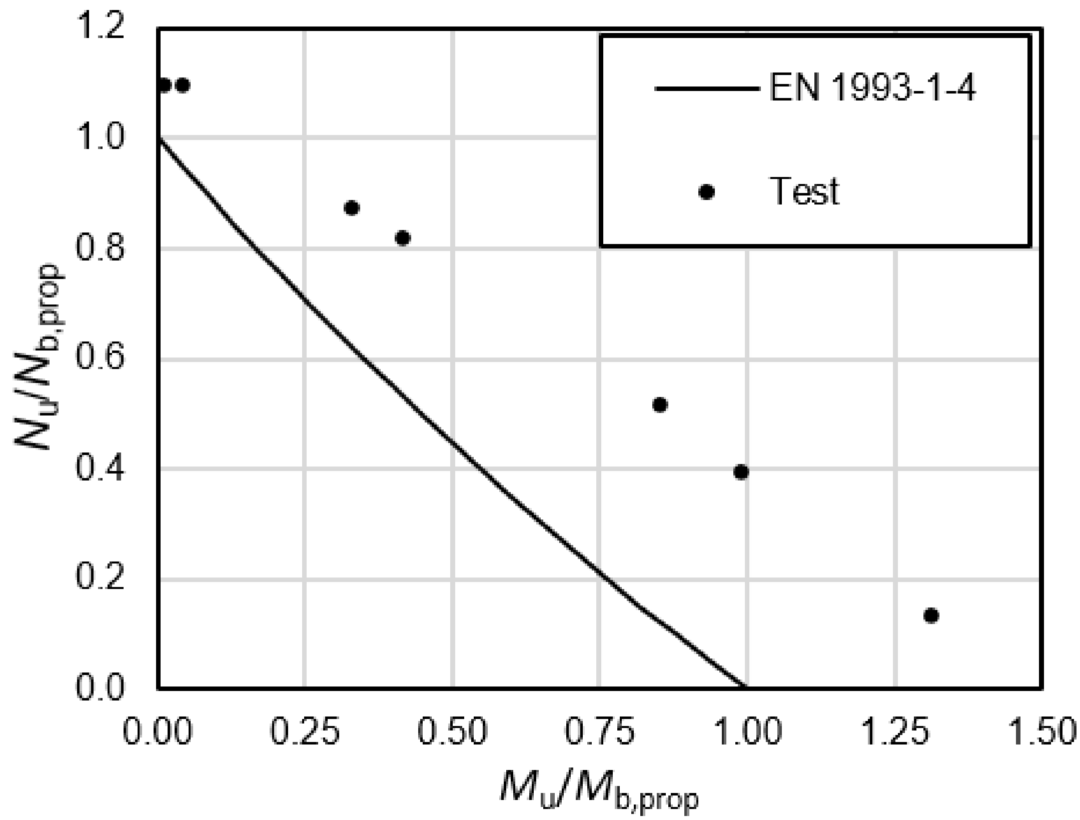
The Finite Element (FE) models were validated against a total of 43 tests; a summary of the comparisons between the ultimate loads from the FE model and those obtained experimentally is presented in Table 1.

FIGURE 5

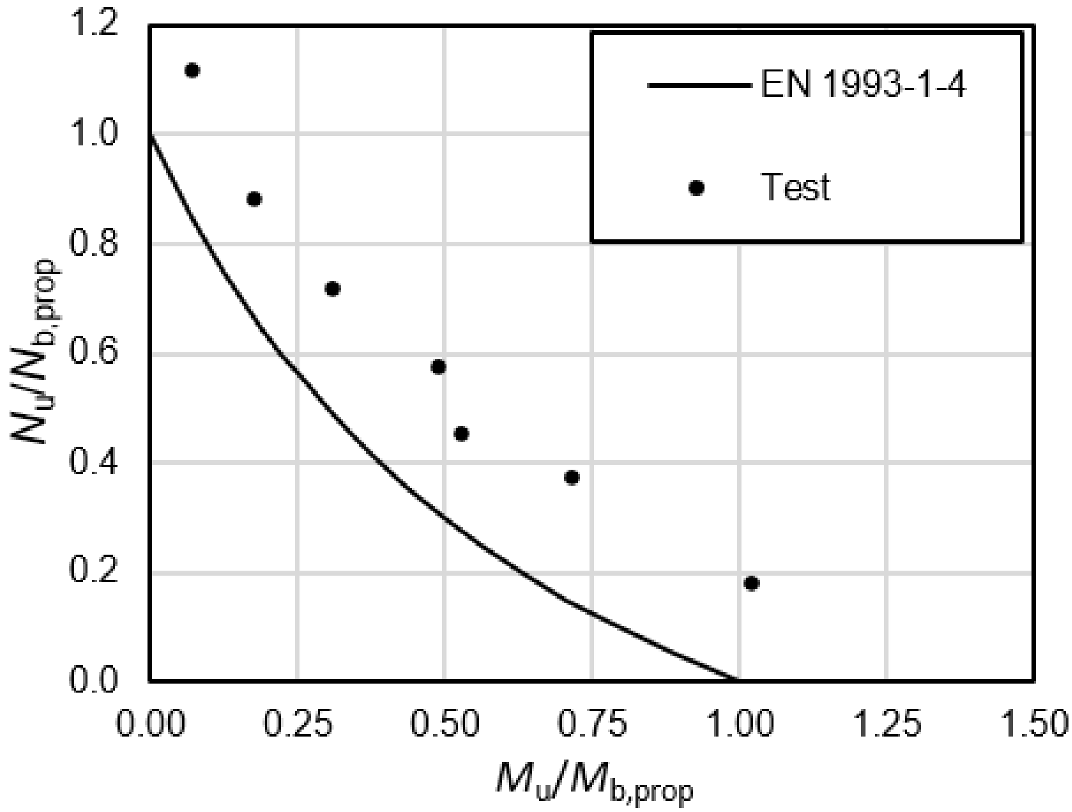
Comparison of test data with (a) buckling curve for pin-ended column tests, and interaction curve for beam-column tests for specimens with (b) $L = 400$ mm and (c) $L = 1400$ mm



(a)


1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.00
0.25
0.50
0.75
1.00
1.25
1.50
$N_u/N_{b,prop}$
$M_u/M_{b,prop}$
EN 1993-1-4
Test

(b)



(c)

TABLE 1

Summary of comparisons of finite element model ultimate loads $N_{u,FE}$ with those obtained experimentally $N_{u,Test}$

Source	No. of tests	$N_{u,FE}/N_{u,Test}$			
		Mean	**CoV**	**Min**	**Max**
Zhang et al. [11]	12	0.98	0.06	0.91	1.09
Zhang et al. [12]	12	0.98	0.04	0.93	1.03
Present study	19	0.99	0.04	0.90	1.06
Total	**43**	**0.98**	**0.04**	**0.90**	**1.09**

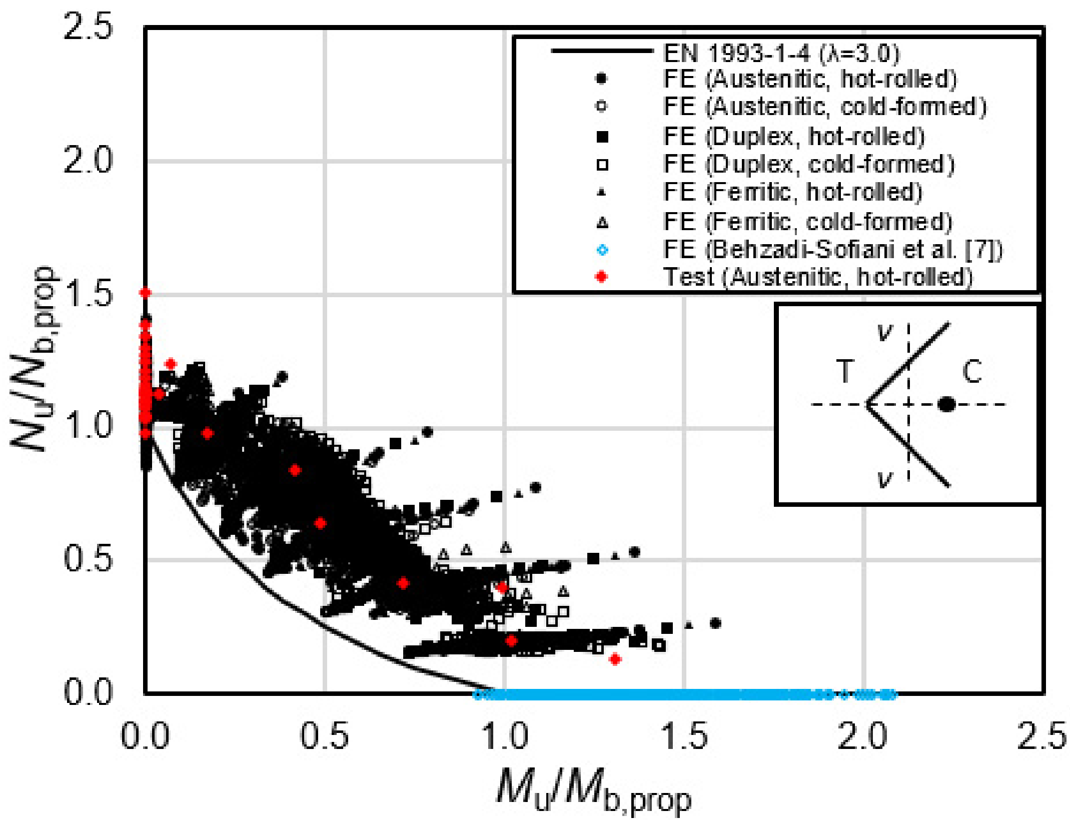
Overall, there is good agreement between the test and FE ultimate loads, with a mean $N_{u,FE}/N_{u,Test}$ ratio (where $N_{u,FE}$ and $N_{u,Test}$ are the ultimate loads from the FE and tests, respectively) of 0.98 and a coefficient of variation (CoV) of 0.04. In addition to the FE model validation presented herein, the developed FE model has also been demonstrated to be suitable for simulating the structural response of equal-leg angle section members with different material characteristics under various loading conditions in several recent studies [4,5,6,7].

3.2 Parametric Study

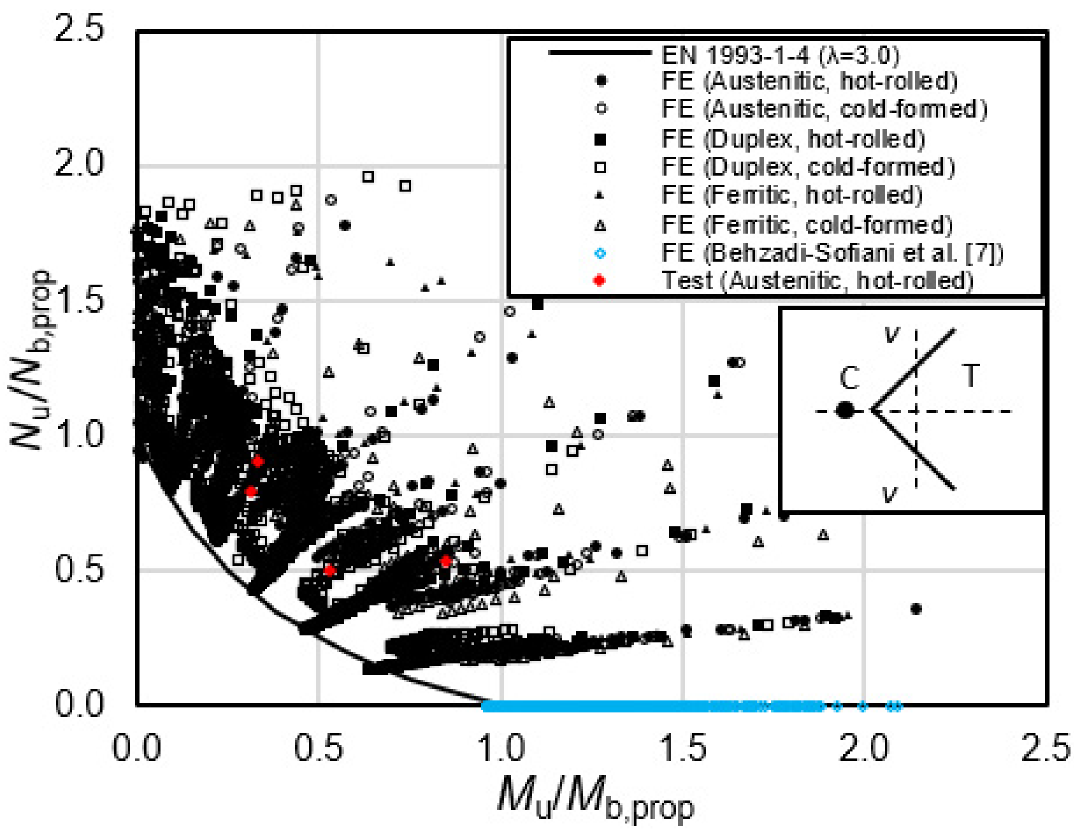
Following validation of the numerical models, a parametric study was conducted. The Finite Element (FE) models were used to generate additional data for the hot-rolled and cold-formed pin-ended angle section columns and beam-columns in the three main families of stainless steel (i.e., austenitic, duplex and ferritic), considering a wide range of cross-section geometries, member lengths and load combinations. A summary of the material properties adopted in the parametric study, taken from [13], is presented in [5]. Leg widths b of 50 mm and 100 mm were analysed, while the thicknesses t and member lengths L were varied to evaluate a spectrum of normalised slendernesses, $\bar{\lambda}_{TF}$ or $\bar{\lambda}$, and elastic buckling load $N_{cr,TF}/N_{cr,F,v}$ ratios. The b/t ratios ranged between 8 and 50, while the L/b ratios ranged between 1 and 100. In addition, the initial eccentricities were varied both in direction (towards and away from the corner of the angles) and magnitude to study a wide range of load combinations. In total, 7920 FE results (120 with zero eccentricity, 600 with positive and 600 with negative eccentricities for 6 production type and stainless steel family combinations) were generated. The results are presented in Figures 6a and 6b for positive and negative loading eccentricities, respectively, in which the normalised axial load $N_u/N_{b,prop}$ (where N_u is the ultimate load obtained from the tests or FE models and $N_{b,prop}$ is the axial compression resistance of the members determined as described in [5]) is plotted against the corresponding normalised bending moment $M_u/M_{b,prop}$ (where M_u is the ultimate bending moment obtained from the tests or FE models and $M_{b,prop}$ is the bending resistance of the members, determined as described in [7]). The results for the angles where the eccentricities are applied in the positive direction (i.e., the tips of the cross-section legs are in compression) are shown in Figure 6a, while the results for the cases where the eccentricities are applied in the negative direction (i.e., the tips of the cross-section legs are in tension) are shown in Figure 6b. For reference, the interaction curve from prEN 1993-1-4 [10] for I-section members (since there is no guidance for angle section members) with $\bar{\lambda}$ = 3.0 is also shown in the figures. Note that, to account for the additional bending moment caused by the shift of the effective centroid, the expression proposed by Rasmussen [8], is adopted.

FIGURE 6

Comparison of test and finite element results for pin-ended stainless steel equal-leg angle section columns and beam-columns bending about the minor-axis against EC3 interaction curve for the cases where the loading eccentricities are applied in the (a) positive direction (i.e., the tips of the cross-section legs are in compression) and (b) negative direction (i.e., the tips of the cross-section legs are in tension)



(a)



(b)

4. Design of Pin-Ended Stainless Steel Angle Section Beam-Columns to Eurocode 3

According to prEN 1993-1-4 [10], members subjected to combined loading with bending about the minor *v-v* axis and axial compression should satisfy the following criterion:

$$\frac{N_{\mathrm{Ed}}}{\frac{\chi_v N_{\mathrm{Rk}}}{\gamma_{\mathrm{M1}}}} + k_{vv}\frac{M_{v,\mathrm{Ed}} + \Delta M_{v,\mathrm{Ed}}}{\frac{M_{v,\mathrm{Rk}}}{\gamma_{\mathrm{M1}}}} \leq 1.0 \tag{1}$$

Here, N_{Ed} and $M_{v,\mathrm{Ed}}$ are the design values of the compression force and maximum bending moment about the minor *v-v* axis along the member, respectively, N_{Rk} and $M_{v,\mathrm{Rk}}$ are the characteristic values of the cross-sectional resistance to compressive axial force and bending moment about the minor *v-v* axis, respectively. The quantity $\Delta M_{v,\mathrm{Ed}}$ is the bending moment due to the shift of the centroid about the minor *v-v* axis, $e_{\mathrm{N},v}$, for Class 4 cross-sections, which is based on the effective width b_{eff} [14] and given thus:

$$e_{\mathrm{N},v} = \frac{b_{\mathrm{eff}}}{\sqrt{2}} \tag{2}$$

The term χ_v is the flexural buckling reduction factor, which should be replaced by χ_{TF} for members where torsional-flexural buckling is critical, while k_{vv} is the interaction factor defined thus:

$$k_{vv} = \begin{cases} 1 + 2.8(\bar{\lambda} - 0.5)n_v & \text{for} \quad \bar{\lambda} < 1.2 \\ 1 + 1.96 n_v & \text{for} \quad \bar{\lambda} \geq 1.2 \end{cases} \tag{3}$$

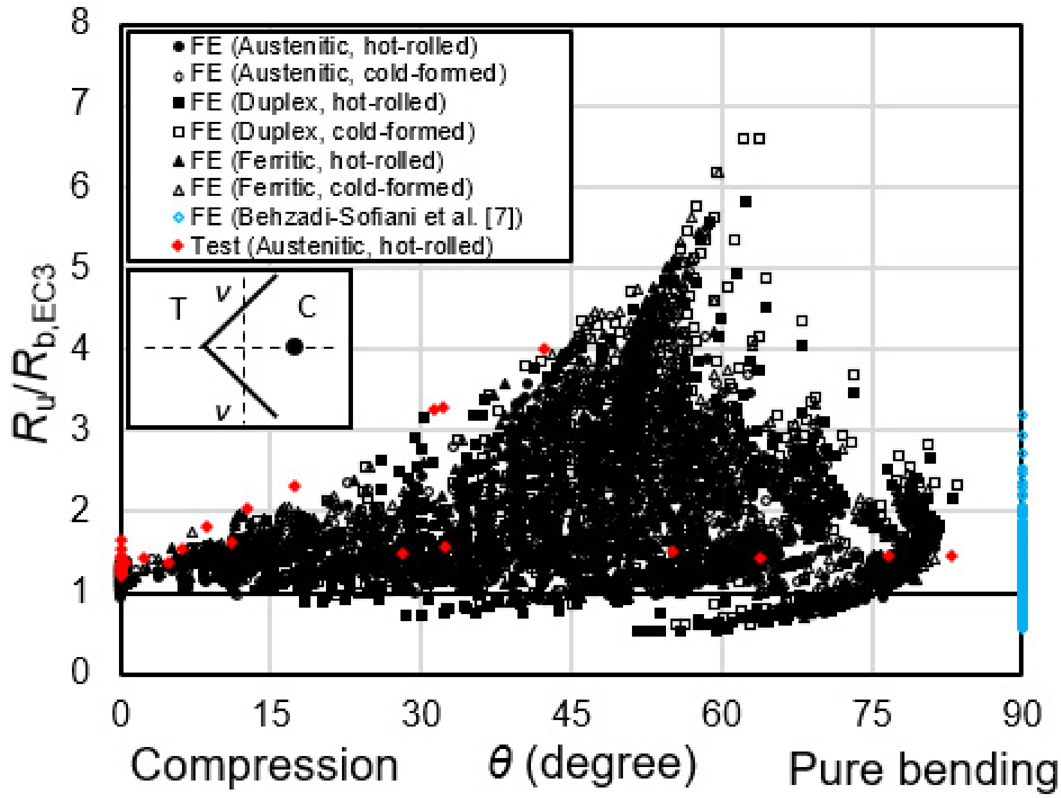
in which $\bar{\lambda}$ is replaced by $\bar{\lambda}_{\mathrm{TF}}$ when torsional-flexural buckling is critical and n_v is given as follows:

$$n_v = \frac{N_{\mathrm{Ed}}}{\frac{\chi_v N_{\mathrm{Rk}}}{\gamma_{\mathrm{M1}}}} \tag{4}$$

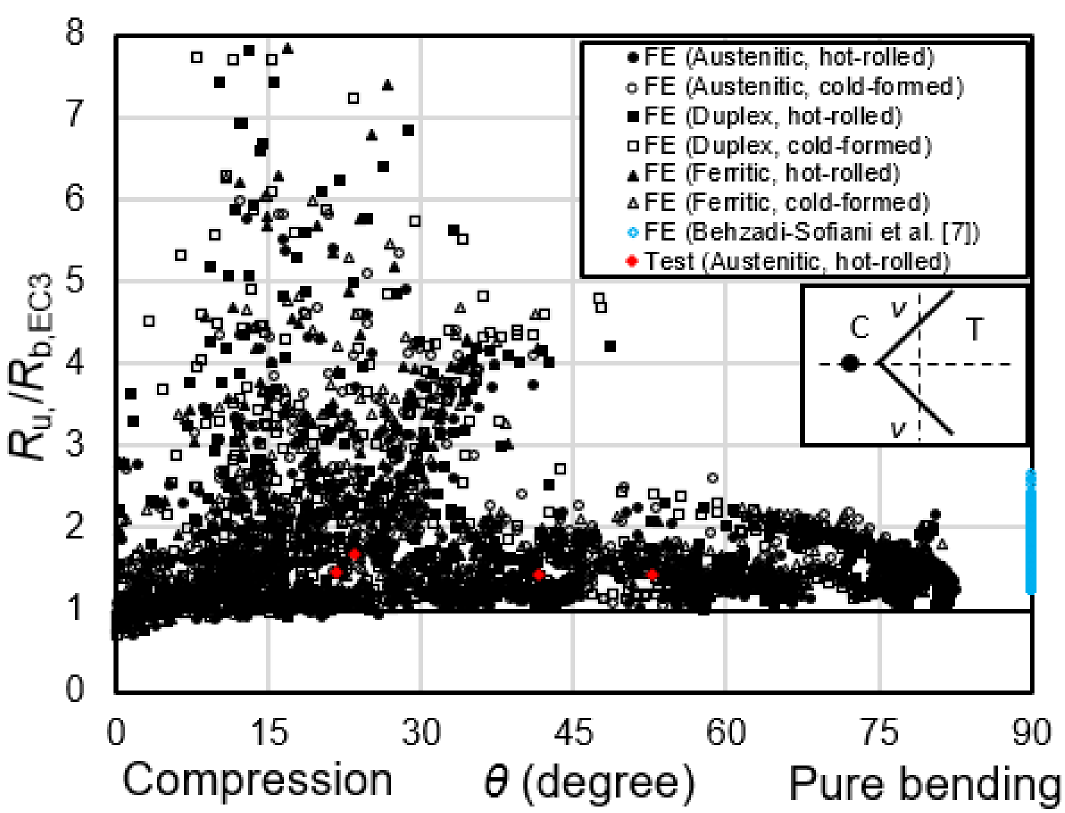
Note that Eq. (3) is specified in prEN 1993-1-4 [10] for I-section members and, in the absence of further guidance, is assumed herein to be also applicable to angles. Comparisons of the test and FE ultimate resistances R_{u} with the resistances predicted by EC3 $R_{\mathrm{b,EC3}}$ are made in Figure 7, where a distinction is drawn between members based on the direction of applied loading eccentricity. In Figure 7, the $R_{\mathrm{u}}/R_{\mathrm{b,EC3}}$ ratio is plotted against θ, as defined in Figure 8.

FIGURE 7

Comparisons of test and finite element results with EC3 ultimate capacities for pin-ended stainless steel equal-leg angle section columns and beam-columns for the cases where the loading eccentricities are applied in the (a) positive direction (i.e., the tips of the cross-section legs are in compression) and (b) negative direction (i.e., the tips of the cross-section legs are in tension)



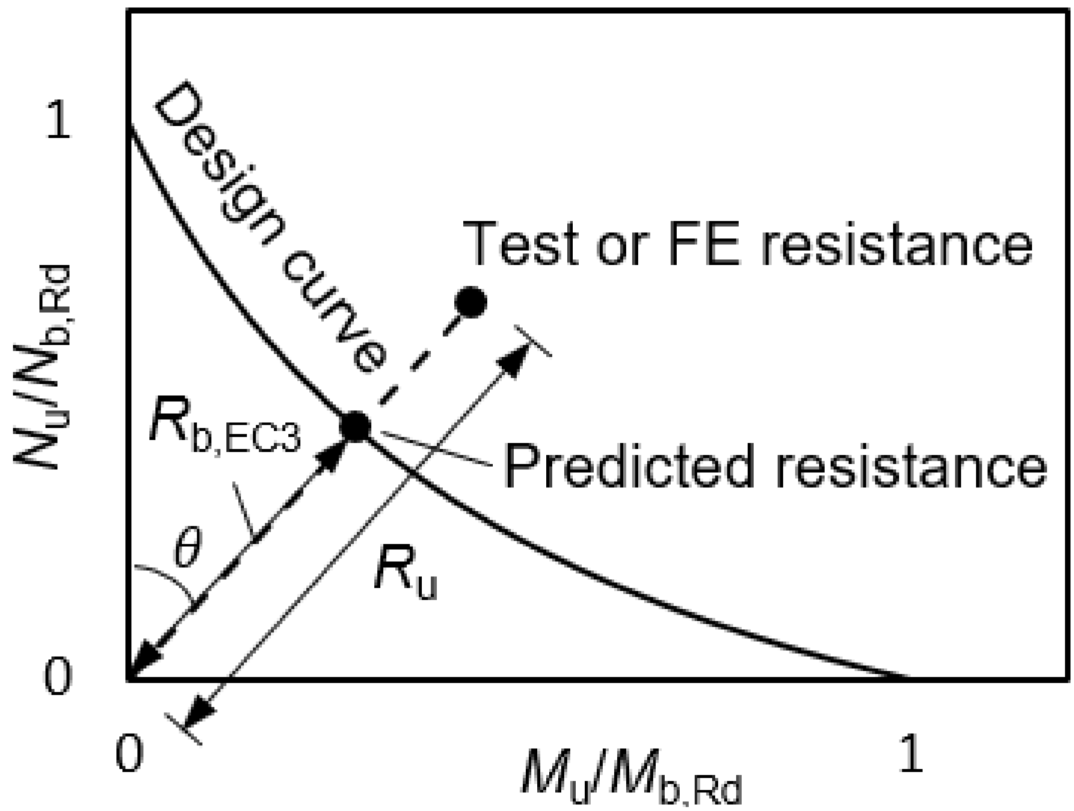
(a)



(b)

FIGURE 8

Definition of parameters R_u, $R_{b,Rd}$ and θ



The EC3 resistance predictions can be seen to be scattered. For cases where the section legs are in compression (see Figure 7a), the scatter of the results is more significant for intermediate to high values of θ, and there are a number of predictions on the unsafe side; this is owing to the fact that lateral-torsional buckling is ignored for minor-axis bending in the current EC3 guidance [6, 7]. On the other hand, consideration of local buckling while lateral-torsional buckling is critical, along with overestimation of the shift of the effective centroid in EN 1993-1-5 [14] result in conservative predictions for other cases in the same group of data. For cases where the tips of the cross-section legs are in tension (see Figure 7b), the predicted resistances are generally conservative for low θ values i.e., where axial compression is dominant; this is owing to the double-counting of the same buckling mode (i.e., torsional and local buckling) in EC3 [1,4,5]. A new interaction curve using the new proposals in [5,7] is needed to provide more accurate resistance predictions for pin-ended stainless steel equal-leg angle section members under combined compression and minor-axis bending.

5. New Design Proposals

Recent proposals for the design of stainless steel equal-leg angle section fixed-ended columns [5] and simply-supported beams [7], along with the expression proposed in [8] for the shift of the effective centroid, are adopted in the present paper to develop new proposals for the design of pin-ended stainless steel angle section columns and beam-columns with bending about the minor axis. The proposed new design formula is thus:

$$\frac{N_{\mathrm{Ed}}}{N_{\mathrm{b,Rd}}} + k_{vv}\frac{M_{v,\mathrm{Ed}} + \Delta M_{v,\mathrm{Ed}}}{M_{\mathrm{b},v,\mathrm{Rd}}} \leq 1.0 \tag{5}$$

where $N_{\mathrm{b,Rd}}$ and $M_{\mathrm{b}\,v,\mathrm{Rd}}$ are member buckling resistances under axial compression and bending about the minor v-v axis, respectively. The new proposals for $N_{\mathrm{b,Rd}}$ [5] and $M_{\mathrm{b}\,v,\mathrm{Rd}}$ [7] are summarised in the subsequent subsections.

5.1 Member Buckling Resistance Under Axial Compression

5.1.1 Torsional-flexural Buckling Critical (i.e., $N_{\mathrm{cr,TF}} \leq N_{\mathrm{cr,F},v}$)

The proposed design expression for determining the buckling resistance of stainless steel equal-leg angle section members under compression [5] when torsional-flexural buckling is critical, is given thus:

$$N_{\mathrm{b,Rd}} = \frac{\chi_{\mathrm{TF}} A f_{\mathrm{y}}}{\gamma_{\mathrm{M1}}} \tag{6}$$

noting that the gross area A is used for all classes of cross-section. In Eq. (6):

$$\chi_{\mathrm{TF}} = \chi_{\mathrm{F}} + \Delta_{\mathrm{F}}(\chi_{\mathrm{T}} - \chi_{\mathrm{F}}) \tag{7}$$

in which the torsional buckling reduction factor χ_{T} is given by:

$$\chi_{\mathrm{T}} = \frac{\bar{\lambda}_{\mathrm{TF}} - 0.188}{\bar{\lambda}_{\mathrm{TF}}^2} \quad \text{for} \quad \chi_{\mathrm{T}} \leq 1.0 \tag{8}$$

the flexural buckling reduction factor χ_{F} is given by:

$$\chi_{\mathrm{F}} = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}_{\mathrm{TF}}^2}} \quad \text{for} \quad \chi_{\mathrm{F}} \leq 1.0 \tag{9}$$

and Δ_{F} is given thus:

$$\Delta_{\mathrm{F}} = \left(1 - \frac{N_{\mathrm{cr,TF}}}{N_{\mathrm{cr,F},v}}\right)^p \tag{10}$$

where

$$p = \begin{cases} 2.0\bar{\lambda}_{\mathrm{TF}} & \text{for} \quad \bar{\lambda}_{\mathrm{TF}} \leq 2.0 \\ 2.93\bar{\lambda}_{\mathrm{TF}} & \text{for} \quad \bar{\lambda}_{\mathrm{TF}} > 2.0 \end{cases} \tag{11}$$

with the torsional-flexural slenderness $\bar{\lambda}_{\mathrm{TF}}$ and ϕ being given thus:

$$\bar{\lambda}_{\mathrm{TF}} = \sqrt{\frac{Af_y}{N_{\mathrm{cr,TF}}}} \tag{12}$$

$$\phi = \left[1 + 1.45\alpha\left(\bar{\lambda}_{\mathrm{TF}} - 0.2\right)^{1.45} + \bar{\lambda}_{\mathrm{TF}}^2\right] \tag{13}$$

For the imperfection factor α, values of 0.6 and 0.49 are recommended for hot-rolled and cold-formed stainless steel angles, respectively. The value of 0.6 is also used for laser-welded sections in prEN 1993-1-4 [10], but could be relaxed to 0.76 if retention of the traditional buckling curves (i.e., curved in this case) was desirable.

5.1.2 Minor-axis Flexural Buckling Critical (i.e., $N_{\mathrm{cr,F},v} \leq N_{\mathrm{cr,TF}}$)

The proposed design expression for determining the buckling resistance of stainless steel equal-leg angle section members under axial compression [5] when minor-axis flexural buckling is critical is:

$$N_{\mathrm{b,Rd}} = \frac{\chi_{\mathrm{F}} A f_y}{\gamma_{\mathrm{M1}}} \tag{14}$$

where

$$\chi_{\mathrm{F}} = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}^2}} \quad \text{for} \quad \chi_{\mathrm{F}} \leq 1.0 \tag{15}$$

in which the normalised slenderness $\bar{\lambda}$ and ϕ are given by:

$$\bar{\lambda} = \sqrt{\frac{Af_y}{N_{\mathrm{cr,F},v}}} \tag{16}$$

$$\phi = \left[1 + \alpha\beta\left(\bar{\lambda} - 0.2\right)^{\beta} + \bar{\lambda}^2\right] \tag{17}$$

with β being a factor allowing for the influence of interactive buckling:

$$\beta = 1.9 - 0.45\frac{N_{\mathrm{cr,TF}}}{N_{\mathrm{cr,F},v}} \quad \text{for} \quad 1.0 \leq \beta \leq 1.45 \tag{18}$$

The imperfection factor remains as specified above: $\alpha = 0.6$ and $\alpha = 0.49$ for hot-rolled and cold-formed stainless steel angles, respectively.

5.2 Member Buckling Resistance Under Minor-axis Bending

For determining the member buckling resistance of stainless steel equal-leg angles under minor-axis bending, the following expression is proposed [7]:

$$M_{\mathrm{b},v,\mathrm{Rd}} = \frac{\chi W_{\mathrm{pl},v} f_{\mathrm{y}}}{\gamma_{\mathrm{M1}}} \tag{19}$$

in which the plastic section modulus $W_{\mathrm{pl},v}$ is used for all classes of cross-section. In Eq. (19):

$$\chi = \frac{1}{\phi + \sqrt{\phi^2 - \bar{\lambda}_{\mathrm{max},v}^2}} \quad \text{for} \quad \chi \leq 1.0 \tag{20}$$

in which the maximum normalised slenderness $\bar{\lambda}_{\mathrm{max}\,v}$ and ϕ are given by:

$$\bar{\lambda}_{\mathrm{max},v} = \sqrt{\frac{W_{\mathrm{pl},v} f_y}{M_{\mathrm{cr}}}} \tag{21}$$

$$\phi = \left[1 + 0.13\left(\bar{\lambda}_{\mathrm{max},v} - 0.40\right) + \bar{\lambda}_{\mathrm{max},v}^2\right] \tag{22}$$

where M_{cr} is the minimum of the minor-axis lateral-torsional $M_{\mathrm{cr,LT},v}$ and the Brazier flattening $M_{\mathrm{cr,Br}}$ critical buckling moment.

5.3 Interaction Factor

The suitability of the existing interaction factor k_{vv} for use with the new proposed end points of the interaction curve (i.e., the proposed axial and bending resistances) is assessed herein. The expression for the interaction factor k_{vv} takes the general bilinear form given thus:

$$k_{vv} = 1 + \left(D_1\bar{\lambda} + D_2\right)n_v \tag{23}$$

where D_1 and D_2 are constants. Eq. (23) can be rearranged into the following:

$$\frac{k_{vv} - 1}{n_v} = D_1\bar{\lambda} + D_2 \tag{24}$$

The $(k_{vv} - 1)/n_v$ values corresponding to the test and finite element (FE) results are plotted against the critical normalised slenderness, $\bar{\lambda}_{TF}$ or $\bar{\lambda}$, in Figures 9a and 9b for cases with positive and negative initial loading eccentricities, respectively. The bilinear EC3 expression for the interaction factor, for I-sections (i.e., D_1=2.8 and $D_2 = -1.4$ with an upper boundary of 1.96), is also shown, and can be seen to lie generally on the safe side of (i.e., above) the experimental and numerical results, but excessively so. A new expression is sought that provides a closer match to the data; the following expressions are proposed:

For tips in compression,

$$k_{vv} = \begin{cases} 1 + \left(2\bar{\lambda} - 1\right)n_v & \text{for} \quad \bar{\lambda} \leq 1.0 \\ 1 + n_v & \text{for} \quad \bar{\lambda} > 1.0 \end{cases} \tag{25}$$

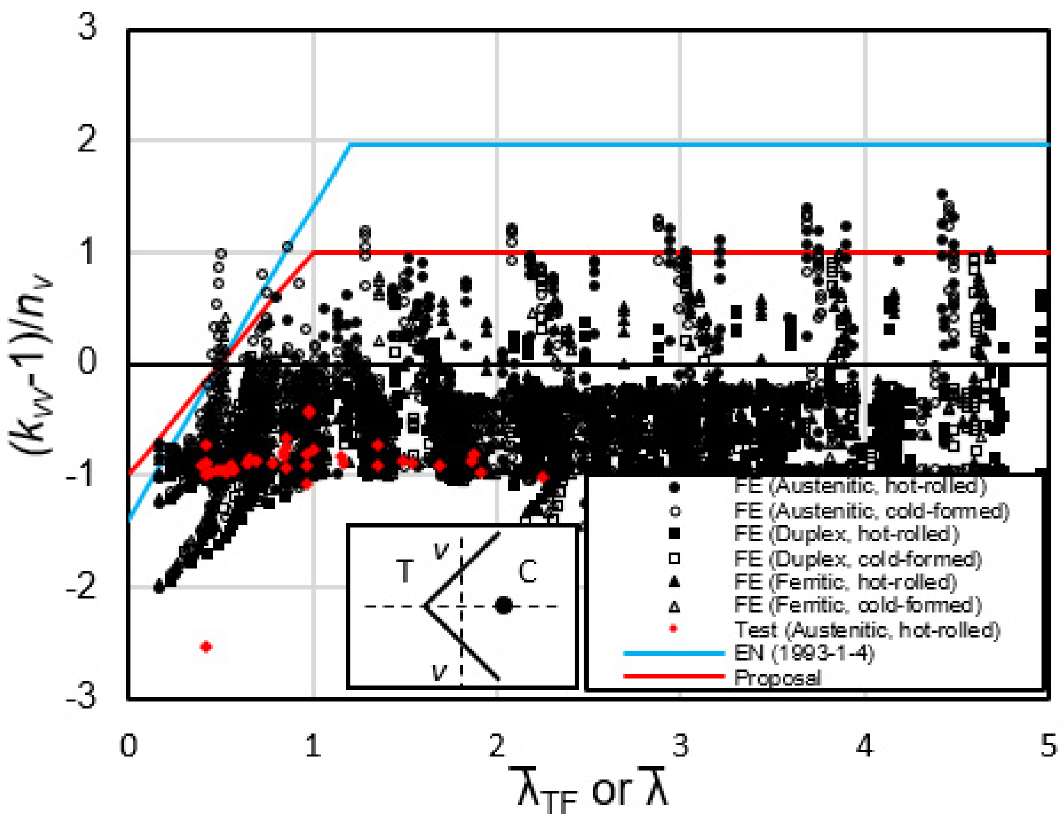
For tips in tension,

$$k_{vv} = \begin{cases} 1 + \left(1.2\bar{\lambda} - 1\right)n_v & \text{for} \quad \bar{\lambda} \leq 2.5 \\ 1 + 2n_v & \text{for} \quad \bar{\lambda} > 2.5 \end{cases} \tag{26}$$

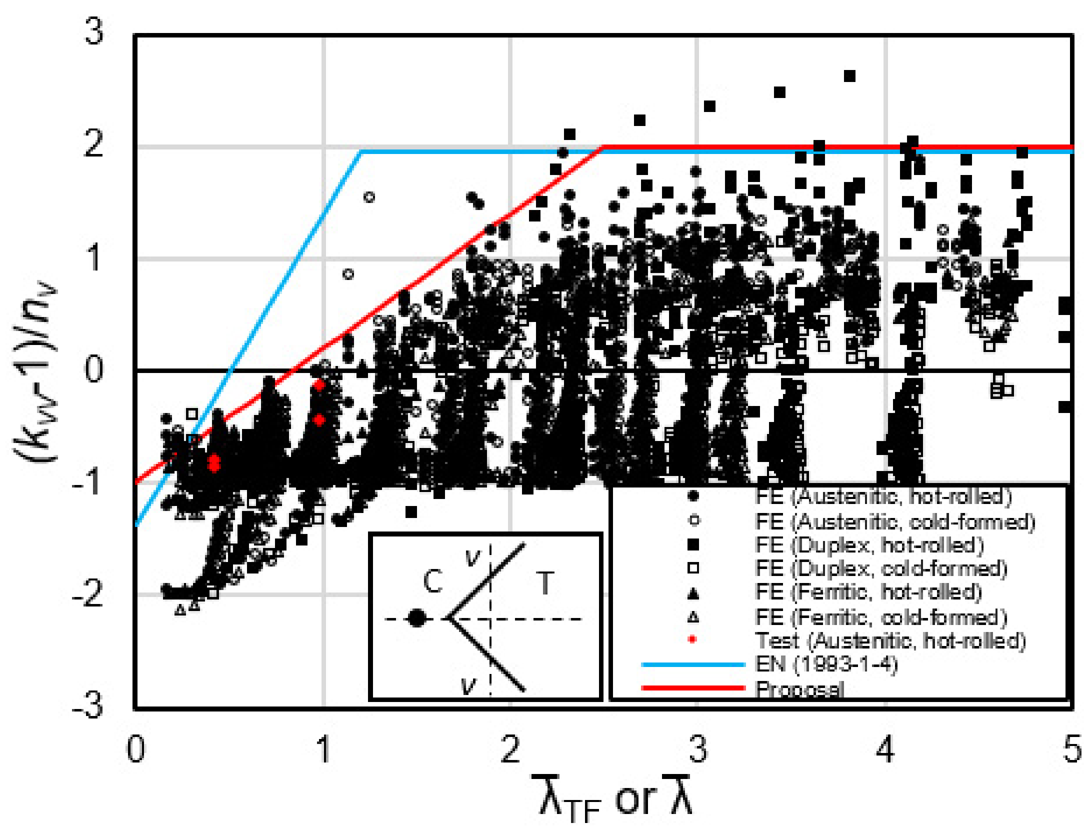
These expressions are plotted in Figures 9a and 9b for the cases where the tips of section legs are in compression and tension, respectively. Note that $\bar{\lambda}$ is replaced by $\bar{\lambda}_{TF}$ when torsional-flexural buckling is critical.

FIGURE 9

Comparisons of test and finite element results with the existing EC3 and proposed interaction factors k_{vv} for combined compression and bending about the minor axis for the cases where the loading eccentricities are applied in the (a) positive direction (i.e., the tips of the cross-section legs are in compression) and (b) negative direction (i.e., the tips of the cross-section legs are in tension)



(a)

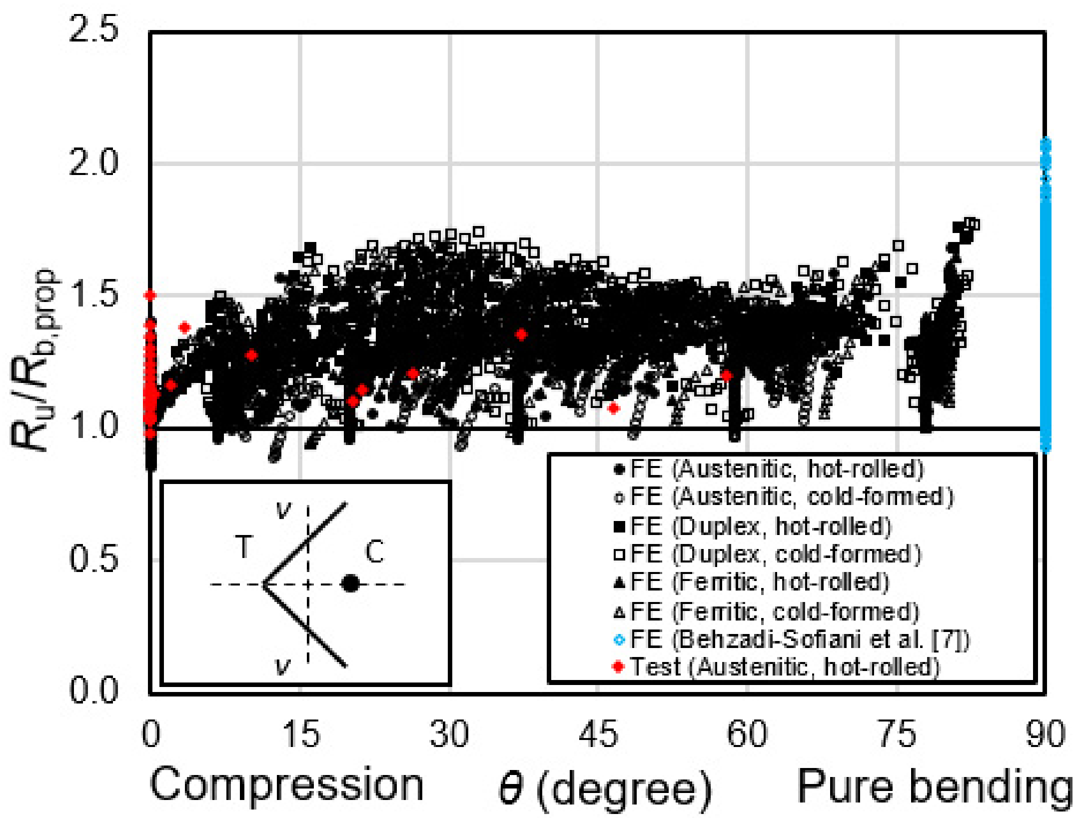


(b)

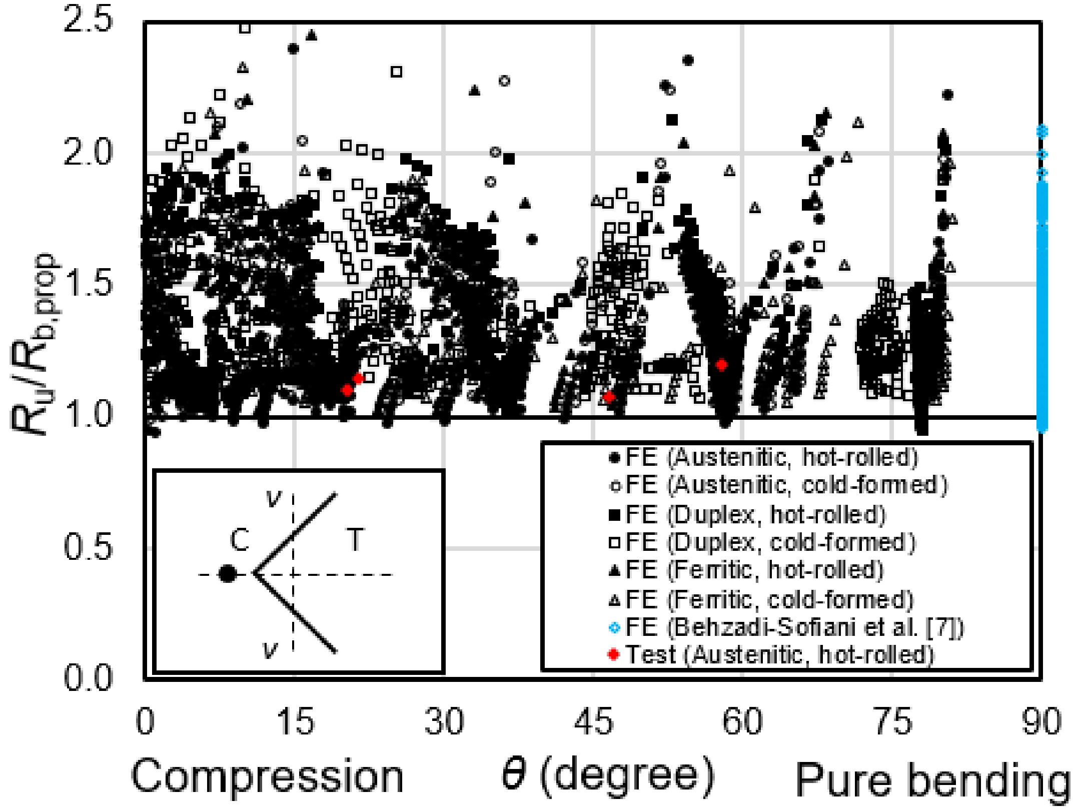
A summary of the comparisons of the test and FE capacities with the resistance predictions according to the new proposals $N_{b,prop}$ is presented in Figure 10. By comparing Figures 7 and 10, it can be seen that the resistance predictions are significantly improved for pin-ended stainless steel angles under compression and combined loading using the new proposals relative to the current Eurocode 3 provisions.

FIGURE 10

Comparisons of test and finite element results with resistance predictions according to the new proposals for pin-ended stainless steel equal-leg angle section columns and beam-columns for the cases where the loading eccentricities are applied in the (a) positive direction (i.e., the tips of the cross-section legs are in compression) and (b) negative direction (i.e., the tips of the cross-section legs are in tension)



(a)


2.5
2.0
1.5
1.0
0.5
0.0
$R_u/R_{b,prop}$
0
15
30
45
60
75
90
Compression
θ (degree)
Pure bending
C
T
v
v
FE (Austenitic, hot-rolled)
FE (Austenitic, cold-formed)
FE (Duplex, hot-rolled)
FE (Duplex, cold-formed)
FE (Ferritic, hot-rolled)
FE (Ferritic, cold-formed)
FE (Behzadi-Sofiani et al. [7])
Test (Austenitic, hot-rolled)

(b)

6. Conclusions

A comprehensive study into the behaviour and design of pin-ended stainless steel equal-leg angle section members subjected to compression and combined compression and minor-axis bending has been presented herein. A programme of physical experiments on pin-ended hot-rolled austenitic stainless steel angle section columns and beam-columns was first reported. Finite Element (FE) models were then developed and validated against the reported test results; good agreement between the test and FE results was found. A parametric study was subsequently conducted on both hot-rolled and cold-formed angle section columns and beam-columns in austenitic, duplex and ferritic stainless steel covering a spectrum of cross-section, member geometries and load combinations, with some 7920 numerical results being generated. These results, combined with the new test results, were used to assess the current EC3 design provisions for pin-ended stainless steel equal-leg angle section columns and beam-columns. The resistance predictions were found to be highly scattered relative to the test and numerical data, with results on both the conservative and unsafe side, depending on the load combination. For column buckling resistance, the current EC3 design provisions account for torsional/local buckling twice, which is the primary source of the observed conservatism. For angles subjected to bending about the minor axis, lateral-torsional buckling can occur, and ignoring this mode of buckling results in unconservative resistance predictions. In addition, the shift of the effective centroid is over-estimated in the current guidance, resulting in a corresponding over-estimation of the minor-axis bending moment. These issues, together with an absence of a specific interaction curve for angle section members, lead to the inaccurate EC3 resistance predictions.

A new design approach for pin-ended stainless steel angle section members under compression and combined loading, reflecting the above findings has been proposed. Overall, the new design proposals have been shown to lead to significantly more accurate strength predictions for both hot-rolled and cold-formed pin-ended stainless steel equal-leg angle section columns and beam-columns.

Acknowledgements

This paper is adapted from B Behzadi-Sofiani, A Wadee, L Gardner. Testing, FE modelling and design of pin-ended stainless steel equal-leg angle section columns and beam–columns. Journal of Constructional Steel Research, 208 (Sep 2023) 107973

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Life Extension of the Heysham B and Torness Nuclear Power Stations

Abstract

The paper describes work for EDF Energy to extend the life of graphite-moderated advanced gas-cooled nuclear reactors by assessing the timing and extent of cracking of fuel bricks. Such cracking has the potential to restrict the mobility of fuel assemblies and control rods in the reactor core. The work focusses on the Heysham B and Torness reactors and the potential susceptibility of the seal ring groove wall (SRGW) feature of their fuel bricks to fragmentation.

Explicit finite element modelling of groups of bricks is described to investigate the prompt (dynamic) and delayed (quasi-static) development of cracks in the SRGW, the models simulating the complex processes of material evolution under irradiation and inter-brick contact forces as cracking develops. The assessment of graphite integrity under dynamic loads and the quasi-static evolution of graphite under irradiation are described. The work demonstrates that early dynamic fragmentation is unlikely, whilst work continues in estimating the timing of quasi-static fragmentation.

Keywords

Advanced gas-cooled reactor (AGR); Graphite; Cracking; Explicit finite element; Fragment

1. Introduction - The Energy Challenge

The energy crisis that has followed the stand-off between Russia and much of the democratic world in the wake of the war in Ukraine has thrown the dependence of many European countries on Russian gas and oil into sharp relief. The immediate outcome has been an abrupt change in the course of government policies on energy resourcing, perhaps accelerating a process that has been driven by environmental concerns related to the use of fossil fuels. In the UK, there has been a policy of diversification of our electrical power generation capacity with an increasing emphasis on renewable resources, such as solar and wind, and a diminution of our reliance on coal and gas. There has long been an element of nuclear generation, too, although the ageing of the current fleet of advanced gas-cooled reactor (AGR) stations has prompted renewed impetus behind pressurised water reactor (PWR) stations, with a new station being built at Hinkley Point to operate alongside that at Sizewell.

1.1 Advanced Gas-Cooled Reactor (AGR) Longevity

The older AGRs have a graphite-moderated core: a cylinder of carbon comprising hundreds of interlocking fuel and interstitial bricks through which uranium fuel assemblies and control rods can pass, cooled by carbon dioxide gas that transfers heat to the working fluid to be used for energy generation. Each brick measures some 0.9m high with a diameter of 0.5m.

Throughout the life of the reactor these core bricks experience irradiation from the fuel assemblies, affecting the structure of the graphite. Over time the bricks lose mass through oxidation of the carbon by the carbon dioxide coolant and undergo dimensional change that both shrinks and later expands the graphite. Just as thermal expansion/contraction can crack glass, dimensional change from irradiation can crack and fragment the graphite fuel bricks as they approach the end of their lives. It is the onset and propagation of this cracking and fragmentation that presents a challenge to the continued operation of the AGRs: mobility of the fuel assemblies and control rods must be unimpeded by graphite fragments or distortion of the channels through which they pass. Proving the continued mobility of fuel assemblies and control rods is, therefore, a fundamental pre-requisite for further operation.

FIGURE 1

Torness Nuclear Power Station, East Lothian, Scotland

2. The Seal Ring Feature at Torness and Heysham B

Of the UK AGR stations, those at Torness (TOR, East Lothian, Figure 1) and Heysham B (HYB, Lancashire) form a twin pair that are hoped to continue in operation until 2028. They utilise a common geometry of core bricks (Figure 2) that incorporates a seal ring (Figure 3) between vertically-adjacent bricks. These seal rings restrict flow of carbon dioxide coolant between the bricks and maintain vertical alignment of a brick stack by restricting relative lateral displacement of adjacent bricks. Each seal ring is composed of four segments of 90° arc that allows some movement of the seal rings within their grooves. A further feature of the bricks is the deep longitudinal keyways (called radial keyways), which restrict movement between horizontally-adjacent bricks and are now known to form the sites of crack initiation in ageing bricks.

Radial keyway root cracks (KWRCs) have been extensively observed in the fuel bricks of the now de-commissioned Hinkley Point B and Hunterston B stations, although these stations were able to remain active for several years following the initial onset of such cracks. Similar cracking is anticipated in the Torness and Heysham bricks, but there are concerns that the seal ring feature that is unique to the HYB/TOR reactors could be a source of graphite fragmentation, affecting the final date of power generation at the sites. These concerns derive from the potential vulnerability of the seal ring groove wall (SRGW, Figure 2) following a KWRC (Figure 3) and it is to assess the threat posed by this cracking mechanism that Atkins (now AtkinsRéalis) has been working with EDF over the past four years.

FIGURE 2

Heysham B/Torness fuel bricks showing circular groove for seal rings

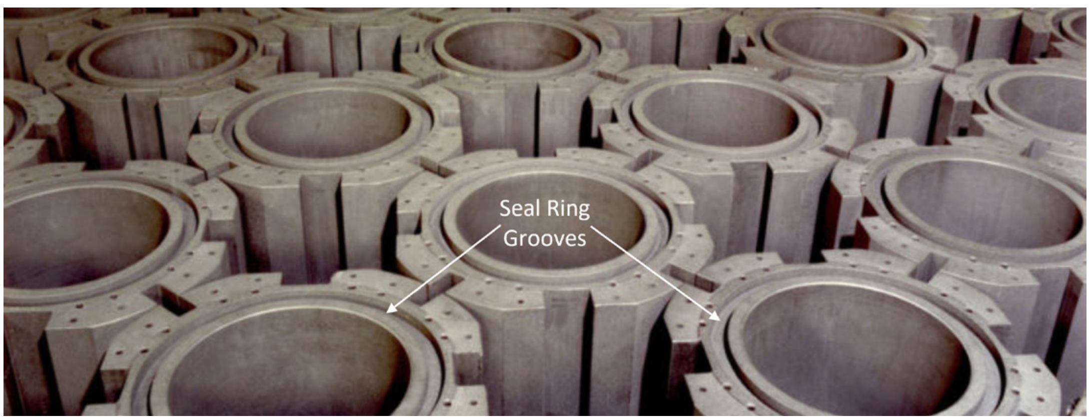
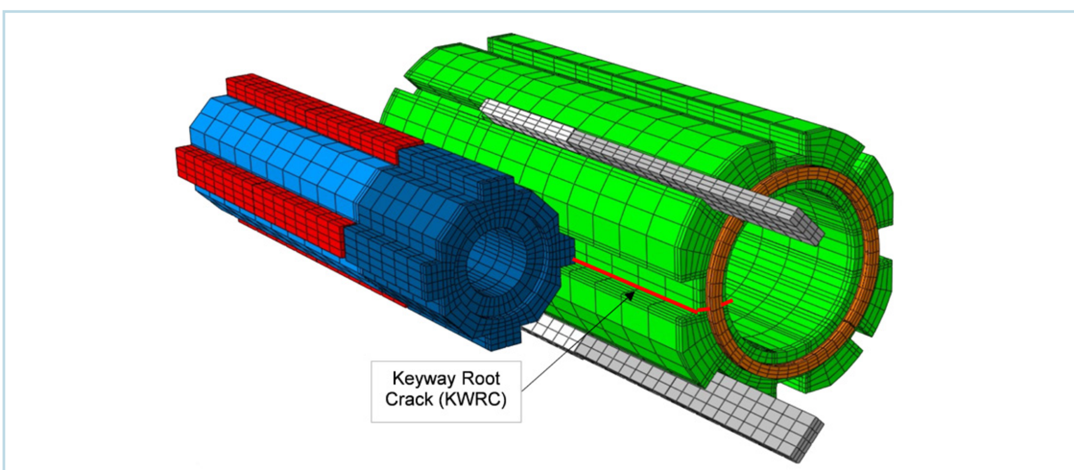


FIGURE 3

Finite element model of Heysham B/Torness fuel brick (green), interstitial brick (blue), loose keys (grey) and seal ring segments (orange). KWRC illustrated in red



2.1 Seal Ring Groove Wall (SRGW) Cracking

When a full-height KWRC forms in a fuel brick (shown modelled in Figure 4), the crack rapidly opens to an initial width that is determined by the dimensional change within the graphite and the forces resisting opening, such as friction and keyway constraint from adjacent bricks. Following this initial opening, the KWRC opens progressively over time as irradiation increases the dimensional change within the graphite. For both the initial opening and the progressive opening a risk of SRGW cracking exists for the HYB/TOR reactor bricks because the seal rings form the principal mechanism by which opening of the KWRC is resisted.

FIGURE 4

Modelling the effect of a full-height keyway root crack

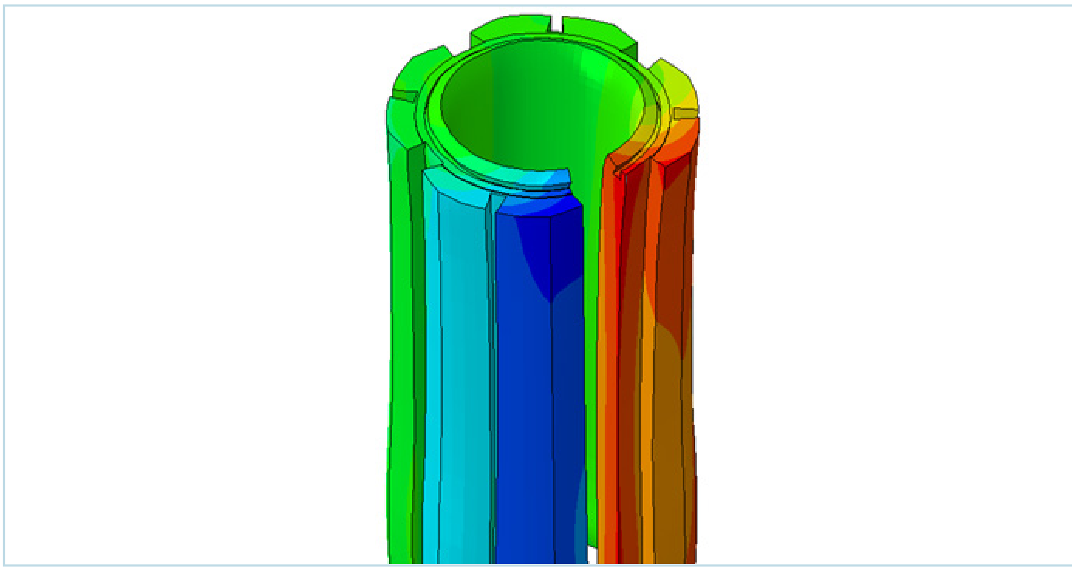


FIGURE 5

Potential SRGW cracking mechanism for the HYB/TOR fuel bricks

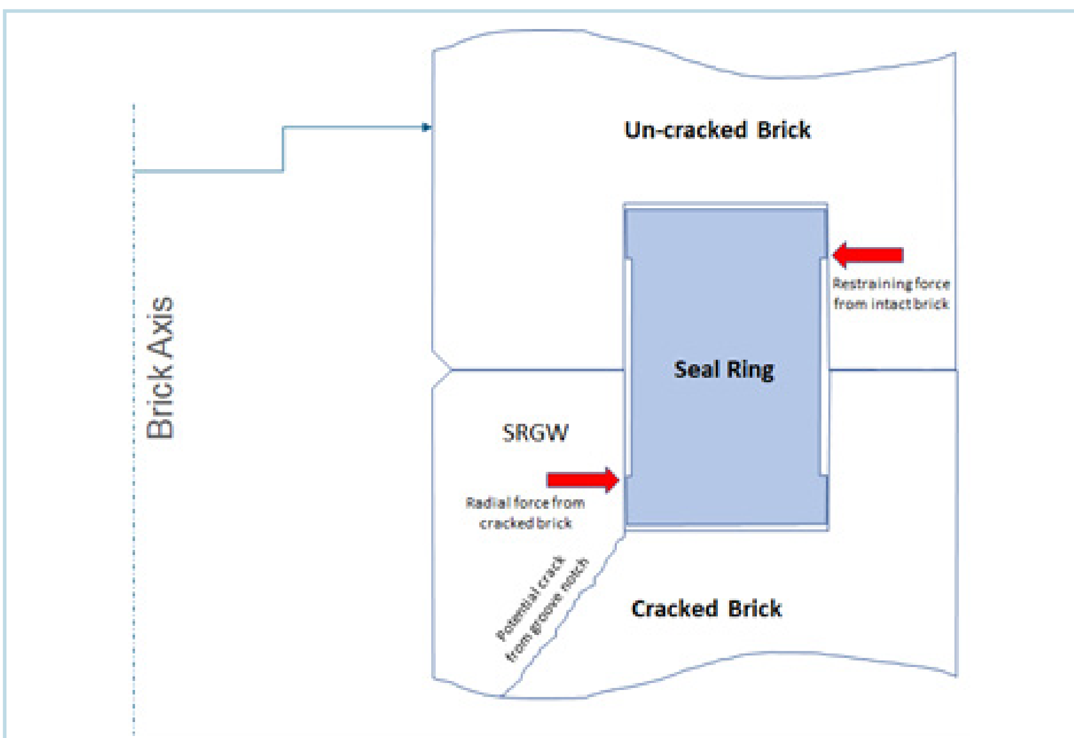


Figure 5 illustrates the mechanism by which SRGW cracking can arise in a fuel brick containing a full-height KWRC. Opening of the cracked brick is resisted by the seal ring through radial pressure on the inner SRGW. The SRGW adjacent to the KWRC is weakened owing to the lack of hoop strength in the SRGW so cracking, as illustrated in the figure, becomes possible. Should this cracking lead to a fragment, it may form debris in the fuel channel, possibly interfering with the mobility of the fuel assembly.

It has been suggested that cracking of the SRGW could occur either at the time of formation of a KWRC – termed a "prompt" crack – or following subsequent progressive opening of the KWRC – a "delayed" crack. Initiation of a prompt SRGW crack is a dynamic event occurring within a fraction of a second, whilst initiation of a delayed SRGW crack is quasi-static arising from a steady increase in the radial pressure on the SRGW. For the continued safe operation of the reactors, understanding the timing of KWRCs, the likelihood of prompt SRGW cracking, and the timing of delayed SRGW cracking are of prime importance.

2.2 Predicting Seal Ring Groove Wall (SRGW) Cracking

Predicting graphite fracture has been the subject of finite element modelling for many years within EDF. The models are complex because they must embody a simulation of the evolution of the graphite material within the bricks whilst representing also the highly non-linear response when bricks and keyways interact through contact. The models simulate reactor brick behaviour by stepping through time, making incremental changes to the dimensions, stiffness, strength and configuration (i.e., cracked or un-cracked). These models allow the interaction forces to be estimated and the risk of cracking assessed. An added complexity arises from the variance of material properties within the bricks. Each brick has slightly different stiffness and strength, whilst each receives slightly different doses of radiation. Hence, an element of probability enters into the calculation of crack timing and the occurrence of fragmentation.

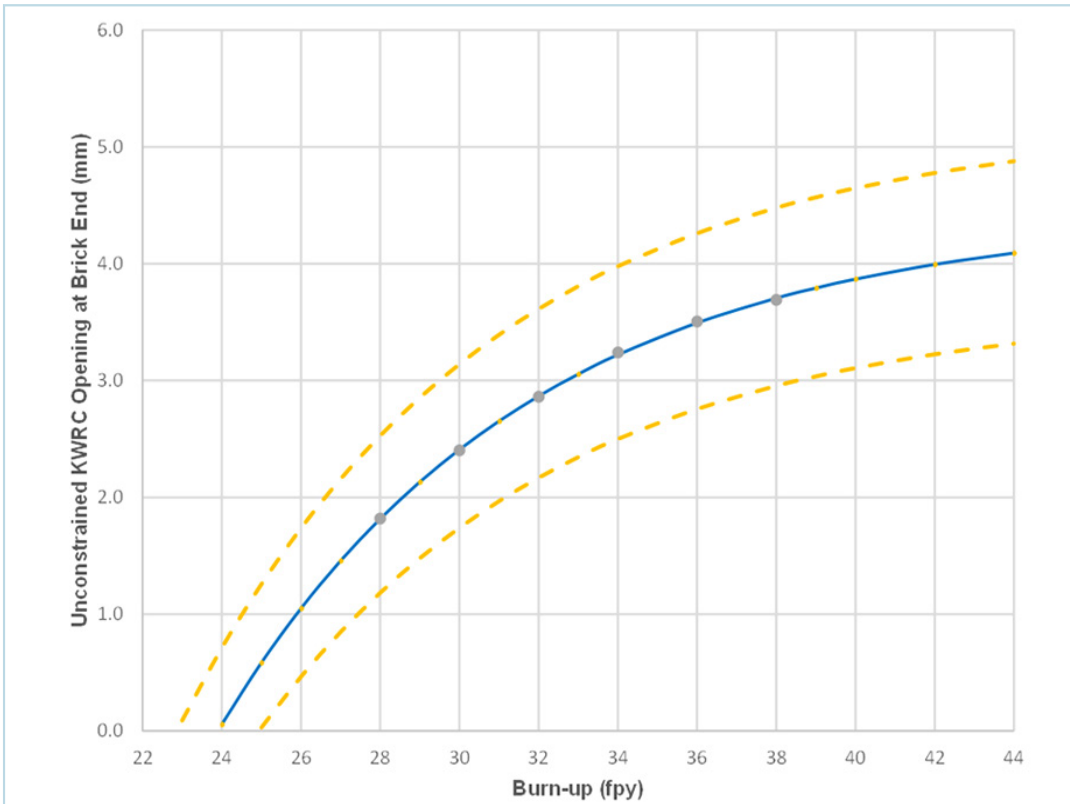
The immediate concern for the HYB/TOR fuel bricks is prompt cracking since, should fragmentation arise, the fragments would immediately present a threat to the continued ability to de-fuel the reactor. To address this concern, AtkinsRéalis proposed an "explicit" approach to modelling: a solution technique involving very small steps in time that is good at coping with sudden changes in behaviour, such as the rapid propagation of a crack or the engagement of contact surfaces. The models developed to address prompt cracking became termed prompt cracking models.

3. Modelling Cracking - Prompt Cracking Models (PCMs)

Existing finite element models, and reactor observations, had allowed estimation of the magnitude of prompt KWRC openings (Figure 6), providing a basis for predicting the likelihood of prompt SRGW cracking. These estimates suggested that, following the observation of the first KWRCs, prompt KWRC openings of greater than 2mm should not be expected for at least 3 full-power years (fpy). A target opening of two millimetres was therefore selected for the assessment of prompt SRGW cracking: if it could be shown that prompt SRGW cracking did not arise at this opening, prompt cracking became less of a threat than delayed cracking, as existing KWRC openings progressively increase over the period.

FIGURE 6

Projected prompt KWRC opening for HYB/TOR fuel bricks showing ±2 σ bands

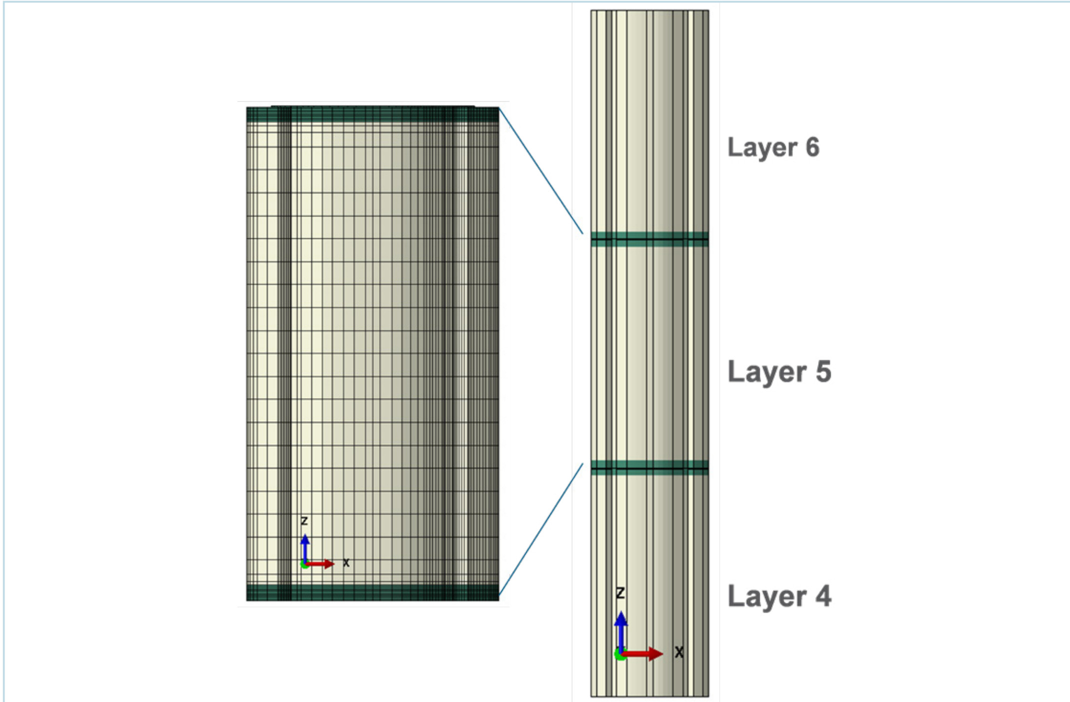


The PCMs have been built to assess the risk of prompt SRGW cracking. The key features of these models are:

- Three vertically-adjacent bricks only are represented (Figure 7)
- Mesh density is matched with supporting strength models, ensuring consistency of crack initiation stress
- Material properties of stiffness and strength are adjusted to account for irradiation
- Equivalent thermal loading simulates the dimensional change arising in the irradiated brick
- A target prompt KWRC opening of the brick of 2mm is applied
- Stiff contacts are applied to all interfacing surfaces – brick end faces, seal rings and SRGWs
- “Cohesive surfaces” simulate the fracture of the KWRC

FIGURE 7

Model (PCM) for HYB/TOR SRGW prompt cracking assessment



The neglect of horizontally-adjacent bricks, which are loosely keyed together, reduces the size of the models, whilst the use of artificial thermal loading avoids the complexity of full simulation of irradiation. The stiff contacts exploit the ability of explicit methods to deal efficiently with non-linearities whilst the cohesive surfaces ensure that propagation of the KWRC is as representative as possible by defining the load and the energy dissipated when the crack propagates.

3.1 Prompt Cracking Models (PCM) Variance

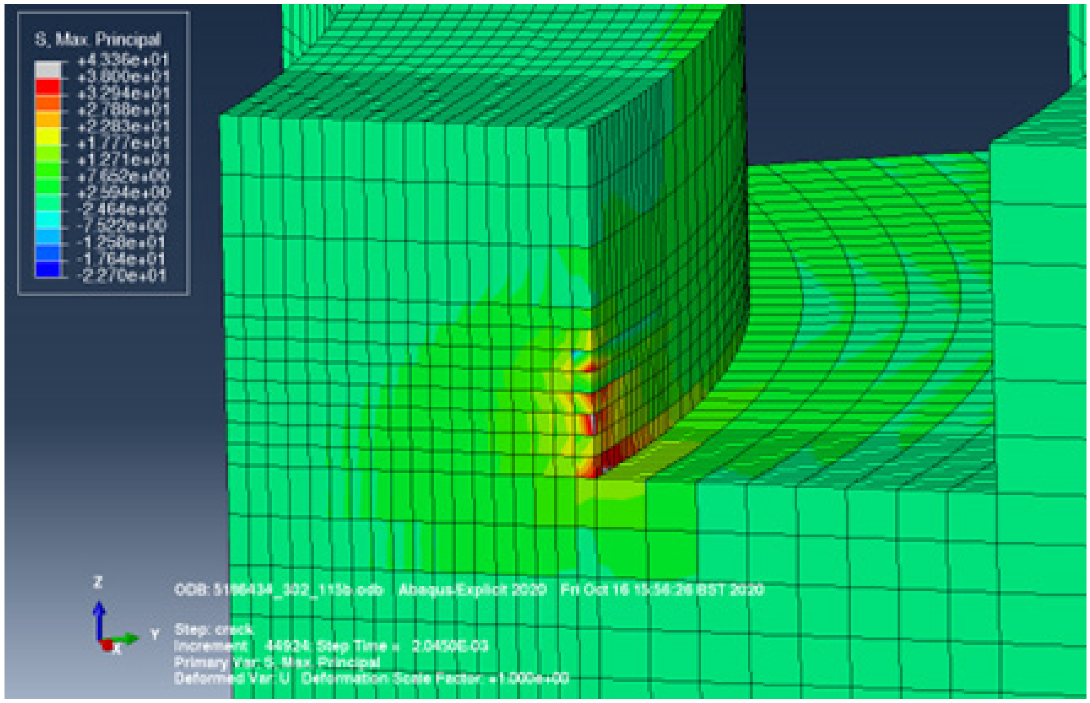
In addition to the material variance to which graphite is prone, variance arises also in the geometry of the fuel bricks and the adjacent keys. There is scope for limited off-axis misalignment of vertically-adjacent fuel bricks, influencing the clearances between seal rings and SRGWs during a KWRC. Also, the angular orientation of the seal ring segments within the groove is unknown (it cannot be determined from in-reactor inspection), so the angular position of the segment interfaces relative to the KWRC is uncertain. As such variance influences the pattern and magnitude of forces transferred between seal ring and groove wall, sensitivity studies have examined a range of possibilities to determine the most critical permutations and assess the probabilistic chances of cracking.

3.2 Stress-Based Integrity Assessment of the Seal Ring Groove Wall (SRGW)

In the first instance it had been the intention to assess the integrity of the SRGW solely on the basis of stress: if the model exhibited SRGW notch stresses greater than a limiting strength value, cracking would be deemed to have been initiated and fragmentation would be assumed. Typical of the stress distributions that emerge from the PCMs is illustrated in Figure 8, which shows the stresses around the KWRC/SRGW notch. A feature of the stress plots from these models is that stress averaging is suppressed because there are stress discontinuities at the corners of the groove that must be respected: the stress fields are not "converged".

FIGURE 8

Typical stress fringe output from PCM looking onto KWRC and SRGW (seal ring not shown)

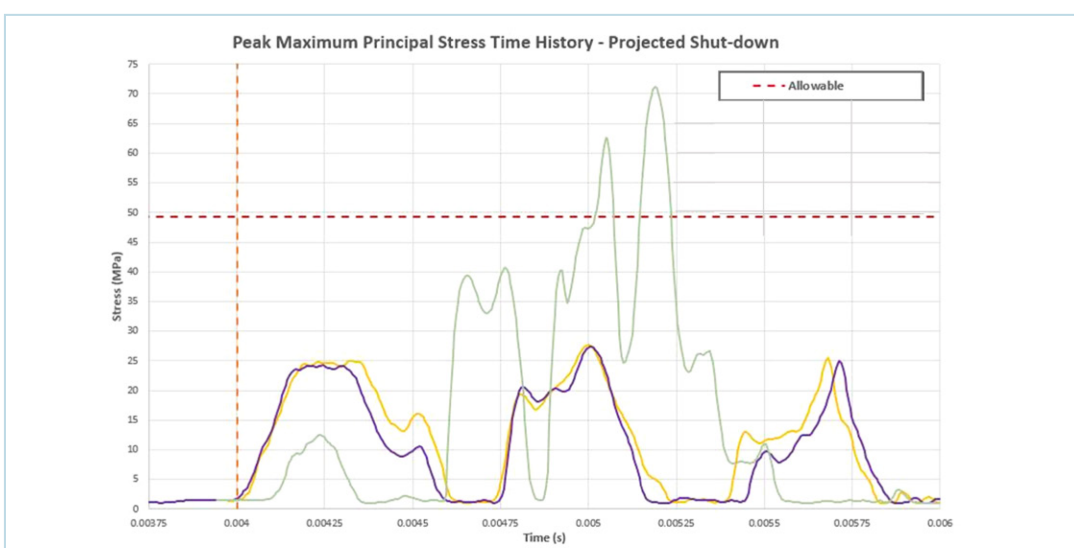


To assess the integrity of the SRGW, a history of the peak stress in this notch is recorded and compared with the strength derived from test (corrected for the effects of irradiation). A typical stress history curve is shown in Figure 9 and, in common with other variants of the model with severe brick misalignment and critical seal ring segment orientation, it exhibits a strength exceedance during the history. Based on the initial premise, this exceedance would indicate a SRGW fracture.

Such a finding is not atypical of an integrity assessment calculation. In the first instance a conservative assessment criterion (often stress or strain at a point) is deployed as an expedient. If a failure is indicated, a more accurate (and expensive) criterion is applied to resolve an apparent problem. Such is the case for the assessment of dynamic impact integrity of the SRGW: the failure stress is exceeded only for a small fraction of a second, so the ability of the impact to do fracture -work sufficient to create a fragment must be considered.

FIGURE 9

Typical SRGW/KWRC notch stress history from a PCM showing SRGW failure stresses following a KWRC at 28, 30 and 32fpy

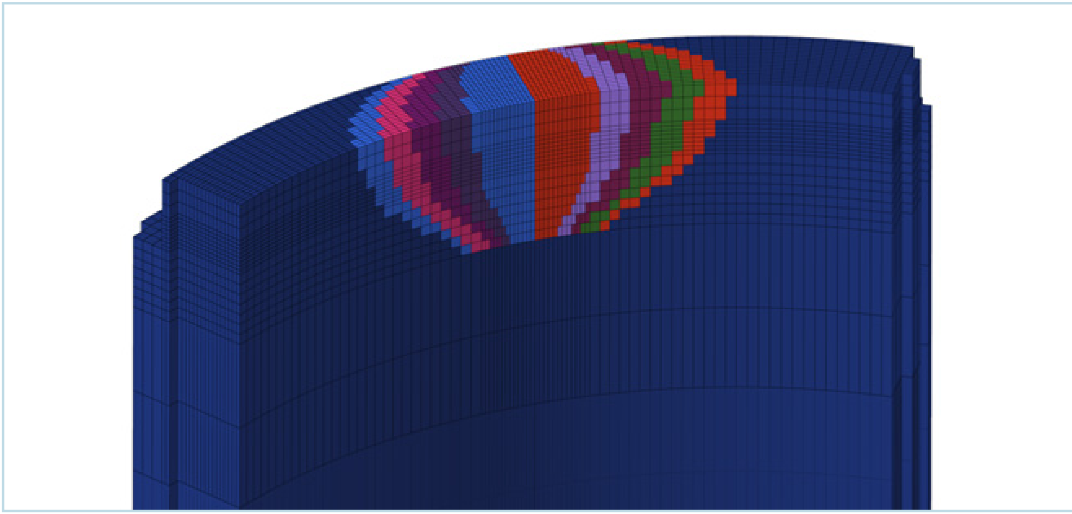


3.3 Energy-Based Integrity Assessment

To address the question of whether sufficient work can be done to fragment the SRGW, work-of-fracture arguments are deployed. As the size of the fragment likely to be formed is unknown, a range of fragment shapes is considered, as illustrated by the different colours in Figure 10, and the energy required to create each calculated. If the energy available to propagate the crack exceeds the work required to complete the crack propagation, the potential for fragment formation exists.

FIGURE 10

Different SRGW fragment sizes considered for prompt fragmentation



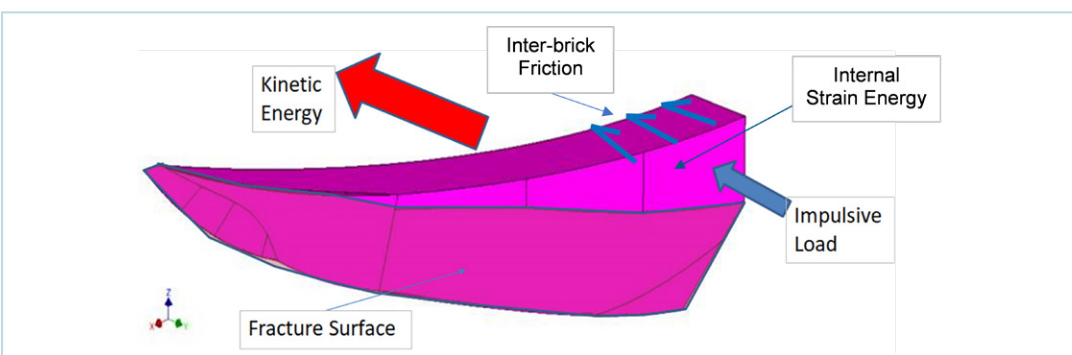
The most difficult aspect of this calculation is the determination of available energy, as it comprises:

- Work done on an incipient SRGW fragment by:
- the seal ring segment and
- friction between adjacent fuel bricks.
- Elastic strain energy released when the crack propagates.
- Kinetic energy in the fragment.

These mechanisms are illustrated in Figure 11 and can be calculated from data extracted during the short period when the notch stress exceeds the strength derived from test. The result of such an assessment is shown in Figure 12, which indicates that the sum of the strain and kinetic energy available and the work done on fragments of a range of sizes falls well short of the fragmentation "energy required" even when two standard deviations are allowed for variance of the graphite work of fracture.

FIGURE 11

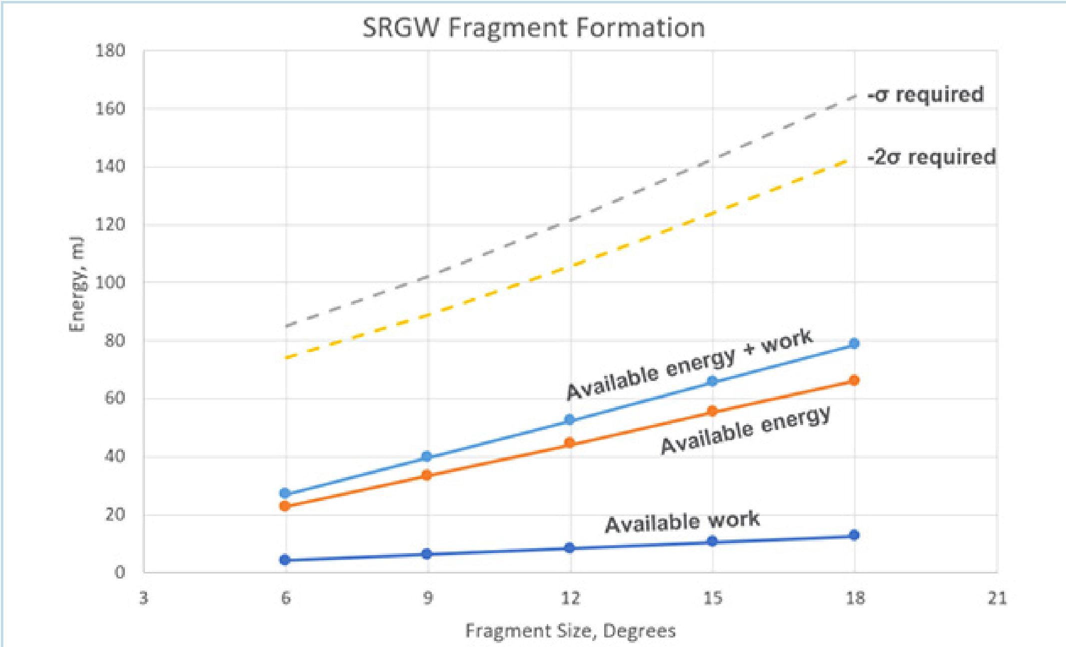
Work and energy components contributing to crack front propagation



This energy assessment demonstrates that, at the target KWRC opening of 2mm, although a crack can be initiated in the SRGW, this crack does not lead to an immediate fragment because there is insufficient energy available to do the fragmentation work.

FIGURE 12

Output from an energy-based fracture assessment with a 2mm KWRC opening



3.4 Seal Ring Groove Wall (SRGW) Prompt Fragmentation with Time

As has been explained, the graphite fuel bricks exhibit dimensional change under irradiation that induces stresses within the brick. These stresses can lead to cracking of the brick, the timing and size of which will be determined by its mechanical properties. In general:

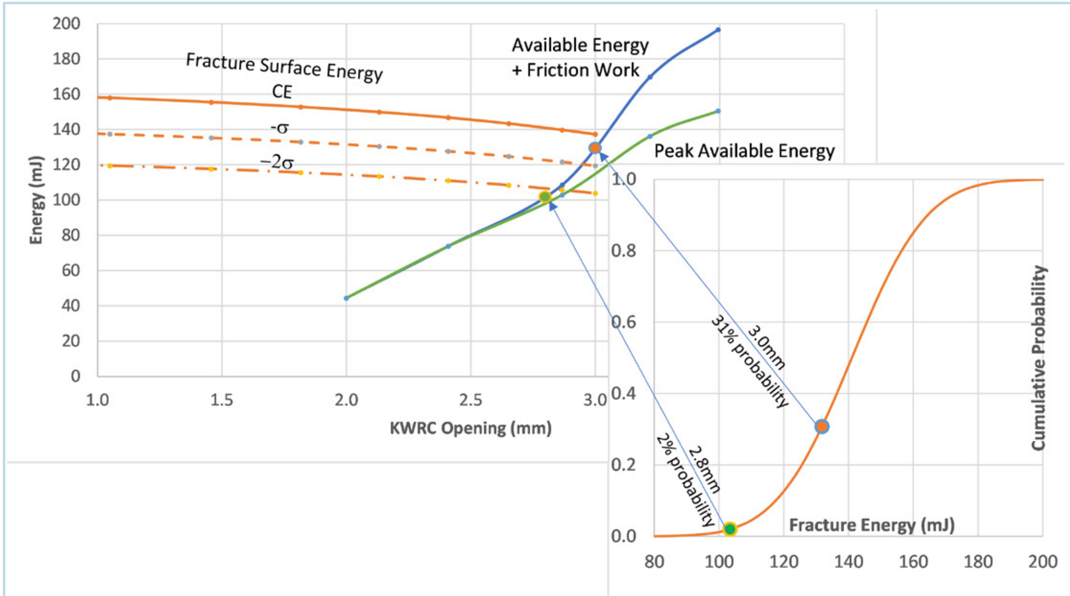
- stiff bricks crack early – stresses are higher for a given dimensional change;
- weak bricks crack early – they are least able to resist internal stress fields;
- KWRC openings increase over time (Figure 6).

These observations suggest the greatest threat for prompt SRGW fragments is found in strong, flexible bricks because this combination delays KWRCs until dimensional change has generated sufficient internal stress for a large, energetic crack opening. Early cracking, from weak or stiff bricks, results in an opening that analysis shows lacks the energy to generate a prompt SRGW fragment. Nevertheless, Figure 6 indicates that 5% of bricks could exhibit KWRC openings of 2mm or more as early as 27fpy so the analysis demonstrates only that SRGW fragments are unlikely before this time.

By examining KWRC openings larger than 2mm it becomes possible to assess at what time prompt SRGW fragments will become prevalent. A summary of this assessment is depicted in Figure 13, which shows that the probability of fragment formation increases rapidly as the instantaneous KWRC opening increases. At 2.8mm of KWRC opening the estimated probability of fragmentation is just 2%. However, a small increase in this opening to 3.0mm increases the probability of fragmentation to 30% owing to the increased availability of strain energy and work done by inter-brick friction to exceed the work required to create the fragment fracture surface. An additional influence at this larger KWRC opening is the reduction in the central estimate fracture surface energy, which reduces as dimensional change increases with increasing reactor burn-up.

FIGURE 13

Energy-based fracture assessment for a central estimate fragment



One aspect of the problem not addressed by this assessment is whether the larger prompt KWRC openings of Figure 6 are attainable in operation. As dimensional change and strain energy increases within a brick, the drive for a KWRC to initiate and propagate increases commensurately. Thus, whilst prompt KWRC openings of 4mm and more might, theoretically, be possible, flaws in the graphite structure of the brick and the declining fracture toughness of the material as it ages usually mean that a KWRC propagates before such openings can be achieved. This consideration weighs further against SRGW fragment formation: when cracking arises, it is rarely with sufficient energy to generate extensive SRGW cracking.

4. The Onset of Delayed Seal Ring Groove Wall (SRGW) Fragmentation

The study of prompt SRGW cracking has shown that, although early, full-height axial keyway root cracking apparently presents a threat of early SRGW fragmentation, the opening of the KWRC at a low reactor burn-up is likely to be modest and transfer insufficient energy to generate a prompt SRGW fragment. As time passes, however, stresses arising from dimensional change increase, so the instantaneous KWRC opening also increases and the probability of a prompt SRGW fragment increases commensurately.

Once a KWRC has formed, irradiation of the fuel brick continues to increase the dimensional change within the brick, and this causes the KWRC to open further. Consequently, following the same mechanism illustrated in Figure 5, further cracking and potential fragmentation will arise. As described in Section 2.1, progressive cracking of the SRGW following further KWRC opening is termed delayed. Fragments that are formed by delayed cracking have the potential to be larger than prompt fragments and therefore present a greater threat to continued mobility of the fuel assemblies in their channels.

Despite this threat of delayed fragmentation, there is some opinion that SRGW fragments arising from progressive KWRC opening will not arise at all. There is evidence that crack growth can be slowed by material creep at the crack tip and this mechanism allows graphite to deform when under high loads in apparent defiance of its semi-brittle nature. This potential to avoid fragmentation is attractive because it serves to suggest that delayed fragmentation is less of a threat than it might appear.

4.1 Modelling Delayed Cracking of Fuel Bricks – Evolution Models (EVMs)

To investigate delayed cracking, the PCMs that have been used to address dynamic crack events have been adapted to address quasi-static, long-term crack propagation. This adaptation has incurred some challenging developments in the modelling techniques because, whilst the PCMs represent a moment in the life of a reactor fuel brick as a prompt crack forms, the adapted model must simulate not only the development of dimensional change and material properties over many years of reactor operation, but also the initiation and propagation of cracks over indeterminate timescales. This requirement arises because crack propagation can arise either quasi-statically (stable) or dynamically (unstable). The models that have been developed for this purpose have been termed evolution models (EVMs).

4.2 Modelling Time in the Evolution Model (EVM) – Time Dilation

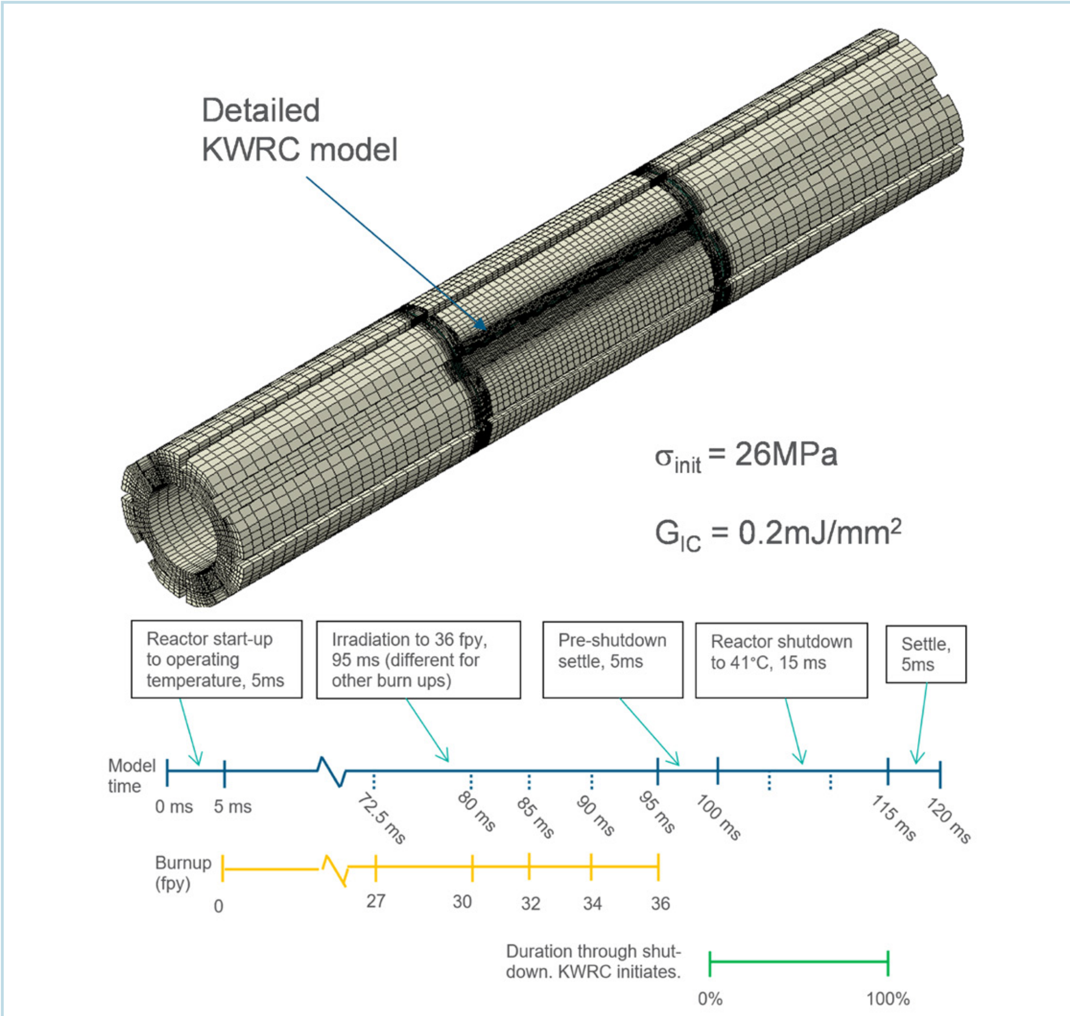
Like the PCMs, the EVMs are based on an explicit time-stepping formulation, this approach being best suited to simulating the complex contacts and separations that arise close to brick/component interfaces. Explicit models are constrained to simulate processes that evolve in fractions of a second, so they are ideally suited to addressing phenomena such as impact and fast fracture formation. However, they are inherently ill-suited to long-term processes, such as material evolution, because their small timesteps are incompatible with reactor operating lives of ~40 years. In the EVMs, this difficulty is addressed using “time dilation”.

Time dilation in the EVMs compresses long-term processes occurring over years, such as graphite evolution arising from irradiation, into milliseconds represented by an explicit analysis: the evolution (real) time is dilated relative to the analysis time. This acceleration in time, illustrated in Figure 14, is possible because strain rates arising from material evolution are measured in fractions of a percent/fpy so time acceleration does not incur large dynamic loads: the key discriminator between static and dynamic processes.

The analysis remains quasi-static, therefore, despite the compressed evolution rates. In the example shown in Figure 14, increments of 1fpy have been compressed into 2.5ms of analysis time – an acceleration factor of >10^{10} - without incurring significant dynamic loads.

FIGURE 14

Time dilation used in delayed crack modelling



Actual dynamic processes, such as rapid crack propagation, apply a constraint on time dilation. If prompt cracking arises, irradiation evolution must be halted to prevent evolutionary changes in the material as the crack propagates. This requirement imposes a complex restriction on the management of the time parameter, which must sometimes be accelerated to achieve manageable run times when graphite core evolution is being simulated, yet at other times adjusted to match real time when dynamic crack propagation is underway. This management is achieved by monitoring the speed and acceleration of nodes in the finite element model, moderating each during periods of graphite evolution to avoid significant dynamic loads, but shutting down evolutionary processes once peak values indicate the commencement of real dynamic events. This technique is termed "active time dilation", which both prevents concurrent material evolution with rapid cracking processes, whilst also evolving the material at the optimum rate to compress analysis times.

4.3 Quasi-Static Crack Propagation

When assessing prompt SRGW cracking using the PCM, it is necessary to determine only whether a fragment can form. Therefore, the PCMs make no attempt to calculate the development of crack patterns: they merely examine the energy balance between fragmentation energy and the available energy following a KWRC. Quasi-static crack propagation and fragment formation differ because a fragment can be formed over an extended time, so it is important to calculate the evolution of strain energy development as the fuel brick undergoes progressive dimensional change, and energy release as a crack propagates. This need to represent the evolution of crack growth demands that a crack is modelled explicitly.

Under quasi-static crack growth, as with prompt cracking, the fuel brick remains vulnerable to the SRGW mechanism illustrated in Figure 5. However, it is susceptible also to other mechanisms elsewhere in the brick, such as secondary radial keyway root cracking where a second radial keyway cracks. The required output from the model is two-fold:

The timing of the cracks to assess when integrity of the bricks starts to be compromised.

The extent of the cracks to ascertain whether they might culminate in fragments.

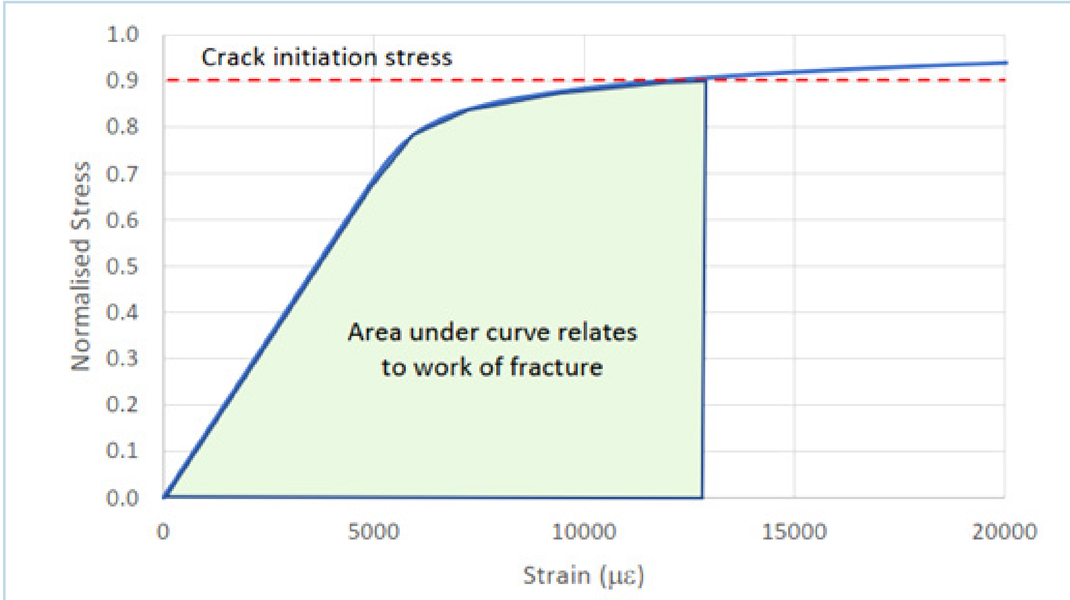
Whilst the cohesive surfaces used for the simulation of KWRC propagation work well when the direction of crack growth is known, for the SRGW the direction of crack growth needs to be established from the stress and strain fields calculated by the model. To achieve this need, element deletion has been implemented within the model: a technique widely used in explicit finite element formulations. This approach to crack modelling is termed "erosion". Erosion has the advantage that no pre-definition of the crack path is required, whilst it has the potential to predict both the timing and the extent of crack growth. It has the disadvantage that it generally requires very refined meshes in the regions where fracture is anticipated. Hence, analysis run times are long because the models have many elements and the time step, which is proportional to the smallest element side length, is small.

4.4 Graphite Failure Model

To calculate when an element should be eroded (deleted), the graphite failure model must recognise when both the crack initiation stress and the fracture energy have been achieved. This need is satisfied by adopting an elasto-plastic stress-strain curve of the form illustrated in Figure 15, wherein the curve is calculated to have absorbed the work of fracture at the point when the crack initiation stress is reached. At this moment the element is eroded, ensuring that both stress and energy requirements are satisfied. In the material model, the energy must be adjusted to account for element size to ensure that the energy in the element at deletion is equivalent to that associated with the fracture surface created – the energy to create free surface.

FIGURE 15

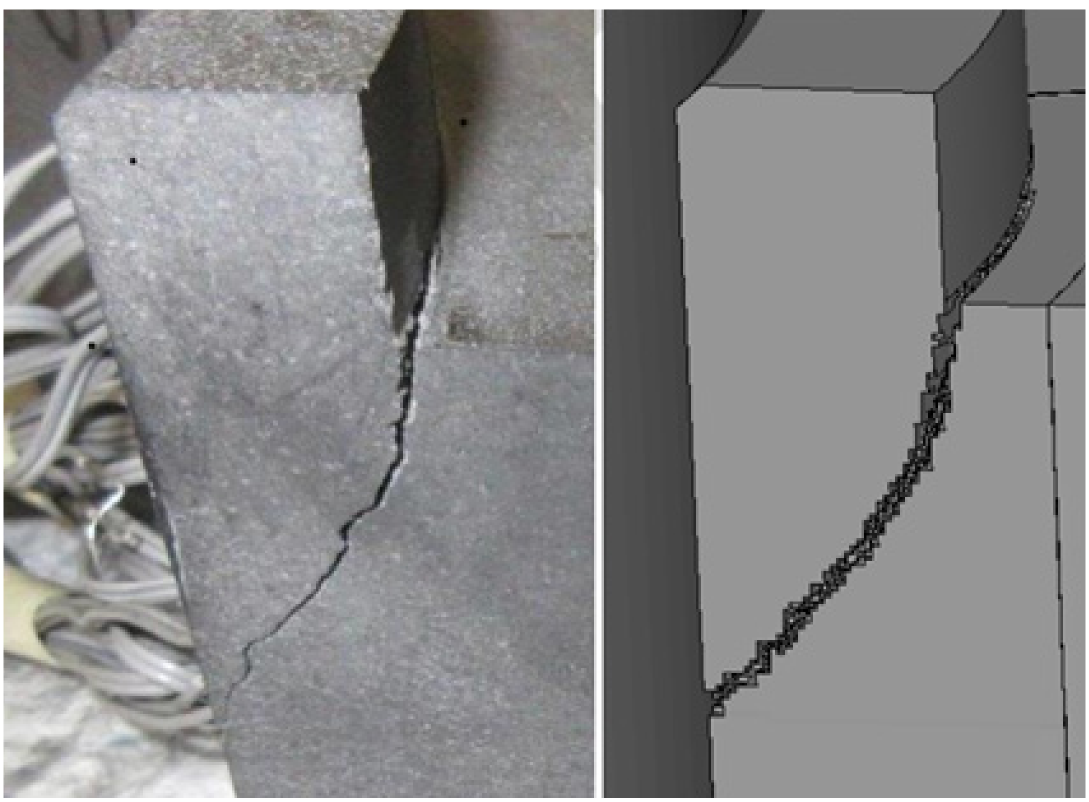
Graphite stress-strain curve for erosion modelling



This fracture model has been "tuned" to match data from a static rig test (Figure 16), but it is corrected to account for changes in material modulus, strength and work of fracture following irradiation. Further validation analysis conducted using this material model has shown that it correlates with data from other tests, reinforcing confidence in its suitability.

FIGURE 16

Correlation between static rig test (left) and graphite fracture model (right)



Difficulties have, nevertheless, been experienced arising from unexpected element erosion. These difficulties often stem from dynamic effects arising at the moment an element is eroded, as erosion results in large force imbalances on nodes immediately adjacent to the crack front. The unwanted effects can be suppressed by judicious damping of high-frequency modal responses. Other issues arise when large contact forces and compressive strains are developed, but techniques have been developed to address these problems also.

4.5 3-Brick Reactor Model

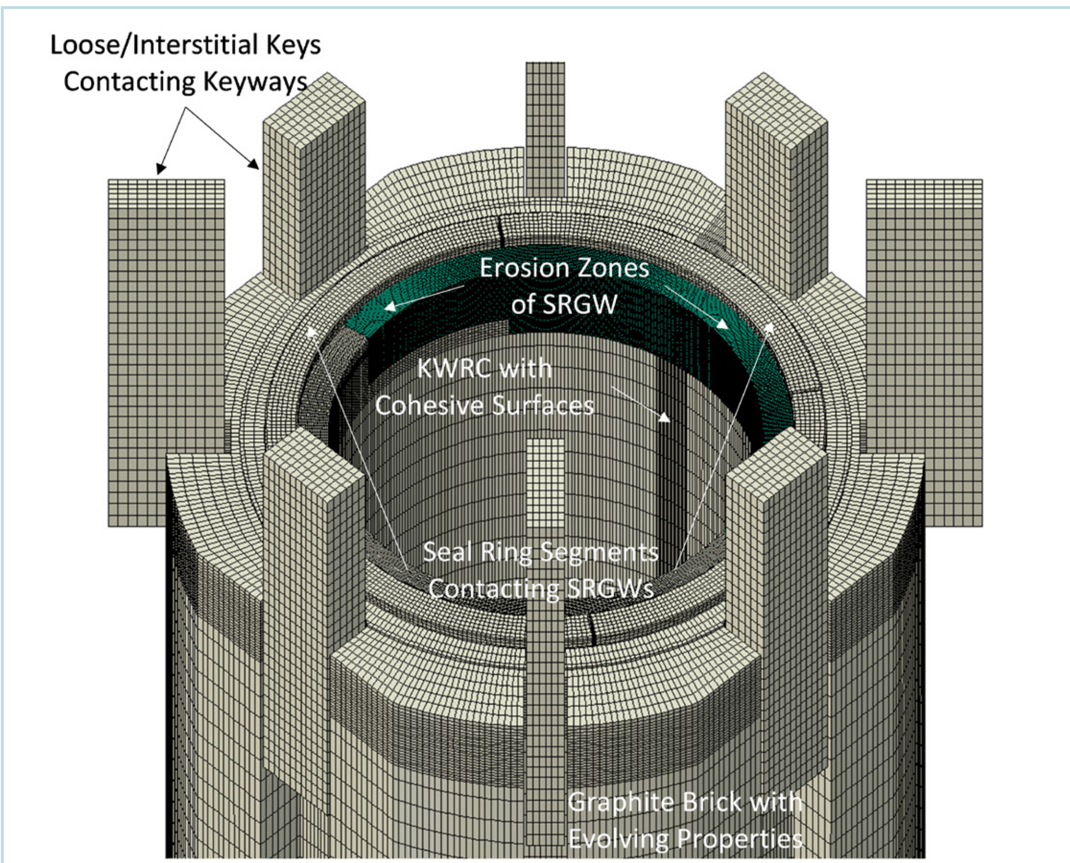
Figure 17 illustrates the main features of the central, cracked brick in the 3-brick EVM, which has been developed for delayed crack modelling. The main features may be summarised as:

- A graphite material model that allows stiffness, strength, dimensional change, creep and work of fracture to evolve over time.
- Seal ring segments that contact the seal ring grooves and restrict relative movement.
- Loose and interstitial keys that contact the radial keyways, restricting relative movement.
- Erosion zones that permit fracture modelling of the SRGW.

Controlling this model is active time dilation that applies varying rates of material evolution to minimise analysis time when the brick is not cracking and slows down or stops evolution when cracks are propagating. This brick model is incorporated into a 3-brick assembly of the type shown in Figure 7.

FIGURE 17

Key features of the cracked brick in a 3-brick EVM

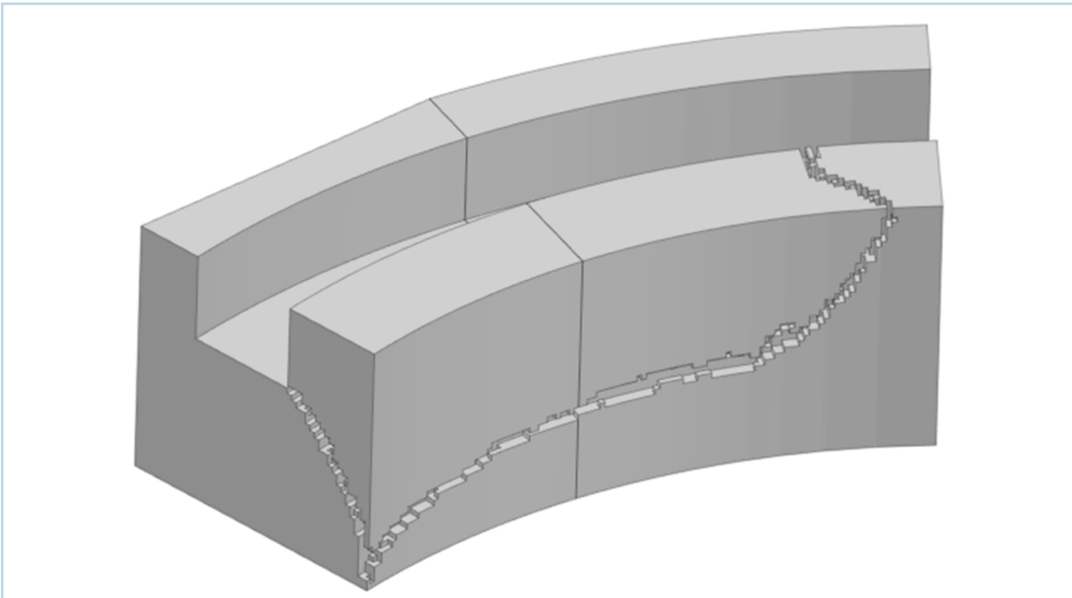


4.6 Output from the 3-Brick Evolution Model (EVM)

Figure 18 illustrates output from fracture analysis of the SRGW on a fuel brick. In this view the seal ring and the adjacent brick are not shown. The geometry of the fragment boundary is visible from the figure and the effect of discretisation in "digitizing" the form of this boundary is apparent. There is evidence of excess element deletion at the crack front arising from the dynamic effects described previously, and efforts are ongoing to minimise the impact of this characteristic.

FIGURE 18

Figure 18: Cracking and fragmentation in the SRGW exhibited by the erosion approach (seal ring not shown)

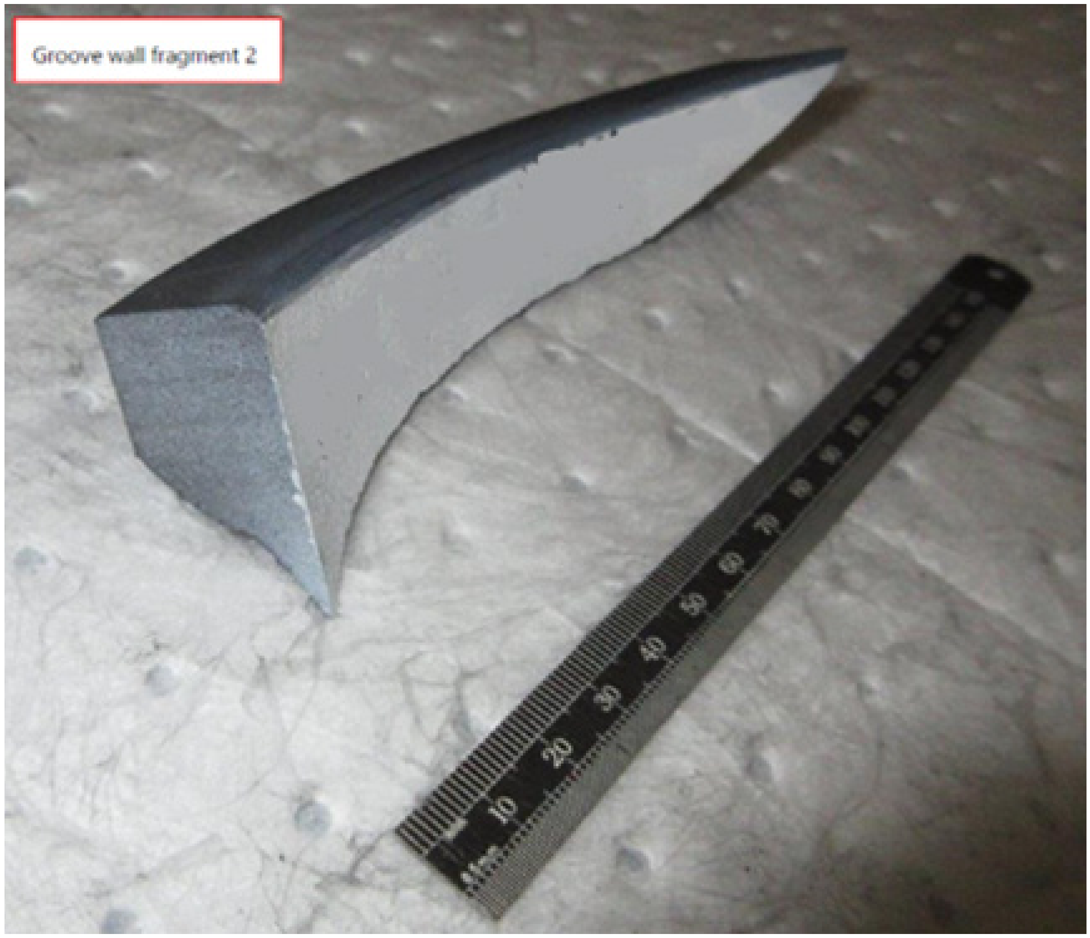


The predicted fragment shape from Figure 18 can be compared with that resulting from rig testing of a static specimen shown in Figure 19. The characteristic shape of the fragment is apparent, although differences in details of some features are visible. Some of these differences arise from the implementation of the graphite erosion model discussed previously. Some, however, arise from the level of time dilation that is applied within the 3-brick EVM, which is time-consuming to run on account of the model size and the small timestep. A target analysis duration of three days is expected to be met, but currently the model is being run too quickly to simulate truly quasi-static KWRC opening. A feature that illustrates this shortcoming is the fragment length, which is under-estimated by the model because inertial forces add to quasi-static mechanical forces, accelerating cracking.

The 3-brick reactor model has exhibited other mechanisms that modify the form of SRGW fragments. Loose keys (Figure 17) that span the interface between vertically-adjacent fuel bricks modify the constraint forces applied through the SRGWs, so failure of such keys must be considered when calculating SRGW time to cracking. Secondary KWRCs also influence strongly the force transmitted through the SRGW between adjacent bricks, so these, too, may delay SRGW fragment formation. Whilst the facilities to incorporate all these effects have been included in the 3-brick model, work remains to be done to have all these components working well.

FIGURE 19

SRGW fragment arising from a static test on a rig specimen



5. Summary – the Future for Reactor Brick Model

The model is currently (August 2023) undergoing further modifications that will reduce the analysis run time and improve the material erosion model. Developments to the evolution component of the graphite model have also been identified that will help the model to mimic more closely the behaviour of fuel bricks in the reactors.

A vital requirement for these modelling techniques, if the reactor model is to support a safety case for ongoing operation of a station, is validation against rig test output and measured reactor data. EDF has undertaken copious rig testing of un-irradiated graphite specimens over many years, so the modelling team is progressively working through the data from these tests, comparing and adjusting the erosion model to achieve a good match of fracture load, energy absorption and crack morphology. Data for irradiated graphite are more difficult to acquire. The approach will be to match the characteristics of crack formation observed during inspections made at times of station reactor outages. Simulating reactor observations can be assisted using material data extracted from trepanned graphite samples from the reactor bricks. At present, however, the reactors exhibit limited cracking so validation data are not extensive.

The target analysis time of three days is thought to be achievable through the introduction of efficiencies in the graphite material model and short-cuts in a variety of modelling features, such as the use of reduced-integration elements, which are efficient when, as in the EVM, element sizes are small. Nevertheless, the fuel bricks in the graphite reactor cores are subject to such a range of variances arising from material properties, existence of inclusions and flaws, geometric alignment, and intensity of irradiation, that to perform a whole-core crack assessment of the reactors addressing all threats of core fragmentation would require a very extensive exploration of the variance space. Therefore, identifying those parameters that represent the most significant risk of early fragmentation, and hence the early threats to continued operation of the reactors, will be the priority for extending the life of the stations. The strategy will then be to continue to extend the scope of the variance studies to assess how the threat to continued operation evolves over time. In this way, it is hoped that the life of the stations can be extended, risk free, despite observed instances of KWRCs, secure in the knowledge that fragments that might interfere with fuel assembly mobility will not occur.

Acknowledgements

The work has been wholly funded by EDF Energy for the purpose of extending the life of the AGRs.

The author is indebted to engineering staff at EDF, and particularly to Mr Jonathan Wright, who has led the SRGW integrity work on behalf of EDF and has provided constant encouragement and guiding advice, whilst making many constructive suggestions. Also, to Mr Bruce Davies, who recognised the potential of the overall approach, and Drs Neil McLachlan and Mark Bradford, who have been active in both supporting and challenging many aspects of the modelling methods. Finally, to Mr Jim Reed, who has been unwavering in his enthusiasm and encouragement.

The Atkins (now AtkinsRéalis) team has comprised many innovative spirits over the course of four years of developments. Foremost amongst these colleagues have been Stuart Bounds, Felicity Starr, James Bostock, Robin Dickenson, Kenneth King, Daniel Smith, Phillip Francis, Douglas Aitchison and Matthew Purcell.

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The Development of Sprayed Concrete Tunnel Lining Design Over the Past 15 Years – A UK Perspective

Abstract

Since the Crossrail project and over the last 15 years, the UK tunnelling industry has seen significant development in sprayed concrete tunnel lining design for the sequential excavation method. This is demonstrated by the wider adoption of composite shell design approaches for multi-layered linings with various interfaces, advances in materials technology and the replacement of conventional steel reinforcement with steel fibres at major tunnel projects. All these have posed new challenges for tunnel engineers.

This paper aims to present the development of tunnel lining design from a UK perspective, based on the author's experience in both research and practical design. Recent developments in understanding the multi-layer lining behaviour will be presented. The use of an elastoplastic constitutive model for concrete and the inclusion of early-age thermal and shrinkage effects to predict the crack width of tunnel lining are then discussed. The latest findings on the stress status of the sprayed waterproofing membrane interface sandwiched between two concrete lining layers under combined ground and groundwater pressure will also be described. The implications of the above developments on efficient lining design and construction for future AtkinsRéalis tunnelling projects will be considered in the final section.

Keywords

Sprayed concrete tunnel; Sprayed waterproofing membrane; Lining design; Numerical modelling; Composite action

1. Introduction

The Crossrail project, now known as the Elizabeth Line, was the biggest tunnelling project in the Northern Hemisphere in 2008. A number of innovations were adopted for the sprayed concrete lining (SCL) tunnels, which was the chosen construction method for several station tunnels, crossover caverns, access shafts and route-wide cross passages in central London. The key innovations include the adoption of the composite SCL tunnel lining configuration in the construction, the use of steel fibres to replace conventional steel reinforcement, etc. These innovations were adopted for the first time in a major urban metro project under the groundwater table in the UK and have led to various benefits, such as reduced embodied CO^2 emission, improved health and safety performance during construction and shortened construction programmes (Su and Thomas 2015). However, the full implications of these innovations to tunnel lining behaviour were not fully understood around that time. Over the last fifteen years, many lessons have been learnt through practical design and construction, as well as academic research on these innovations. This paper aims to provide a comprehensive overview of the advancements in sprayed concrete tunnel lining design for the sequential excavation method from a UK perspective, serving as a valuable reference for AtkinsRéalis' future projects globally.

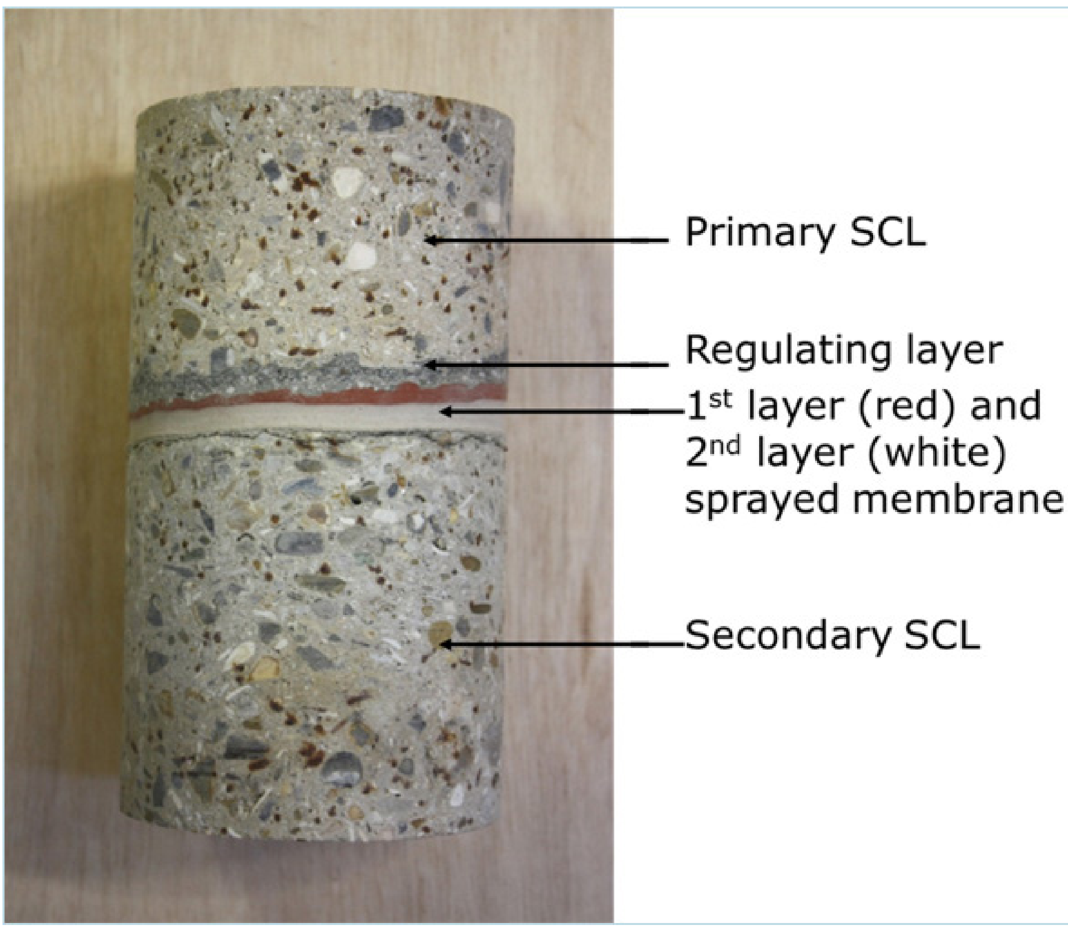
This paper will first introduce the design approach adopted for Crossrail's SCL tunnels, representing the most advanced approach in 2010. The development of an understanding of the behaviour of multi-layer permanent linings with various interface types will be described. This paper will then introduce the latest industry practice of utilising elastoplastic constitutive models to predict the crack width in fibre-reinforced concrete tunnel linings. Following that, the paper will discuss the latest research findings concerning the stress status of the sandwiched sprayed waterproofing membrane interface when under combined ground and groundwater pressure. In the end, the implications of these developments on the lining design efficiency will be briefly discussed, allowing for a comprehensive understanding of this emerging multi-layer lining framework.

2. Crossrail Design Approach

Crossrail SCL tunnels adopted three different multi-layer lining configurations. The first two consist of a permanent primary lining, a sprayed or sheet waterproofing membrane, and a permanent secondary lining. This paper will refer to these configurations as 'partial composite lining' and 'non-composite lining'. The primary and secondary linings predominantly utilise steel fibre reinforcement, with conventional steel reinforcement only for the secondary lining invert. At tunnel junctions, an additional layer known as the thickening layer is sprayed onto the intrados of the primary lining. This layer is reinforced with steel and establishes a direct concrete-to-concrete contract with the primary lining, referred to as the 'fully composite lining' (the third configuration) in this paper. The thickening layer is followed by the sprayed or sheet waterproofing membrane and the secondary lining. A typical composite SCL tunnel lining with sandwiched sprayed waterproofing membrane is shown in Figure 1.

FIGURE 1

Typical composite SCL tunnel lining with sandwiched sprayed waterproofing membrane



In the early 2000s, the introduction of the first sprayed waterproofing membrane for tunnel applications marked a significant development. The membrane supplier asserted that the double-bond nature of the sprayed waterproofing membrane would effectively create a composite structure when applied between two layers of permanent linings. This composite action, characterised by shear transfer at the membrane interface, was believed to offer benefits such as reduced lining thickness. This claim was readily accepted by the UK tunnelling industry. Following the same principle, the Crossrail Civil Engineering Standard explicitly stated that composite action (i.e. shear transfer at the membrane interface) should not be considered in the design of SCL tunnels (Crossrail 2010). As a result, the partial composite linings, featuring a sprayed membrane sandwiched between two layers of permanent linings, were treated in the design as non-composite linings with a sheet membrane. The design did not consider any tension or shear transfer at the membrane interface. In the Crossrail SCL tunnel design, linear elastic beam elements were employed to simulate the primary and secondary linings. Compression-only interface elements were utilised to represent the non-composite membrane interface. The plastic behaviour of the steel fibre-reinforced concrete lining was modelled using a plastic hinge function with restricted rotation angles.

Although the Crossrail SCL tunnel design was considered highly advanced in the early 2010s, the limitation of not considering composite action in the design prevented full exploitation of the opportunity that truly composite actions afford. During the construction phase, unexpected longitudinal cracks were observed, and their underlying causes were only well understood until recently (Su, 2023c). Furthermore, the anticipated lining thickness reduction was not fully realised after adopting the partial composite SCL configuration. These observations collectively indicate a need for a more comprehensive understanding of the behaviour of multi-layer tunnels with different interface types. The subsequent sections of this paper will highlight some recent developments within the multi-layer lining (MLL) framework (Su, 2022a).

3. Composite Actions Within a Multi-Layer Lining Framework

This section presents an improved understanding of the principle of composite action and its short- and long-term impact on tunnel lining behaviour.

3.1 The Principles of Composite Action

When a composite lining is in pure bending under the action of an external global long-term consolidation bending moment Mglobal, a reversing "zigzag" shaped stress block would be expected to occur within each of the individual beams. Depending on the magnitude of shear stress transfer at the membrane interface, there could be full composite, partial composite or no composite action, as shown in Figure 2. These three degrees of composite action correspond to direct concrete-to-concrete contact (full composite action), sprayed membrane interface (partial composite action) and sheet membrane interface (no composite action). These stress blocks can be split into two components: (1) bending stresses and (2) axial stresses, as shown in Figure 3. Essentially, the effect of composite action is to convert bending stress to axial stress so that using the whole lining cross-section better resists stress and reduces the maximum stress at the extreme fibre. The high degree of composite action is ideal for composite structures utilising steel elements to resist tension. This is not ideal for composite lining because neither the primary nor secondary concrete layer is ideal for resisting a combined tension and bending status (Su et al. 2019). In addition, for actual tunnels constructed in the ground, the SCL tunnel with a higher degree of composite action will attract more bending moments, which in turn will be converted to axial compressive or tensile stresses. This may lead to cracks appearing at specific positions of the thickening layer or the secondary lining (Su 2022b).

FIGURE 2

Stress and strain distributions through linings for different degrees of composite action assuming linear elastic behaviour (from Su and Bloodworth 2018)

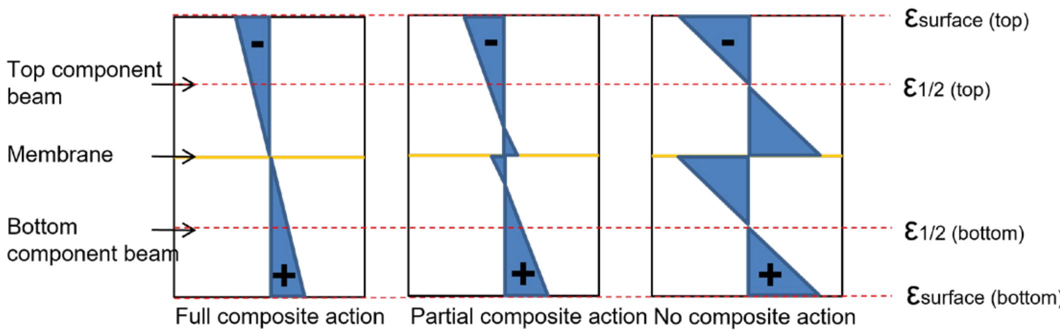
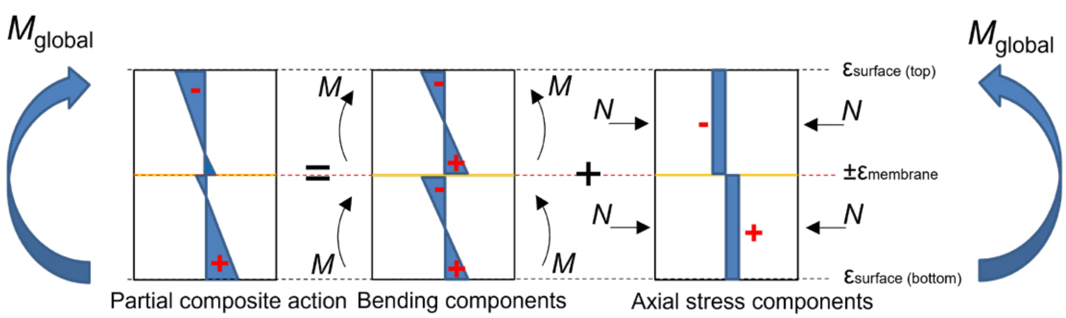


FIGURE 3

Breakdown of composite lining stresses due to global bending into bending and axial stress components (from Su and Bloodworth 2018)



3.2 The Effects of Composite Action on the Tunnel Lining

For the partial and fully composite linings, composite action gives rise to different short- and long-term effects on tunnel linings. In the short term, immediately after the installation of the secondary lining and prior to the application of external ground loads or groundwater pressure, the secondary lining is bonded to the primary lining. The double bond nature of the sprayed membrane (in partial composite) and the direct concrete-to-concrete contact (in full composite) restricts the secondary lining movement due to early-age thermal and shrinkage effects. Consequently, tensile stress is typically generated in the secondary lining during this stage.

The maximum tensile stress is typically observed at the crown and knee position of the secondary lining, as shown below in Figure 4 (left). The stress at the knee position is usually not a concern due to steel reinforcement. In comparison, the maximum tensile stress at the secondary lining crown is a significant concern due to the lining being only reinforced by steel fibres. The higher the degree of composite action, the greater the maximum tensile stress at the secondary lining crown. Hence, there is an increased risk of secondary lining cracks.

In contrast, if a sheet membrane is used (in a non-composite configuration) or debonding occurs at the membrane or direct concrete-to-concrete interface, different stress distributions may arise, leading to no cracks or cracks appearing at different positions within the lining. The secondary lining tensile stress distribution for a typical non-composite lining configuration is shown in Figure 4 (right). Over the past decade, longitudinal cracks have been observed at the crown position of the secondary lining (partial composite) and the thickening layer (full composite) on several major tunnelling projects in the UK. This highlights the need for further research on this emerging topic.

In the long term, once the primary and secondary linings have experienced the long-term ground load and groundwater pressure, the resulting bending moment is partially converted into axial compression and tension forces in both linings, as discussed earlier. Understanding the distribution of these converted forces between the primary and secondary linings is crucial to understanding the lining system's long-term behaviour. Based on a series of numerical analyses and observations from real projects, it is concluded that an ideal sprayed membrane interface for composite SCL tunnels with relatively thick primary and secondary linings that are constructed in stiff clay should have a high tensile and shear bond between the primary lining and the sprayed waterproofing membrane and high tensile and shear strength of sprayed waterproofing membrane itself but low normal and shear stiffness of the sprayed waterproofing membrane. The purpose of the former is to ensure the integrity of the composite SCL tunnels under various loading conditions, while the latter is to reduce the loads the secondary lining will resist. A comprehensive exploration of the long-term impact of composite action on the secondary lining will not be elaborated further in this paper. More detailed information on this topic can refer to the works of Bloodworth and Su (2018), Su and Bedi (2019), and Su (2022b).

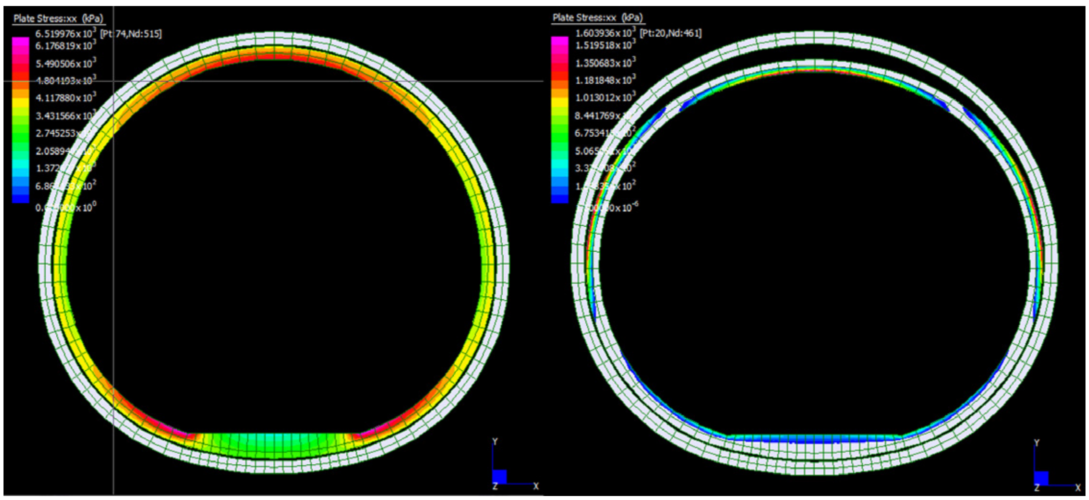


FIGURE 4

Secondary lining stress for SCL tunnels with a bonded interface (left) and an unbonded interface (right) (from Su et al. 2019)

4. Numerical Analyses of Multi-Layer Tunnel Linings

Building upon the improved understanding of composite action in concrete tunnel linings discussed in the previous section, this section will provide a concise overview of a case study.

In a deep tunnel project, the designer was tasked by the contractor to determine the optimal time (in days) for commencing the casting of the next ring of secondary lining concrete without causing excessive width cracks in the current early-age secondary lining ring under temporary construction loads. The full composite lining system adopted in this project involved no membrane interface between the SCL primary lining and the cast in-situ concrete secondary lining. Waterproofing admixture was added to the primary lining concrete mix as the main waterproofing measure. Both lining layers were reinforced solely with steel fibres.

This design posed several challenges, including estimating the peak and residual tensile stress capacity of the early-age cast in-situ concrete lining reinforced with steel fibres. Accurately predicting the strain induced by secondary lining early-age thermal and shrinkage effects proved a complex task. Compounding the difficulty is the identification of gaps between the two layers of linings during an earlier secondary lining concrete pour in another tunnel. These gaps were attributed to settling caused by the self-weight of the secondary lining concrete at the crown area and volume contraction resulting from early-age thermal and shrinkage effects. As a result, there needs to be more certainty regarding the bonding conditions between the two layers of linings. A numerical parametric study was conducted to account for the uncertainty in bonding conditions.

Various combinations of bonding conditions between the rings under construction and previously completed rings were considered. The primary and secondary linings were simulated using volume elements, enabling the observation of principal tensile stress at the lining surface. Figure 5 shows the deformation and principal tensile stress of the secondary lining at two crucial stages of the analysis. These visual representations provide insights into the response of the secondary lining under different loading conditions.

The successful construction of the cast in-situ concrete secondary lining in accordance with the designer's intent resulted in a maximum site-measured crack width of slightly less than 0.3mm, well in alignment with the prediction. This achievement is significant as it demonstrates the effectiveness of the modelling approach in predicting crack width in steel fibre-reinforced concrete linings. Previously, this modelling approach has only been adopted to predict the long-term crack width, which cannot be immediately measured for verification. This case study provides tangible evidence supporting the effectiveness of the modelling approach. Meanwhile, using volume elements in the analysis enables a comprehensive understanding of stress distribution across the entire depth of different tunnel lining layers. This cannot be achieved by using beam or plate elements to model the tunnel lining. For a more detailed description of the modelling approach, please refer to Bloodworth and Su (2018) and Su and Bloodworth (2019). Furthermore, an additional case study investigating the impact of early-age thermal and shrinkage on the performance of the SCL tunnel thickening layer can be found in Su (2023c).

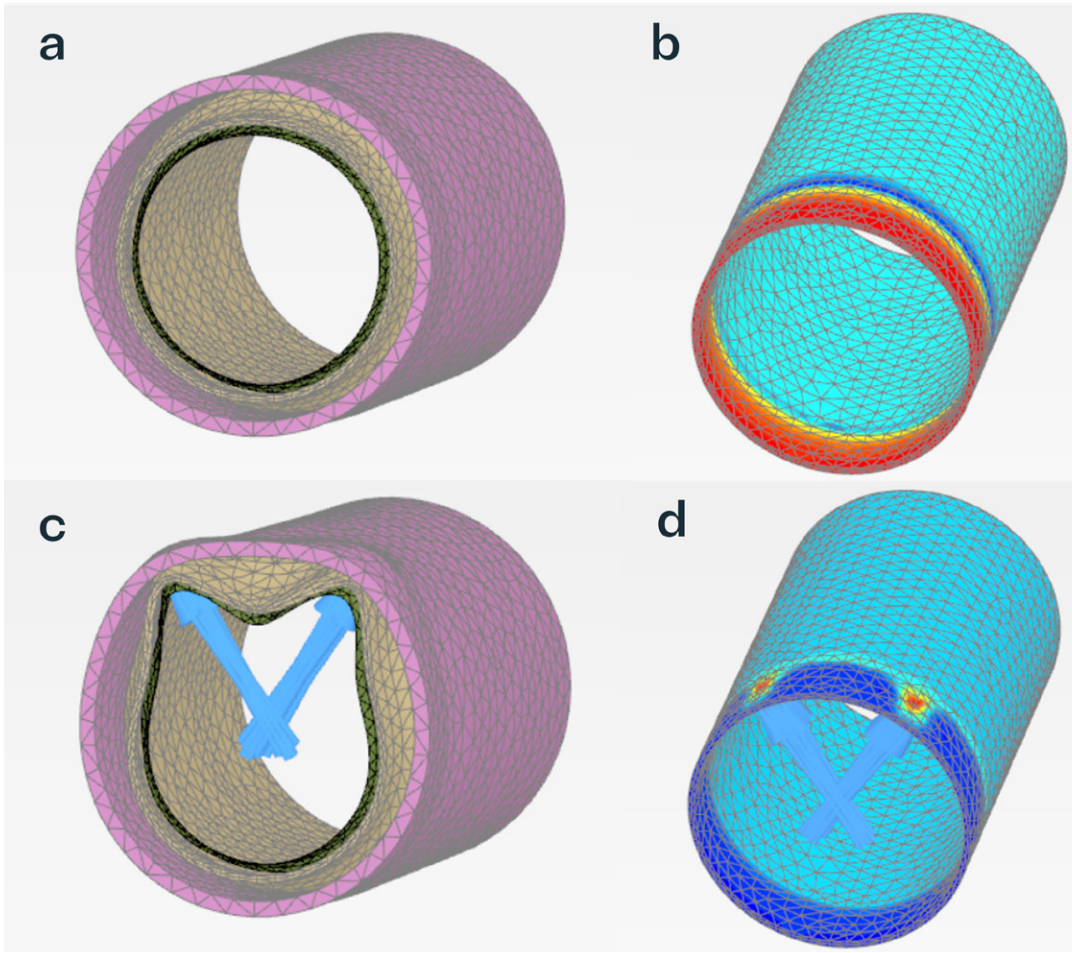


FIGURE 5

Early-age thermal and shrinkage-induced secondary lining deformation (a) and principal tensile stress plot (b). Subsequent construction load-induced lining deformation (c) and principal stress plot (d) (from Su 2022a)

5. Testing of Bond Strength of Sprayed Membrane

Understanding the mechanical properties of the membrane interface is crucial for its effective use as a construction material in tunnel linings (Dimmock et al. 2014). Early laboratory research primarily focused on the mechanical properties of the dry membrane interface (Su and Bloodworth 2016, 2018). However, it was later discovered that the moisture condition of the membrane interface significantly influences its mechanical properties (Holter 2016, Holter and Geving 2016). This led to a shift in research focus towards understanding the long-term mechanical properties of the membrane interface in wet conditions and its impact on lining performance. Currently, the main obstacle hindering the widespread adoption of partial composite SCL tunnels using sprayed membranes is the relatively low tensile bond strength obtained from existing testing methods. Based on experience in designing SCL tunnels with sheet membranes, designers typically assume that the sprayed membrane and its interface with the primary lining intrados will be subjected to tension under groundwater pressure. Consequently, the dolly test, which applies direct tension to the membrane, is commonly employed to verify the bond strength on-site.

To investigate the long-term bond strength of composite SCL specimens with wet membranes, tests were conducted by applying static downward loads to effectively pull the membrane apart. These tests yielded a minimum tensile strength of 0.2 MPa (Diez et al., 2019). This implies that partial composite SCL tunnels with sprayed membranes would lose their structural integrity if constructed more than 20m below the groundwater table. Consequently, partial composite SCL tunnels can only be designed as non-composite SCL tunnels, with the secondary lining designed to be sufficiently thick to withstand groundwater pressure and long-term consolidation ground loads, if present. This explains why the Crossrail project did not achieve the expected reduction in lining thickness when adopting a composite SCL tunnel configuration. In recent years, the author has conducted detailed investigations challenging this conclusion. The following section will delve into the layout and the stress state of the membrane interface, providing further insights into this issue (Su and Bloodworth, 2022; Su, 2023b).

5.1 Functions of the Membrane Interface in Composite Shell Linings

A composite shell lining physically comprises primary and secondary linings with a sandwiched sprayed membrane. From a structural perspective, there are two interfaces between the membrane and the concrete linings – the primary-membrane and secondary-membrane interfaces. Conceptually, the sprayed membrane and the two interfaces can be described together as the 'membrane interface'; the definitions of these terms and their relationships are shown in Figure 6. The membrane interface functions on two levels in the composite shell lining, as shown in Figure 7 (Su and Bloodworth, 2022). The first level is to ensure the primary and secondary linings work compositely without failure occurrence at the membrane interface, which is a prerequisite for the second level function. The second level is in the determination of the lining forces (i.e., axial force and bending moment) induced in the primary and secondary linings under various loading conditions as a consequence of the composite action. This section focuses on the first level function of the membrane interface, specifically on the tensile failure (i.e. debonding) of the membrane interface caused by the application of water pressure.

FIGURE 6

Definition of technical terms in composite shell lining (from Su and Bloodworth 2022)

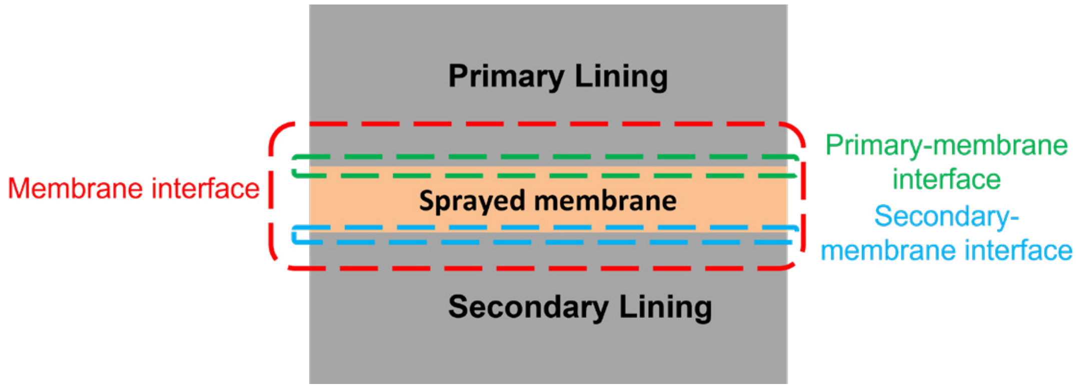
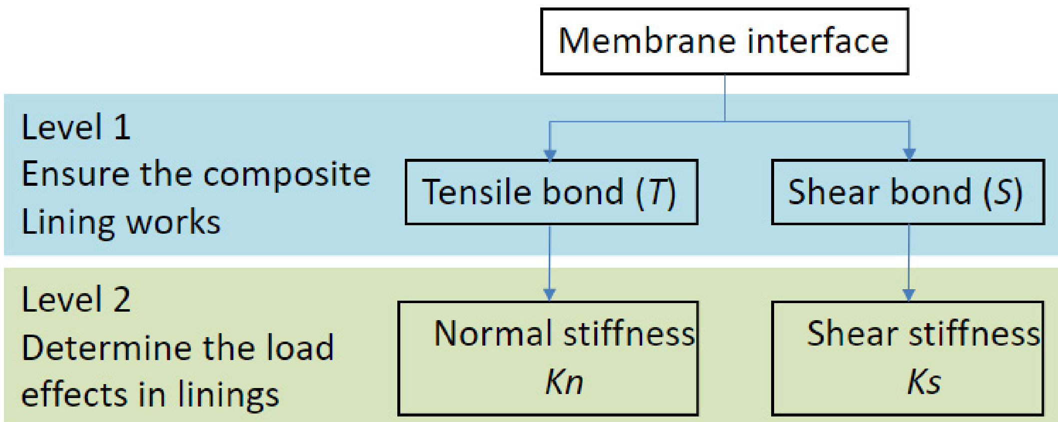


FIGURE 7

Functions of sprayed waterproofing membrane interface (from Su and Bloodworth 2022)



5.2 Interface Stresses Resulting from Ground and Groundwater Pressure Application

In this section, we use a "holding hand" analogy to illustrate the stress status of the membrane interface in the composite lining system. Figure 8 shows three people holding each other's hands and two vertical bars. Each person represents one of the three components: the primary lining, sprayed membrane, and secondary lining, from left to right. The holding hands between the people represent the interfaces between the sprayed membrane and the two linings. These interfaces are where the bond between the membrane and the linings exists. The strength and effectiveness of this bond play a crucial role in the overall behaviour of the composite lining system. The vertical bars represent the axial stiffness of the primary and secondary linings. They represent the ability of the linings to resist deformation and generate internal strains and stresses when subjected to external loading. In this analogy, we consider a scenario where only water pressure is acting, and there is no ground loading or self-weight. We assume the primary and secondary linings have equal thicknesses, resulting in equal axial stiffness.

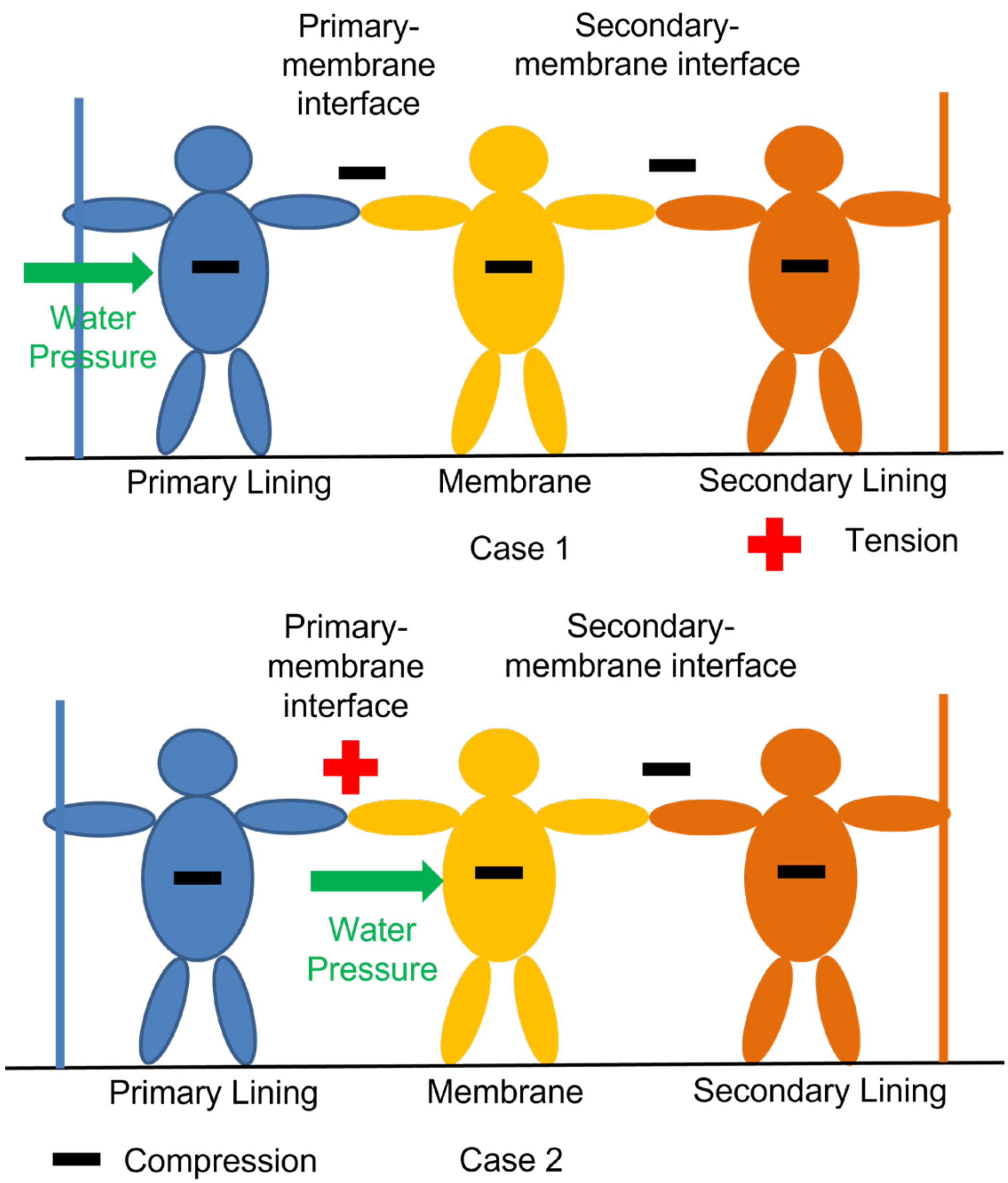
In Case 1, when water pressure is applied to the primary lining extrados, the primary lining will resist a certain percentage of the water load. At the same time, the remainder will transfer via the membrane and be opposed by the secondary lining. In this case, both linings, membrane and the two interfaces are in compression in the normal direction (i.e. radially). In Case 2, when the water pressure applies to the membrane extrados, the membrane, the secondary lining and the secondary-membrane interface will be under compression. The primary lining and the primary-membrane interface will be under tension. Now, if we consider superposing the effect of short-term ground loading on the primary lining, its stress state should change from tension to compression. This leaves the primary-membrane interface as the only element that is in tension.

With the understanding that the primary-membrane interface is under tension while the sprayed membrane is under compression when under groundwater pressure, it becomes clear that the failure mechanism in this composite lining system under the combined ground and groundwater pressure application would be debonding at the primary-membrane interface. The cohesive tensile failure within the membrane itself is not a valid failure mechanism under this loading combination, which was previously reported in the long-term tensile test by Diez et al. (2019).

To accurately assess the bond strength at the primary-membrane interface, it is crucial to develop a testing methodology that applies tension specifically to this interface while maintaining compression within the membrane itself. This ensures that the testing conditions replicate the actual stress state experienced by the membrane interface in the field. The understanding of the stress status of the primary-membrane interface and the membrane itself provides new hope for the use of partial composite SCL tunnels to achieve lining thickness reduction by considering its long-term tensile bond in the design if it is verified by testing.

FIGURE 8

'Holding hands' analogy for load effects in membrane interface (from Su and Bloodworth 2022)



6. Application to AtkinsRéalis' Projects

This paper discussed the recent development in the multi-layer lining configuration, covering the understanding of the fundamental engineering principles, practical numerical modelling applications and the research that addresses the remaining challenges of the composite linings. For the moment, there is a tunnelling boom not only in the UK but globally, including AtkinsRéalis' key markets, such as Canada and Australia. Tunnel designers in these countries have started to adopt multi-layer lining configurations with the objective of achieving more sustainable solutions for clients. The cutting-edge knowledge and skills presented in this paper will place AtkinsRéalis in a leading position for the procurement of global tunnelling projects with more sustainable solutions.

7. Discussion and Conclusions

Crossrail was the first major tunnelling project in the UK to adopt the steel fibre-reinforced partial composite SCL tunnel lining configurations with the sprayed waterproofing membrane in urban areas and under groundwater tables. Due to the incomplete understanding of this topic around that time, the following design assumptions and approaches were adopted, and consequences were observed:

- Composite action was assumed beneficial to tunnel lining, so it was not allowed to be considered in the design.
- The sprayed membrane was assumed to be under tension under groundwater pressure.
- Laboratory testing applying long-term tension to the sprayed membrane, resulting in cohesive membrane failure under relatively low tensile stress.
- Based on these laboratory test results, it is assumed that the sprayed membrane would lose its bonding to the primary lining substrate.
- Consequently, the membrane interface was designed as a sheet membrane interface, only transferring compression but no tension or shear.
- The desired significant reduction in lining thickness for the Crossrail SCL tunnels hoped for was not fully achieved.
- The simulation of Crossrail SCL tunnels utilised beam elements for the tunnel linings and compression-only interface elements for the sprayed membrane interface.
- The plastic behaviour of the fibre-reinforced concrete lining was simulated using a plastic hinge function with limiting rotation angles.
- The opportunity to understand the impact of early-age thermal and shrinkage effects of the secondary lining on both linings within a partial composite lining configuration was missed at the design stages.

Based on the author's extensive practical and research experience, the following conclusions regarding the multi-layer tunnel lining have been reached.

- The adoption of partial or full composite SCL tunnels has both short- and long-term effects on tunnel performance.
- The restraint effect from the sprayed membrane or primary lining concrete intrados can induce tensile stress in the secondary lining when undergoing early-age thermal and shrinkage volumetric contraction. This leads to potential cracks at the secondary lining or thickening layer crown position.
- The composite action induced by the sprayed membrane or direct concrete-to-concrete contact interface converts bending into axial compression or tension in tunnel linings. In soft ground conditions, the long-term tunnel deformation is primarily vertical squatting, which can result in secondary lining cracks at the crown position.
- It is crucial to use volume elements to accurately simulate the partial or full composite action between the layers of tunnel linings. Using beam elements alone cannot capture the composite action and accurately record stress distribution within each layer.
- The use of advanced elastoplastic constitutive models has proven successful in predicting the crack width of fibre-reinforced concrete tunnel linings.
- When groundwater applies pressure to the sprayed waterproofing membrane in a partial composite tunnel, the primary-membrane interface is under tension, while the membrane itself is under compression.
- The failure mode at the membrane interface under groundwater pressure is an adhesive failure at the primary-membrane interface rather than a cohesive failure within the membrane.
- More laboratory tests with appropriate testing configurations are needed to generate the correct stress status at the membrane interface.
- With the advancements and understanding mentioned above, the industry is now ready to explore the implementation of real composite lining tunnels with significantly reduced secondary lining thickness, realising their full potential.

Acknowledgements

This paper was originally presented at the Tunnelling Association of Canada (TAC) 2023 Conference, Toronto, Canada, 24-26th September 2023.

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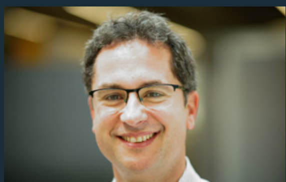
04 Fire Engineering

Hot Smoke Demonstrations for Emergency Strategy Assessment



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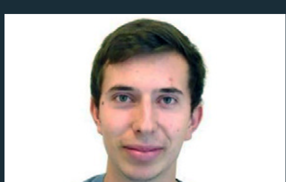

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Abstract

This paper introduces the findings from a series of hot smoke demonstrations carried out to investigate the impact of pre-defined emergency strategies on tunnel safety during the self-evacuation phase for a bi-directional tunnel. The tunnel response assessment was performed with an innovative approach to carry out high performance hot smoke demonstrations able to reproduce realistic fire scenarios in terms of smoke and heat generation (up to 5 MW). Different ventilation strategies (mechanical, natural) as well as the response of fire-related systems (smoke detection, PA/VA) under dynamic fire conditions coupled with the evacuation process were considered in this research.

Keywords

Fire safety; Hot smoke; Road tunnel; Full-scale test; Natural ventilation.

1. Introduction

In case of fire, systems in the tunnel should be operated to control smoke and allow occupants to evacuate safely. This requires implementation of pre-defined strategies based on a complex set of emergency measures that need to take into account variables including fire location, fire intensity, meteorological conditions, fire detection activation response as well as human behaviour among others. Being familiar with the response of such complex operational processes and systems is critical for tunnel operators in their support and management of the self-evacuation phase. Figure 1 provides a representation of tunnel emergency management systems interaction.

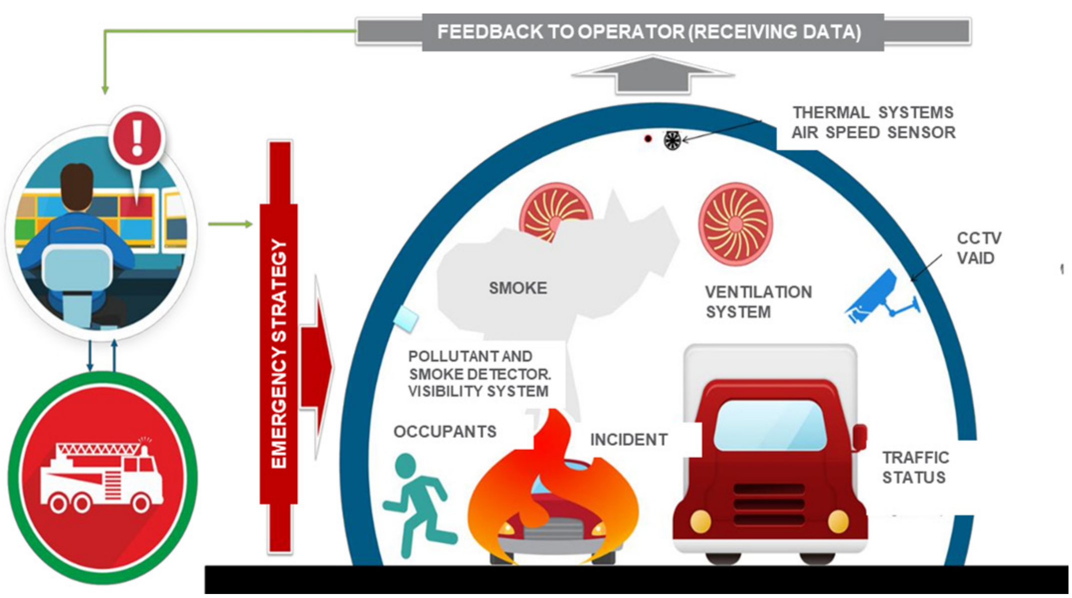
Smoke demonstrations have proved to be a valuable tool in providing information/evidence to assist tunnel owners, operators and emergency services to become familiar with such emergency strategies and to identify potential issues that can compromise tunnel safety [1]. However, several challenges or limitations arise when trying to demonstrate, under representative vehicle fire conditions, the response of emergency systems – such as lack of smoke buoyancy and low heat release in cold or warm smoke systems approaches as well as smoke toxicity and risk of tunnel damage with other approaches [2].

In this paper, the value of being able to overcome these limitations and provide support and evidence for tunnel safety decision taking is presented from the Saltash Road Tunnel (UK) case study where, during the on-going upgrading, the following main aspects were investigated:

- The response of different ventilation strategies (mechanical and natural) in terms of smoke management and safe evacuation under as realistic as possible fire conditions (up to 5 MW peak heat release).
- The response of recently installed fire-related detection systems (smoke detector and linear heat detector) as well as the impact on the tunnel safety level.
- The evacuation process under realistic evolving smoke conditions.

FIGURE 1

Emergency protocol – Tunnel, systems, tunnel user interaction.



2. Understanding Saltash Road Tunnel

The Saltash Tunnel is a single bore, bi-directional three-lane tunnel that carries the A38 on a curved alignment beneath the town of Saltash in Cornwall.

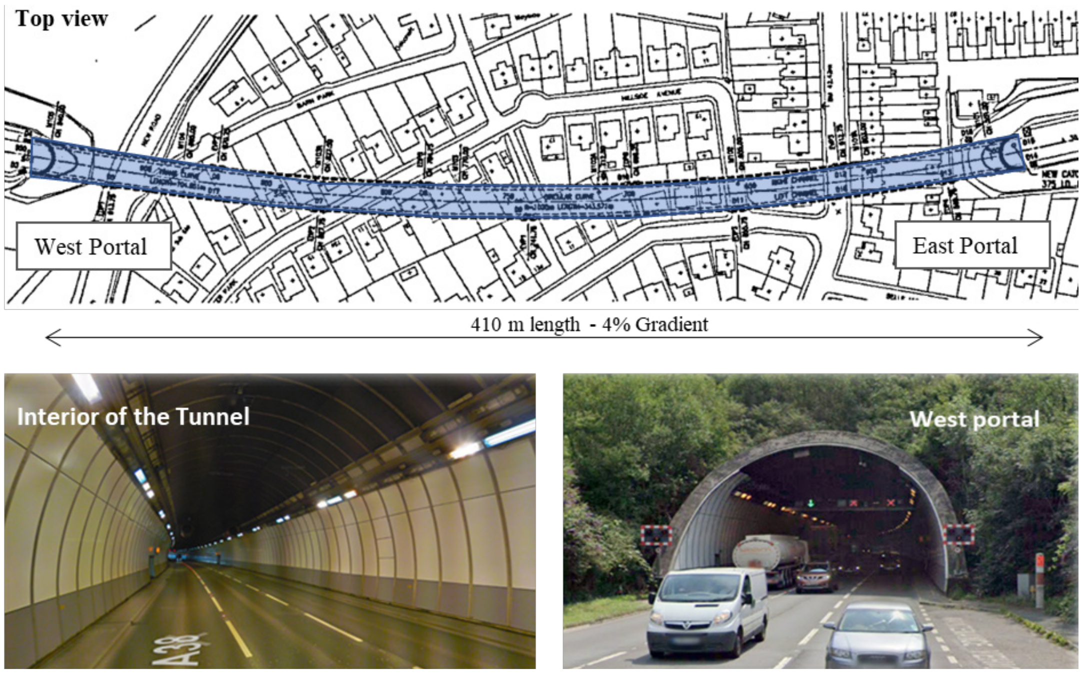


FIGURE 2

Saltash Tunnel configuration

The three-lane carriageway through the tunnel runs from a roundabout east of the adjacent Tamar Bridge to a roundabout west of the tunnel. A tidal flow traffic system operates through the tunnel and across the Tamar Bridge and is controlled from the Tamar Bridge Control Room. The tunnel cross-section has a five-centred arch profile along its full length of 410 m with a cross-sectional area of 92 m^2 (see Figure 2).

The tunnel is provided with a longitudinal ventilation system for both pollution and smoke control. The ventilation system comprises six fans mounted in three pairs, each pair located over the centre traffic lane at intervals through the tunnel. Control of the ventilation system is automatic for pollution control and semi-automatic in case of fire with the option to deploy a natural ventilation strategy or a longitudinal ventilation strategy.

Saltash Tunnel, as part of its overall tunnel upgrade works, was intended to explore and investigate the response of the tunnel systems, in particular the ventilation and fire detection systems in case of fire.

3. Smoke Demonstration Objectives and Requirements

3.1 Objectives

The aim of the smoke demonstrations is to support the tunnel operator to understand the response of the tunnel against a vehicle fire under realistic conditions and assess the tunnel safety level. The assessment is focused on the self-evacuation phase and therefore, special attention on the response of pre-defined emergency protocols to detect the fire, control smoke and instruct evacuation. Special attention is paid to:

- **Smoke behaviour pattern** based on ventilation strategies (mechanical – natural) as well as other factors such as fire location, fire growth, meteorological conditions, tunnel gradient, fire mode, activation times as well as to identify potential options/strategies for improvements in operational actions.
- **Fire-related system response** and the potential impact on the tunnel safety and tunnel operator awareness based on detection times.
- **Safe evacuation process** based on evolving smoke propagation conditions (e.g. fire phases, interaction ventilation system and smoke, meteorological conditions) and operational procedures (e.g. ventilation activation time and sequencing, evacuees' communication strategy and evacuation process).

3.2 Smoke Demonstration Requirements

Given that the Saltash Tunnel is in operation, the following minimum requirements during the smoke demonstration were defined by the tunnel operator:

- **Tunnel availability (minimise business interruption):** the tunnel should not be closed more than 8 hours as the tunnel forms part of a strategic route. During this period all the required activities (i.e. set-up, demonstration, leaving tunnel) need to be concluded.
- **Demonstration performance**: the demonstration should be as realistic as possible aiming to replicate the conditions of a representative car fire of around 5 MW peak heat release.
- **Replicability:** demonstrations should replicate similar fire conditions in terms of smoke temperature, smoke flow, HRR (Heat Release Rate) curves for like-for-like comparison.
- **Tunnel safety:** demonstrations need to be performed in a safe environment for both infrastructure, systems, staff, and evacuees. Tunnel protection requirements need to be avoided or minimised.

4. Proposed Technology – Smoke Generating Machine (SGM)

Most approaches in the industry consist of cold smoke, pool fires or even full-scale vehicle fire [3]. However, several challenges arise when trying to challenge the performance or response of emergency systems and strategies under realistic circumstances with these methods [2].

Some of these main limitations are the lack of buoyancy that make it not suitable for verifying the detection systems based on temperature or for assessing the effectiveness of the smoke management strategy and observation of destratification effects in the evacuation phase (e.g. cold smoke methods). Also, the production of toxic smoke as well as the potential major protection requirements due to unconfined flames smoke (e.g. warm smoke and full-scale vehicle fires) [4], and required long tunnel closures (e.g. full-scale vehicle fires).

For these reasons and in order to be able to address the project objectives and client minimum demonstration requirements, an innovative high performance smoke generating machine, developed under a R&D framework, was deployed in Saltash Tunnel. The overall design and performance of the SGM was defined in order to overcome the limitations of commonly used available smoke approaches in terms of tunnel availability, safety, fire size and curves generation as well as replicability.

The SGM comprises an assembly of three interconnected systems: the heat generator system (HGS), the smoke generator system (SGS) and the monitoring and controlling system (MCS). Thus, the HGS is in charge of heating up the smoke to a pre-defined temperature. The SGS oversees the required white and non-toxic smoke flow and the MCS is in charge of monitoring and controlling/regulating in real time the performance of the SGM in terms of amount of smoke and temperature. It is able to reproduce similar effects in temperature and smoke flow for common vehicle fires (up to 6MW) in a safe way avoiding unconfined flames in the tunnel that may compromise the tunnel safety level. The SGM is provided with a set of safety systems able to stop the smoke release at any time. The generated smoke is white and non-toxic as well as non-conductive, non-corrosive eliminating any potential damage to tunnel users and tunnel systems. The smoke flow and temperature at 2.10 m above the ground can reach up to 550°C and 25m^3/s (smoke generation mixed with air coming from fans), see Figure 3.

Its overall dimensions are similar to that of a vehicle and is mounted on a trailer. This allows the system to be quickly towed into place and perform a non-intrusive and clean demonstration allowing the tunnel to re-open and operate normally on conclusion of the demonstration.

5. Smoke Demonstration Scenarios

5.1 Smoke (Fire) Scenarios

The fire scenario intended to be represented is a car fire originated by an impact between two vehicles coming in different directions. A set of three (3) hot smoke demonstrations and one (1) cold smoke demonstration were defined over two (2) consecutive nights. The duration of each hot smoke demonstration was about 10-15 mins. All demonstration were done at the same location within the tunnel and with similar fire conditions in terms of smoke flow and temperature curves to allow like-for-like comparison, except during the evacuation scenario which was undertaken under lower HRR to promote smoke destratification and less tenable conditions.

FIGURE 3

High performance smoke generating machine: Performance and configuration.

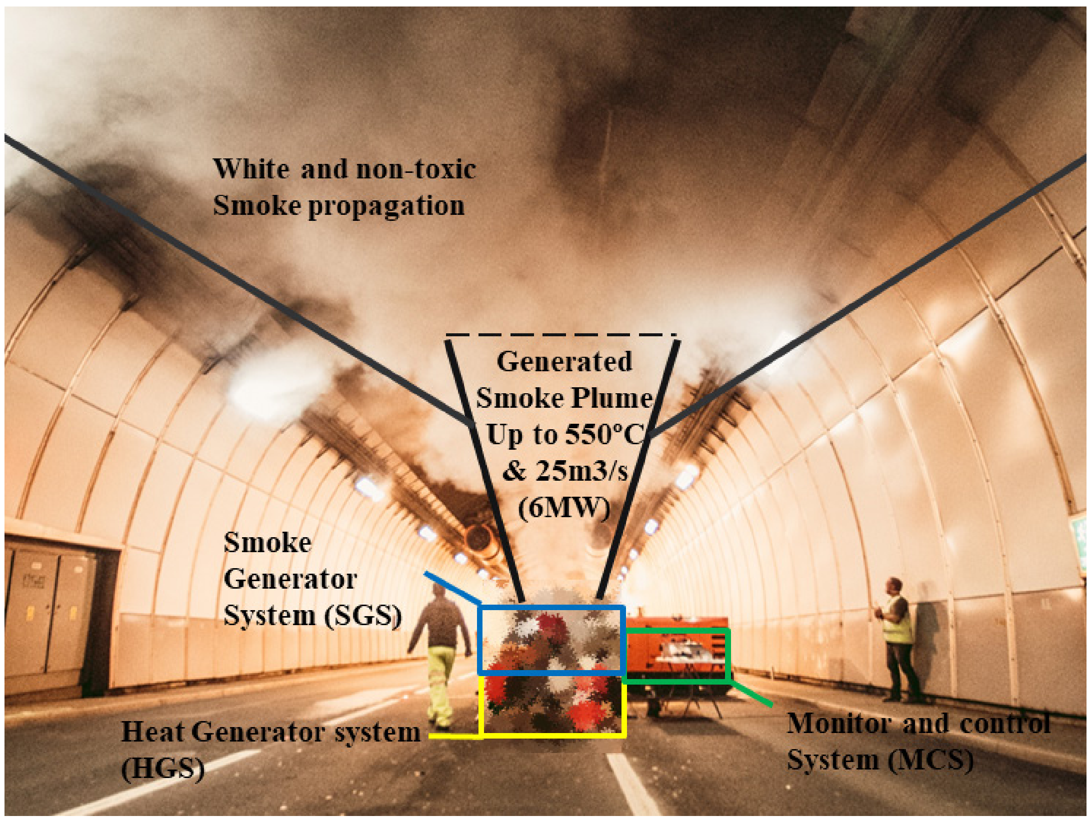


Table 1 summarises the smoke demonstrations including the type of ventilation strategy investigated, whether or not the live response of evacuation systems and evacuation process was considered as well as the and the heat released.

TABLE 1

Smoke scenarios

Id	Demonstration type	Ventilation	Evacuees in tunnel	HRR [MW]
CS1	Cold smoke	Natural	No	≈0MW
HS2	Hot smoke	Natural	No	≈5MW
HS3	Hot smoke	Longitudinal	No	≈5MW
HS4	Hot smoke	Natural	Yes	≈3MW

5.2 Location of the Hot Smoke Machine

The location of the hot smoke machine was approximately at the halfway point in the tunnel (195 m from the West Portal).

5.3 Ventilation Strategy

For those demonstrations with natural ventilation, no jet fans were activated at any point during the demonstration. Smoke propagation relied on tunnel gradient, smoke buoyancy and wind conditions.

In case of mechanical ventilation, the strategy was to ventilate toward the West portal preventing backlayering. This direction of the ventilation was decided during the demonstration day based on the direction of the prevailing wind. Only 1 out of 3 banks were activated assuming that one bank would be destroyed by the fire and the other one was under maintenance. The activated one is selected to work embedded in smoke. The activation of the jet-fans was set at about 150s from the beginning of the demonstration.

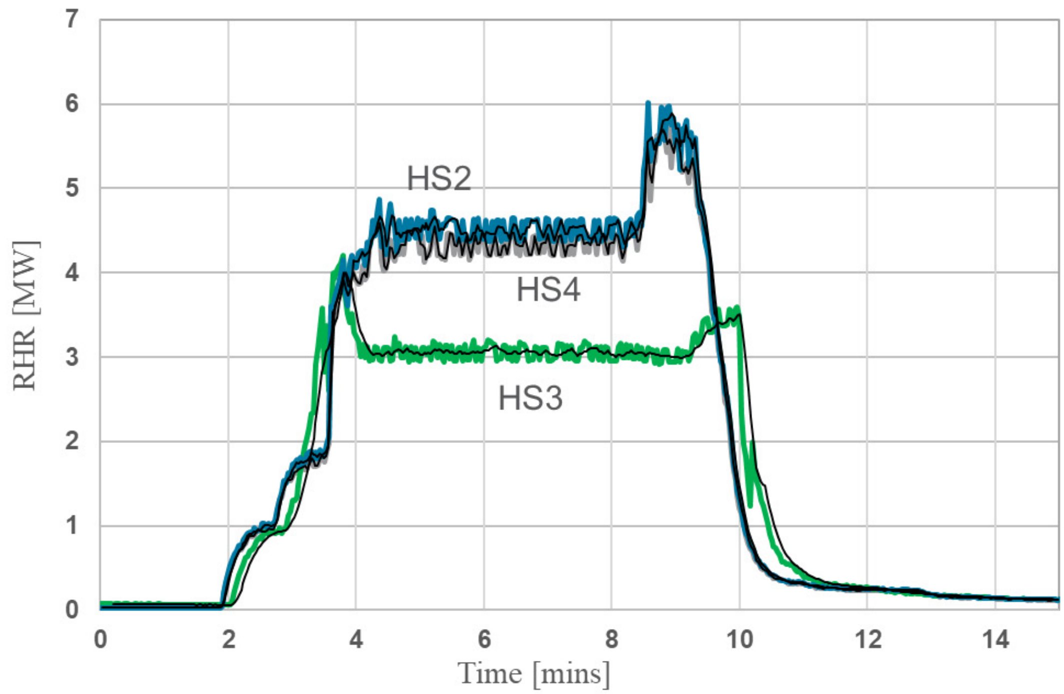
5.4 Heat Released during the Demonstrations

During the demonstrations, it was intended to reproduce similar HRR curves for HS2 and HS3. However, for HS4 a lower HRR was defined to promote higher level of destratification and challenge the evacuation process, see Figure 4.

Regarding the HRR curves, four fire phases were defined representing a growth phase, developed phase, a peak phase and a decay phase. The growth phase duration was about 2 mins. The developed phase duration was about 7 mins. The peak phase was about 1 min, and the decay phase was about 2 mins of duration. The convective heat released during the demonstrations (ranging from 3.2MW to 5.9MW) is provided in Figure 4, where HRR during HS2, HS3 and HS4 is represented in blue, grey and green. The HRR values are calculated based on the temperature increase (relative to the ambient temperature) of the smoke generated (mass flow) during the demonstration at 2.10 m above the ground.

FIGURE 4

HRR demonstration curves.

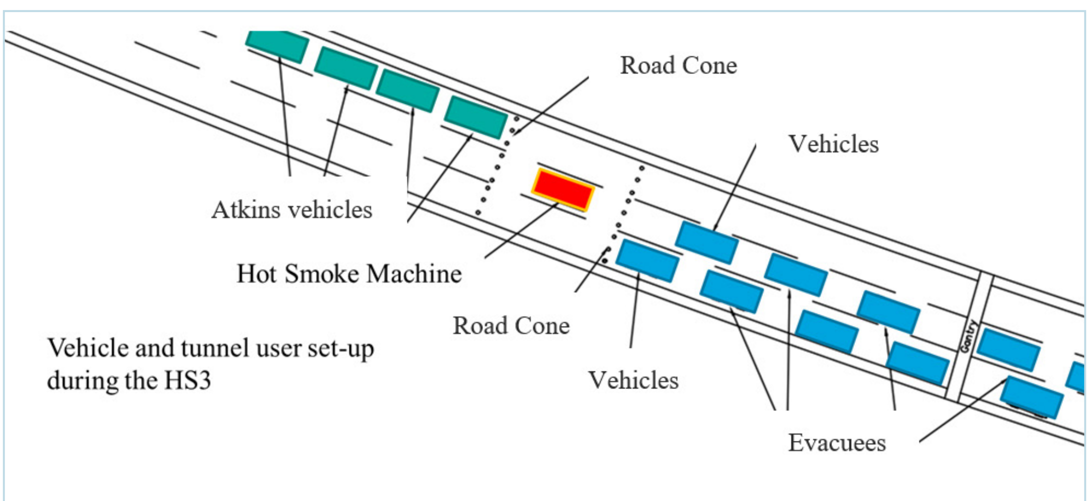


5.5 Evacuation Process

Twenty seven persons including individual passengers, families and people with reduced mobility were involved in the evacuation process during demonstration HS3.

FIGURE 5

Evacuation scenario set-up.

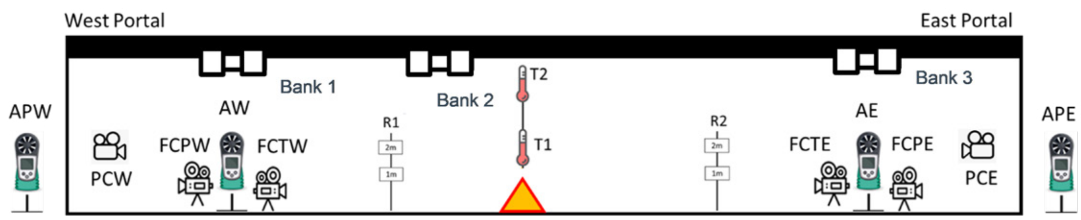


5.6 Instrumentation

In order to monitor key variables, a set of instrumentation was deployed along the tunnel. Thus, 6no. cameras at 1.5m above the ground, 4no. thermocouples at different locations and heights, 4no. anemometers at 1.5m above the ground and 2no. in-tunnel rods with two illuminated heights (2.0 m/3.0 m) were installed, as represented in Figure 6.

FIGURE 6

Sensor distribution for Day 1 demonstrations. [Legend: A-anemometer, P-portal; W-west; E-east; TW-toward the west; TE- toward the east; C-camera; T-thermocouple; R-rod; F-fixed.]

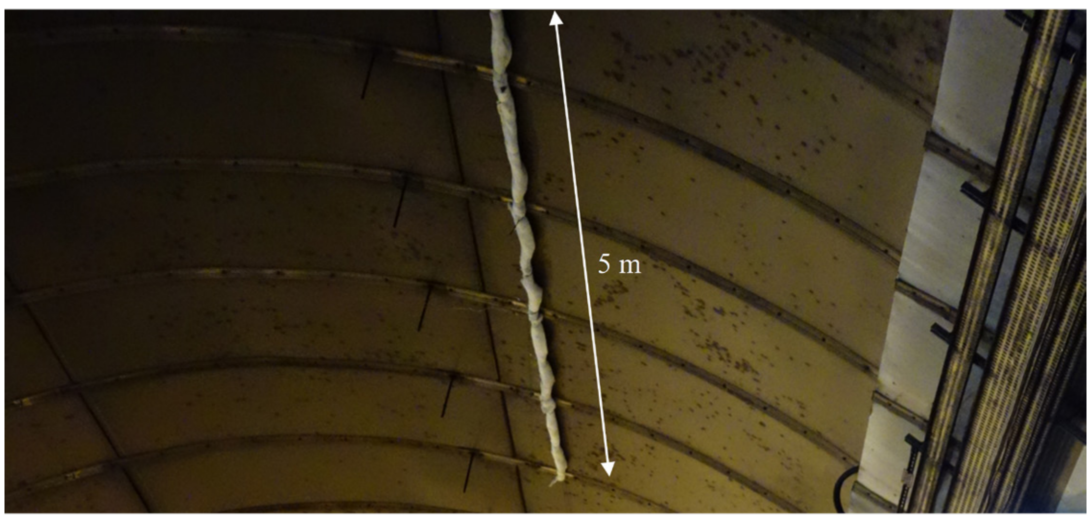


5.7 Additional Safety Measures

After reviewing the characteristics of the systems close to the location of the hot smoke machine, it was decided to protect a small section (5.0 m) of the linear heat detector with a protective ceramic blanket as shown in Figure 7.

FIGURE 7

Tunnel protection in Saltash Tunnel.



6. Hot Smoke Demonstration Observations

6.1 In-Tunnel Ambient Conditions

The ambient conditions 15 mins. before the beginning of the demonstration are summarised in the Table below:

TABLE 2

Max, min and average* ambient conditions 15 min. before demonstrations.

Id	In-tunnel temperature [°C]	In-Tunnel air speed [m/s]
CS1	Min (11.9) – Max (12.3) –Ave (12.1)	Min (1.0) – Max (1.9) –Ave (1.45)
HS2	Min (11.7) – Max (11.9) –Ave (11.8)	Min (1.2) – Max (1.7) –Ave (1.45)
HS3	Min (11.7) – Max (12.7) –Ave (12.2)	Min (0.9) – Max (2.5) –Ave (1.70)
HS4	Min (14.2) – Max (14.7) –Ave (14.4)	Min (0.0) – Max (0.9) –Ave (0.45)

Positive air speed values indicate air is flowing from the West Portal to the East Portal.
* Mean value between min and max.

6.2 CS1 – Cold Smoke Demonstration with Natural Ventilation Strategy

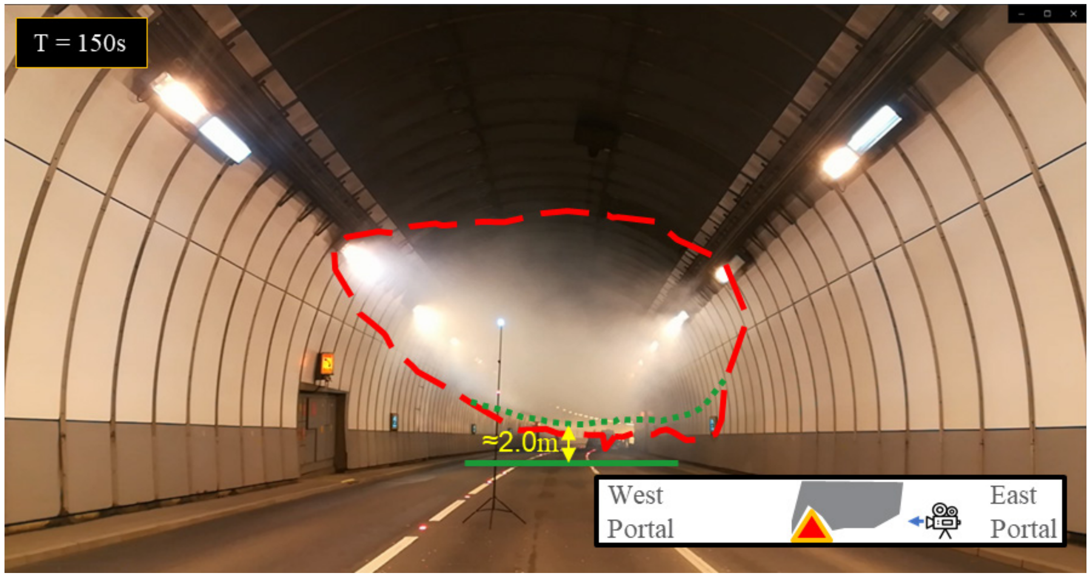
A summary of the key observations is given below:

- The cold smoke demonstration started at 00:49 am (6th October).
- Due to the configuration of the SGM, the smoke released is pushed upwards to the tunnel soffit providing an initial stratification phenomenon.
- The temperature difference of the cold smoke with the ambient temperature is approximately 4°C.
- The average in-tunnel air speed (1.45 m/s) coming from the West pushes the cold smoke toward the East Portal (Tamar Bridge).
- Due to the lack of buoyancy of the smoke, there is no smoke flowing towards the West portal at any point during the demonstration.
- None of the smoke detectors and linear heat detectors were triggered by the presence of the smoke.
- Early destratification appears while smoke is propagating along the tunnel (e.g., 2.0 m free smoke layer at 150s and no free smoke layer at 240s)

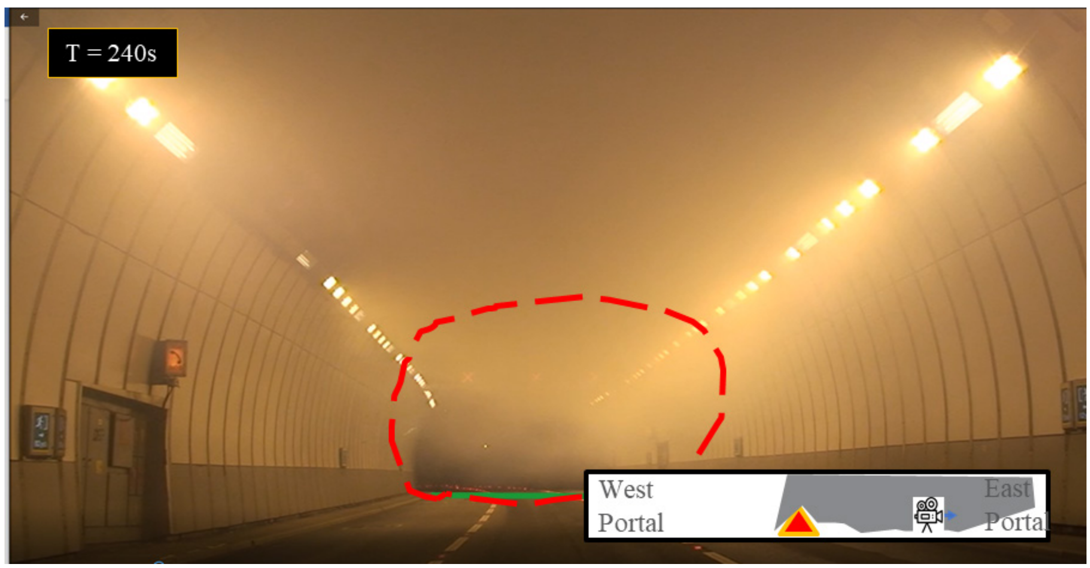
Figure 8 represents the cold smoke propagation at 150s and 240s. A red line represents the smoke layer. A solid green line represents the ground location where the free smoke layer measures are taken (dotted green line). At the bottom of the image, a schematic is provided indicating the smoke propagation and the camera taking the footage.

FIGURE 8

Cold smoke and natural ventilation at 150s and 240s. a) Views from the portal to the hot source and b) towards the portal



(a)



(b)

6.3 HS2 – Hot Smoke Demonstration with Natural Ventilation Strategy

A summary of the key observations is given below:

- The hot smoke demonstration with a natural ventilation strategy started at 0:57 am (6th October).
- Due to the configuration of the SGM as well as the high temperature of the smoke, the smoke propagates along the tunnel soffit with a clear stratification.
- Smoke propagates in both directions (eastbound and westbound), however due to the gradient and the in-tunnel air speed (1.45 m/s), it is observed that most of the smoke is pushed toward the East Portal (Tamar Bridge).
- The smoke travelling to the West portal remained stratified during the whole demonstration and stay confined due to the wind condition and gradient at about 60 m. from the smoke source location, reaching bank 2 (see Figure 9).
- The smoke travelling to the east reaches the portal in approximately 145s.
- Smoke propagates stratified within the tunnel during the whole duration of the demonstration with minor destratification at the East portal at the end of the demonstration (due to the cooling effect between hot smoke and fresh air).
- The smoke detection system was first triggered within the first 30 seconds from the beginning of the demonstration.
- The linear heat detector temperature was about 60°C when detect the fire (around 3 mins) .

Figure 10 represents the hot smoke behaviour at 150s and 240s where both the smoke propagation is indicated with a red line and the free smoke layer is represented in green. It can be observed that free smoke layer height is more than 4.0 m, except at the East portal which drops to about 3.0m.

FIGURE 9

Confined smoke at 60 m from the hot smoke machine (westbound).

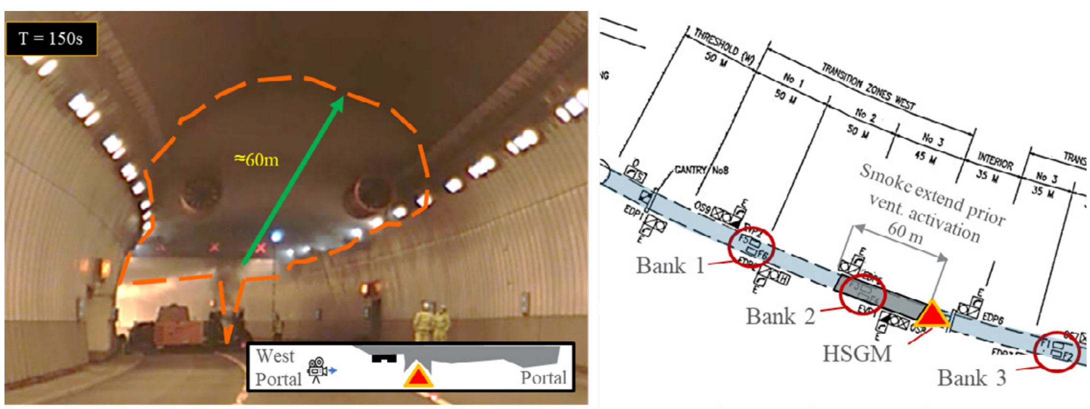
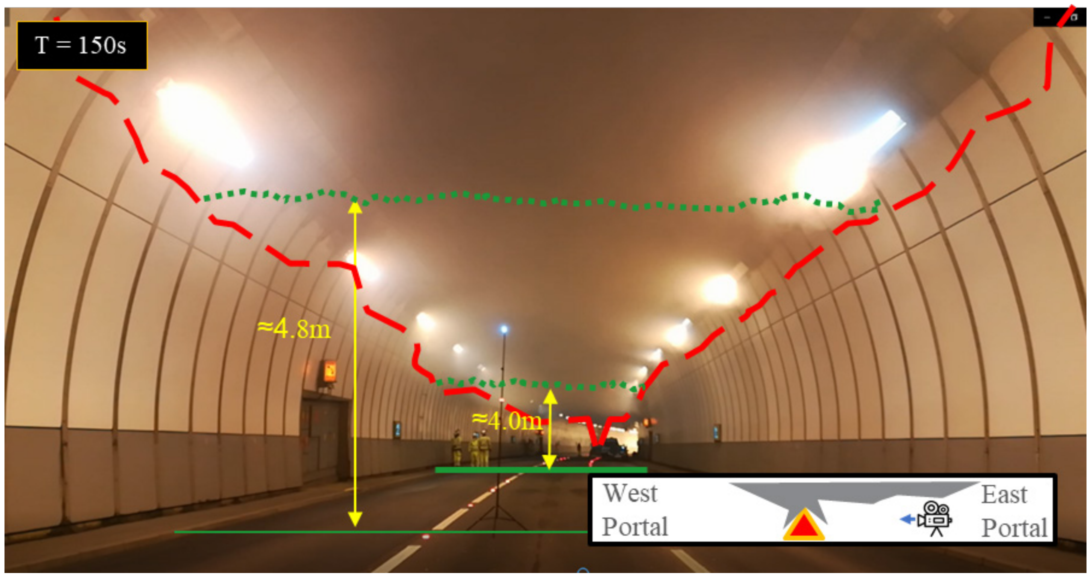
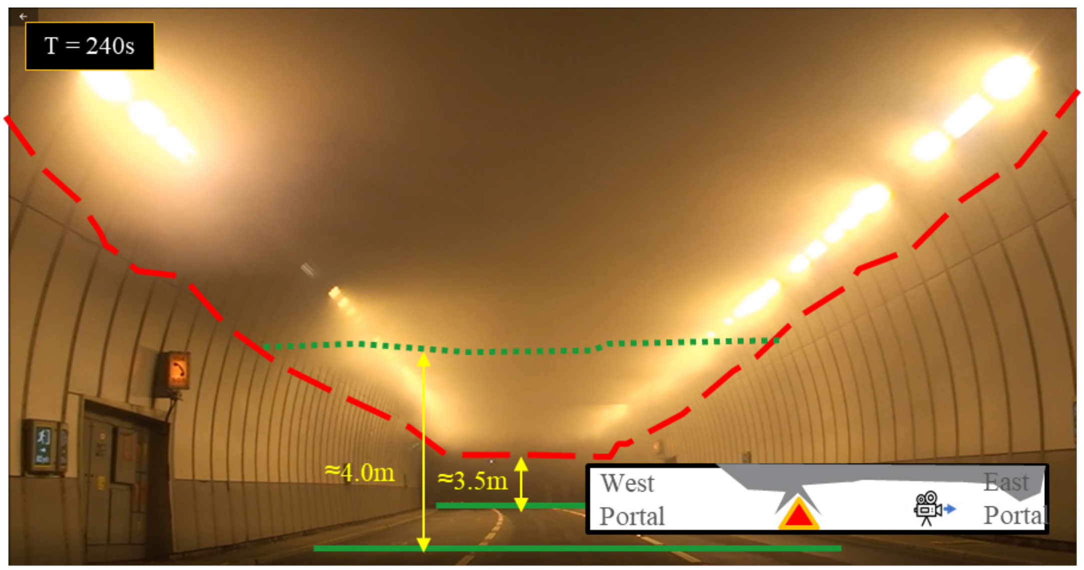


FIGURE 10

Hot smoke demonstration: a) smoke propagation at 150s, view from the portal to the hot source- b) smoke propagation at 240s, view towards the portal



(a)



(b)

6.4 HS3 – Hot Smoke Demonstration with Longitudinal Ventilation Strategy

A summary of the key observations before jet fan activation is given below:

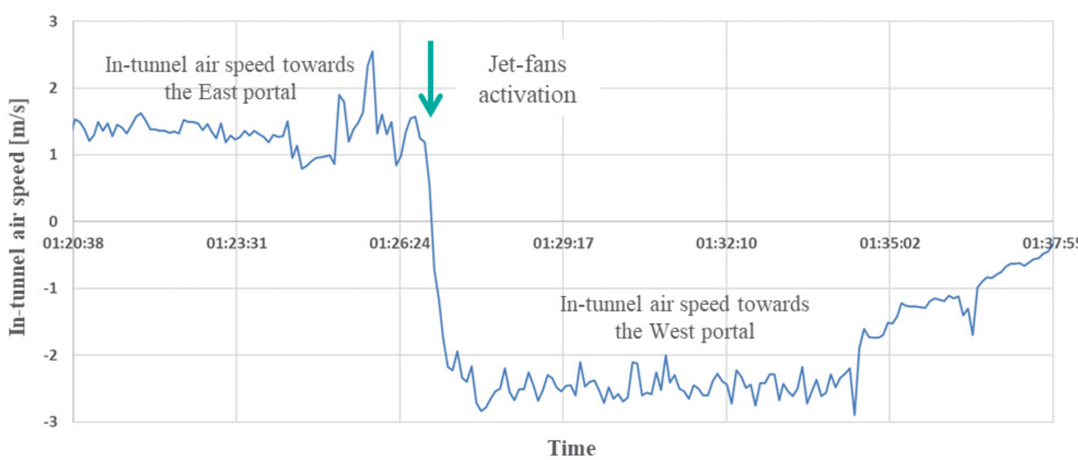
- The hot smoke demonstration with mechanical ventilation started at 01:23am (7th October).
- Due to the configuration of the SGM as well as the high temperature of the smoke, the smoke propagates along the tunnel soffit with a clear stratification.
- Smoke propagates in both directions (eastbound and westbound), however due to the gradient and the in-tunnel air speed (1,7 m/s), it is observed that most of the smoke is pushed toward the East Portal (Tamar Bridge).
- The smoke propagating to the East reached the portal in approximately 130s.
- Smoke propagates stratified within the tunnel prior jet-fan activation with minor destratification at the East portal at the end of the demonstration (due to the cooling effect between hot smoke and fresh air).
- According to Saltash operators, the smoke detectors were activated within the first 30s from the beginning of the demonstration.

A summary of the key observations after jet fan activation (at 120s from the beginning of the demonstration) is given below:

- The in-tunnel air direction is reversed reaching speed value of about 2.5 m/s towards the West portal in less than 1 min after the fan activation (see Figure 11).
- Smoke on the East portal is pushed back. It remains stratified till it gets to the hot smoke machine. A minimum of 5.5 m free smoke layer is observed (see Figure 12)
- Smoke reached the hot smoke source at about 280s.
- Smoke destratification between Bank 1 to the West portal is observed in the whole section when smoke reached the activated jet-fans.
- From Bank 1 to the hot smoke machine, smoke de-stratification also occurs as smoke cools down due to the outside air entrainment.

FIGURE 11

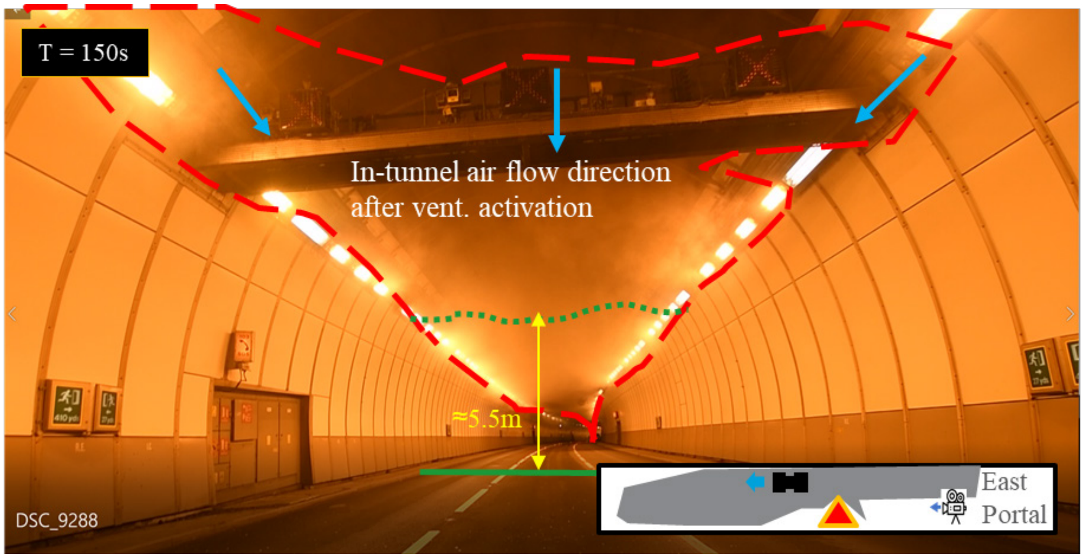
In-tunnel air speed during HS3



Figures 12 and 13 represent the hot smoke behaviour at 150s and 240s from a camera at the East and West portal, respectively. It can be seen the direction of the in-tunnel air speed (blue lines) as well as which cameras have been used for the presented footage.

FIGURE 12

Smoke propagation toward the East portal being controlled by the ventilation at a) 150s and b) 240s. View from the East portal to the hot source.



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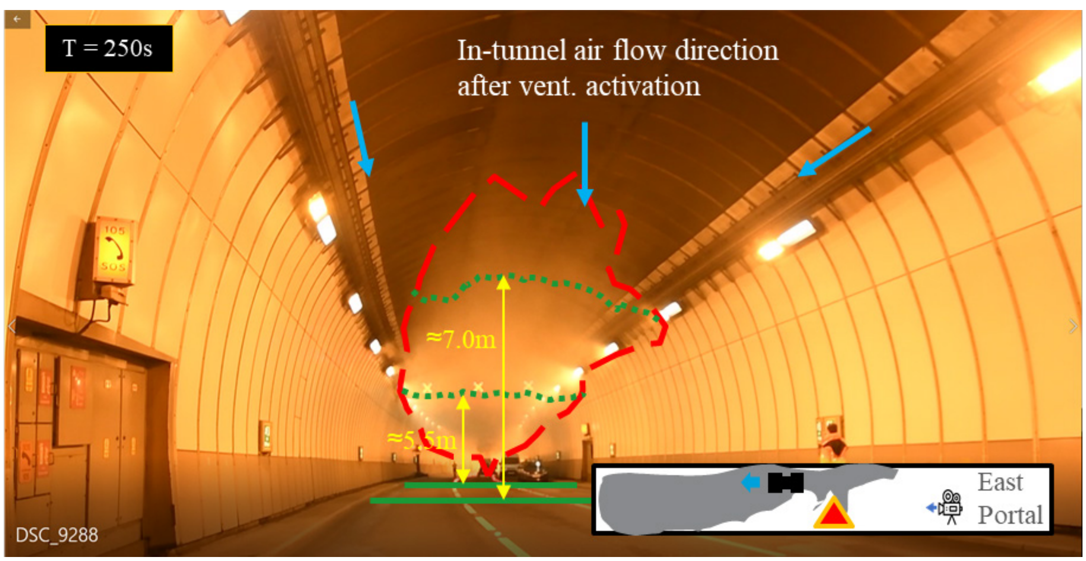
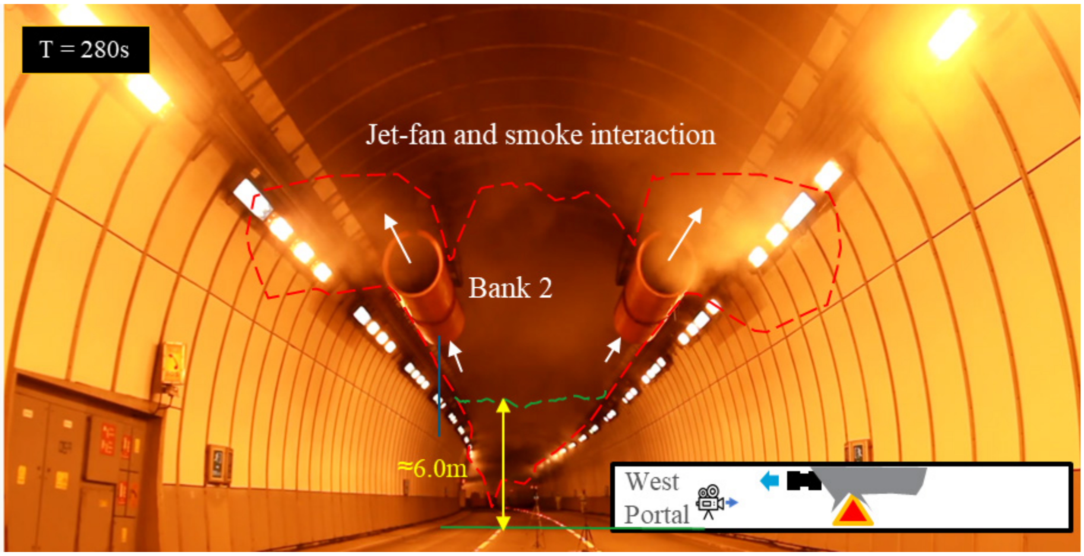


(b)

FIGURE 13

Smoke destratification due to jet fan activation a) 280s and b) 300s. View from the West portal to the hot source.



(a)

(b)

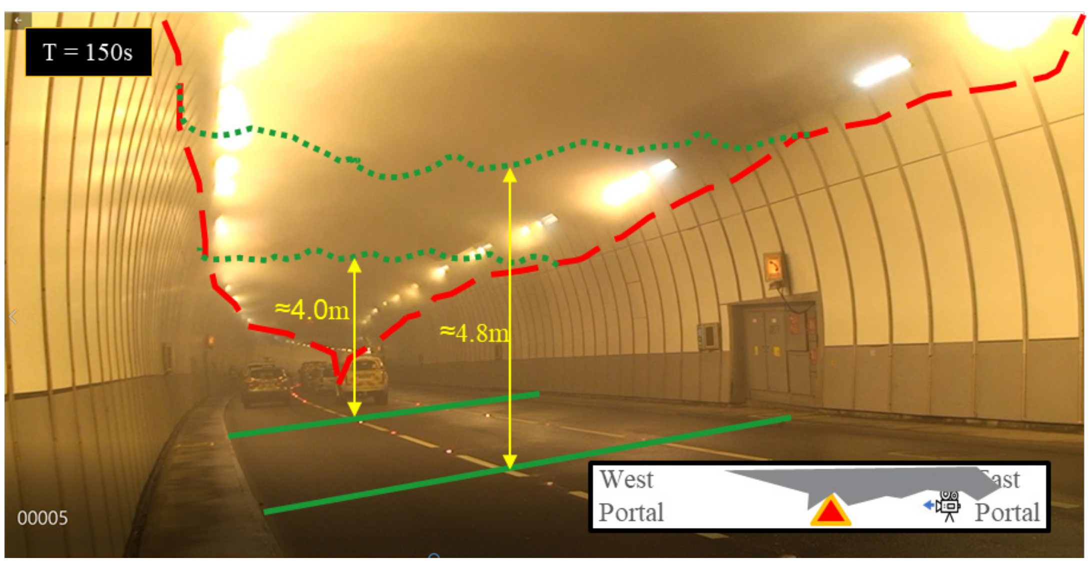
6.5 HS4 – Hot Smoke Demonstration with Natural Ventilation and Evacuees

Regarding the evacuation process, the following key observations are provided below:

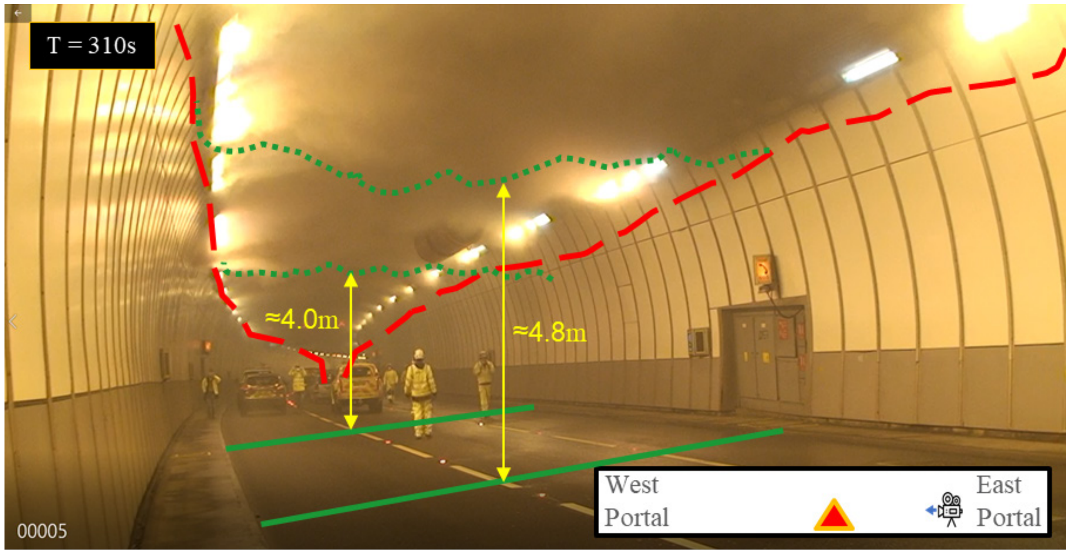
- The hot smoke demonstration with mechanical ventilation started at 21:00 pm (7th October).
- The smoke detectors and LHD detected the 'fire' quite early on however for exercise smoke realism the PA & Evacuation system was not immediately activated. In real conditions the system would be activated on detection of a fire, either automatically or by Operator intervention.
- Thus, the PA system was activated at about 180s instructing the tunnel users to evacuate the tunnel immediately. Wayfindings were also operated indicating the direction of the shorter exit.
- At that point evacuees started to get out the vehicles and began the evacuation process toward the East portal. Evacuation was completed within 7 mins, and it was done in a free smoke environment.
- The smoke travelling to the West Portal was confined at about 60 m. from the hot smoke machine, reaching Bank 2. No evacuees were located in this part of the tunnel but, under the demonstration conditions, evacuation is expected to be done under tenable conditions.
- Smoke propagation to the East portal shows higher level of destratification than in HS1 (section 6.3). At about 600s the tunnel section was full of smoke. It was deducted that this was due to the lower HRR during this demonstration.
- In Figure 14, the smoke evolution vs. evacuation process at 150s, 310s and 600s is represented.

FIGURE 14

Smoke evolution vs. evacuation process in case of natural ventilation strategy at a) 150s, b) 310s and c) 600s.



(a)


T = 310s
≈4.0m
≈4.8m
West
Portal
East
Portal
00005

(b)


T = 600s
West
Portal
Portal

(c)

7. Conclusions

7.1 Cold Smoke vs Hot Smoke Demonstration

In this investigation, smoke detectors and linear heat detectors were not able to detect the presence of the cold smoke. Smoke propagation speed within the tunnel was found to be slower than during the hot smoke demonstration with similar average air speed (1.45 m/s). Also, it presented an early destratification. These findings justify the use of hot smoke for realistic fire conditions when trying to understand the fire related system, smoke propagation and smoke control performance.

7.2 Natural Ventilation versus Mechanical Ventilation (Similar HRR Scenario)

This section compares HS2 and HS3 where similar HRR were reproduced to allow comparison of smoke management by natural and mechanical ventilation methods. The main aspects to highlight are:

- At the beginning of the fire scenario, when no jet-fan is activated, both scenarios present similar smoke behaviours despite small propagation speed differences due to minor ambient condition differences.
- While natural ventilation allowed smoke to be stratified during the whole demonstration, it was observed how the activation of the jet fan created smoke destratification and, therefore, could compromise a safe evacuation.
- Selection of specific jet-fans to be activated is an important variable if using this ventilation strategy.
- Even in this scenario natural ventilation provided a safer strategy, it is important to highlight that this strategy relies on the ambient conditions and different smoke propagation might be expected with extreme wind conditions. However, in these extreme scenarios mechanical ventilation may provide longer tenable conditions for evacuation. This fact provides evidence that a combination of ventilation strategies based on the fire location may provide an improvement in tunnel safety.

7.3 Natural Ventilation vs Natural Ventilation (Different HRR)

This section compares HS2 and HS4 which were reproduced to compare the impact of smoke propagation under different HRR and how this may affect the evacuation process. The main aspects to highlight are:

- At the beginning of the fire scenario both scenarios present similar smoke behaviours.
- Higher smoke destratification occurs during the demonstration with lower HRR.
- Even if during the evacuation exercise all the evacuees abandoned the tunnel in a free of smoke condition, these findings provided evidence that lower HRR scenarios needs to be considered when assessing the evacuation process under natural ventilation conditions.

7.4 Response of Fire Detection System

In HS2, HS3 and HS4, the smoke detectors and linear heat detector response was proved to be effective in early detection of the fire and the location of the hot source. Based on the data provided by the tunnel operator, the smoke was detected within the first 30s. from the beginning of the demonstration, where the HRR was around 1MW. The temperature recorded by the linear detector was 60°C at the time of detection (about 3 mins), but this system, as indicated previously, was protected in the area near the hot source location.

7.5 Client Requirements

During the demonstrations the client requirements were fulfilled as follows:

- **Tunnel availability:** During the first night, demonstrations CS1, HS2 and HS3 were done within 6 hours out of the 8 hours available. On the second night, this duration was reduced to 3 hours.
- **Demonstration performance:** The convective heat released during the demonstrations ranged from 3.2MW (HS2) to 5.9MW (HS3) which is representative of car fires.
- **Replicability:** During HS2 and HS3, similar (within 5-10%) HRR curves and peaks were reproduced.
- **Tunnel safety:** Tunnel protection was only required along a small section (5.0 m) of the linear heat detector. A protective ceramic blanket was used to provide the protection.

Acknowledgments

Originally presented to and published by the International Symposium on Aerodynamics, Fire and Ventilation in Tunnels, September 27–29, 2022, Brighton, UK.

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Risky Business - Developing an Approach to Managing Technical Systemic Risks

Abstract

Systemic Risk Management is a discipline familiar to the financial world, having been born out of the systemic failures which resulted in the 2008 financial crisis. Since November 2019, a small team has been working within the UK Ministry of Defence (MOD) to develop a pragmatic interpretation of Systemic Risk Management which can be applied to technical risks. The approach is complementary to both traditional programme/project risk management (which tends towards bottom-up escalation), and contemporary Enterprise Risk Management (ERM) which tends to look top-down for risks to objectives. Systemic Risk Management provides a means to identify and manage cross-cutting and transverse risks which could be impacting multiple areas of the organisation, and risks within one area of the business that could have a disproportionate effect elsewhere. Currently these could slip though unnoticed and potentially recur across the enterprise. The team took inspiration from a variety of sources, including ERM, Viable Systems Model and Cynefin, before settling on an indicator-based approach that could be readily understood by risk management practitioners without needing to bombard them with seemingly abstract theoretical constructs. The result has been the production of guidance material for identifying and managing Technical Systemic Risks which has been tested through significant stakeholder engagement, and is being piloted within the UK MOD. Whilst this approach has been developed for use within UK MOD to manage Technical Systemic Risks, it can extend to Systemic Risks in general, and has utility for any large organisation grappling with complex interdependencies between disparate technical and organisational activities.

Keywords

Systemic risk; Systems thinking; Enterprise/ Risk management

1. Introduction

Systemic Risk is well recognised within the financial sector. When systemic financial risks manifest themselves, the results are hard to ignore. Economies wobble, companies go bust, suddenly a whole load of assumptions about how the world works turn out to be less reliable than they used to be, and the pain is felt far and wide. Systemic Risks are insidious. They can build up over time, sometimes reflecting a build-up of residual risks which were never dealt with first time around, sometimes the result of multiple local mitigations to problems which in reality should have been owned further up the chain, or sometimes just reflecting repeating patterns of organisational behaviour.

A good recent example of Systemic Risk is the global sub-prime mortgage crisis of 2008, where the combination of well-intentioned efforts to provide mortgages to those on low incomes, led to complex financial instruments (starting with mortgage-backed securities and moving on to credit default swaps) put the entire financial system at risk through the interconnected nature of the markets and some unhelpful perverse incentives within the ratings agencies. The film "The Big Short" provides a very approachable narrative on Systemic Risk in the financial sector and would be good background watching to help to understand the subject.

The Gray Review into Defence Acquisition (Gray 2009) noted "systemic problems" such as immature technical solutions and changing requirements. Subsequently, it has been observed that Systemic Risks are a potential source of unnecessary friction, inefficiency and delay within the acquisition and business-as-usual processes. This appears to be particularly prevalent in technical activities, making Technical Systemic Risks a high priority to address first. The intent is to enhance existing governance frameworks to ensure that pan-Defence Technical Systemic Risks are identified, understood and mitigated appropriately.

This paper aims to describe the observed nature and characteristics of Technical Systemic Risks and sets out an approach to managing these risks, which can be extended to manage Systemic Risks in general, that could be readily adopted by other organisations facing similar challenges. Whilst the primary focus of this paper is Technical Systemic Risks much of it applies to Systemic Risks in general.

2. Defining Technical Systemic Risk

One of the biggest challenges with developing an approach to managing Technical Systemic Risks (TSRs) was that the term itself was not defined, either in the official MOD policy for Risk Management captured in Joint Service Publication (JSP) 892 or the wider literature. Breaking it down into the "systemic risk" and "technical" aspects was helpful, as it allowed further analysis of related terms and approaches.

For a definition of "technical", the formal starting point was the official MOD policy for Technical Governance and Assurance of Capability, JSP 901 Pt 1, which states:

"The term 'Technical' should be considered to cover the broad range of professional, specialist, engineering, science, quality and related disciplines that enable Defence capability to be procured and supported safely and effectively across the capability lifecycle. This includes people involved in a broad range of capability management activities including solution maturation; requirements and acceptance; in-service support; Project, programme and portfolio management (P3M); and test and evaluation."

Two useful definitions of "technical risk" were also identified. (NASA 2021) defines Technical Risk as

"The risk associated with the evolution of the design and the production of the system of interest affecting the level of performance necessary to meet the stakeholder expectations and technical requirements."

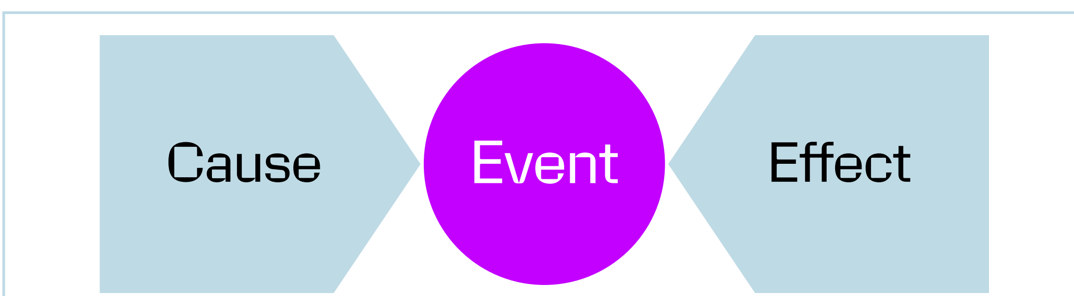
The guidance also highlights the need for effective uncertainty analysis to underpin the assessment of likelihoods and consequences for each risk.(INCOSE 2015) defines Technical Risk as

"The possibility that a technical requirement of the system may not be achieved in the system life cycle. Technical risk exists if the system may fail to achieve performance requirements; to meet operability, producibility, testability, or integration requirements; or to meet environmental protection requirements. A potential failure to meet any requirement that can be expressed in technical terms is a source of technical risk." It also states that: "Technical risks should not be confused with project risks even if the method to manage them is the same. Technical risks address the system itself, not the project for its development. Of course, technical risks may interact with project risks."

Finally, we considered the traditional "bow-tie" model of risk, and whether it would be too limited to use in this context. The central concept of this model is that the combination of an event with an underlying cause, leads to the adverse effect, where the risks are categorised by where the cause lies, not by where the effect manifests itself. This is perfectly reasonable for the majority of risks that remain self-contained within their area, but is less helpful when, for example, a financial cause leads to a technical effect and neither party is empowered to own the mitigations at each end.

FIGURE 1

The "Bow Tie" model of risk



In terms of "systemic risk", the most useful definition came from the Systemic Risk Centre (Systemic Risk Centre 2021) which takes a holistic approach to financial markets, stating that "Systemic risk refers to the risk of a breakdown of an entire system rather than simply the failure of individual parts." Whilst its research is focussed on interactions between participants in financial market systems, the centre has key research strands on "endogenous risk" and "amplification mechanisms". Endogenous risk refers to risks which are due to interactions and events taking place within a system, rather than impacting upon it from outside. Amplification mechanisms are the ways in which endogenous risk manifests itself in the financial system and translates into concrete events.

So Technical Systemic Risks are:

- Related to both the performance of technical engineered systems, and to the technical activities which develop and support them.
- Amplified by interactions between interrelated elements across the socio-technical system leading to emergent effects which may be driven by feedback loops and unintuitive patterns.

This emphasis on organisational aspects suggested that both the Cynefin framework, see (Kurtz & Snowden 2003), and the Viable System Model (VSM) would be insightful here. There were clear resonances with Cynefin, where traditional risk management acts in the Complicated domain but systemic risk management requires approaches which are better suited to the Complex domain – most likely in spotting patterns through "retrospective coherence" and identifying time-lags between causes and events. Similarly, the VSM (Beer 1972), and particularly the VSM pathologies described in (Cusin 2015) were very helpful in framing and positioning the various candidate Technical Systemic Risks which emerged from stakeholder engagement against Systems 1-5 in the VSM model.

However, for most risk managers, an approach requiring them to understand both complex adaptive systems and cybernetics in order to identify and mitigate risks was always going to be a non-starter. Hence the need for something more accessible.

3. An Indicator-Based Approach to Identifying Systemic Risks

Risk and opportunity management (ROM) within Defence tends to be inwardly focused. For example, Project ROM will look to address risk and opportunities impacting project deliverables and outputs. Business Unit (BU) ROM will look to address risk and opportunities impacting BU outputs and objectives. Enterprise ROM considers risk to the delivery of the enterprise's objectives taking a top-down view of potential barriers and blockers but staying within the scope of the particular enterprise.

What is needed is a way to identify and manage common, cross-cutting and output risk and opportunities that are prevalent across and within technical activities. These need to be collectively and effectively managed to the benefit of all impacted parties. Systemic ROM encourages risk practitioners to think beyond their area of responsibility and consider the likelihood of occurrences elsewhere in Defence for further action. It encourages the identification of a "best person" to manage the impact and mitigation of the risk outside of their area of responsibility.

Technical Systemic Risks have been observed to exhibit some of the characteristics shown in Figure 2.

A set of descriptions for the Technical Systemic Risks characteristics is provided in Table 1. These have been further developed into a series of indicators and potential mitigation activities as part of this study but are omitted from this paper due to length constraints.

FIGURE 2

Characteristics of Technical Systemic Risks

TABLE 1

Characteristics of Technical Systemic Risks

Characteristic	Description
Consistently Recurring	The risk is common to multiple activities across Defence and would be best managed through a coordinated higher-level mitigation activity. It may also be recurring, unless action is taken to reduce the probability of future occurrence.
Product of Organisation, Behaviours and Processes	"Every time we do x, there is a risk of y happening". A review of how the business operates is an appropriate mitigation.
Interdependence	The risk is a function of interlinkages and interdependences within and across organisations. Consequences can be amplified by system connectivity (A minor impact in one area / activity could have a disproportionate effect elsewhere), or the risk could lead to a critical failure that could compromise activity elsewhere in Defence.
Systemic View	The true impact of the risk is only observable at a higher, aggregated level. Causes that are not effectively manageable and impacts treatable by one area of the business alone are indications of a systemic risk and require a wider business risk management approach (potentially because there is not a single obvious owner).
Wider System Impact	The risk may have significant wider adverse effects, or the local mitigation (which may be appropriate to that BU activity) may have adverse effects elsewhere in Defence.
External Causes	Caused by an event that does not directly impact a Business Unit output but impacts on the overall capability the Business Unit is contributing to. On wider consideration, the most appropriate response may require mitigation action within a non-effected business unit, and/or elsewhere in the system.

To simplify identification of candidate Technical Systemic Risks, a set of indicators has been defined to support this set of characteristics together with assessment criteria to assist with risk quantification and prioritisation. These can be applied to a risk under consideration, as part of established risk management practices and, if affirmative, suggest the risk should be considered as systemic and indicate its significance for management action.

As noted above, due to space constraints these indicators have been omitted from this paper, but more details can be found in the Knowledge in Defence website (MOD 2021) in the Systems Engineering area. It would be interesting to relate these characteristics to the System of System 'pain points' identified by (Dahmann 2014).

4. Relationship to P3M Risk Management and Enterprise Risk Management

Enterprise Risk Management (ERM) is being investigated and adopted in several parts of UK MOD. It offers a top-down route to identify and manage the risks inherent in achieving the strategic objectives of an enterprise. (Hopkin 2018) provides this as a comprehensive definition of ERM:

a. ERM involves the identification and evaluation of significant risks, assignment of ownership, implementation and monitoring of actions to manage these risks within the risk appetite of the organisation.
b. The output is the provision of information to management to improve business decisions, reduce uncertainty and provide reasonable assurance regarding the achievement of the objectives of the organisation.
c. The impact of ERM is to improve efficiency and the delivery of services, improve allocation of resources (capital) to business improvement, create shareholder value and enhance risk reporting to stakeholders.

What is most striking about this is the focus on the strategic objectives of the organisation as a means to provide context and direction to risk management activities. This makes it eminently suitable for managing both the change portfolio and business-as-usual operations of a Front Line Command.

4.1 Comparison of ERM with TSR and Traditional P3M Risk Management

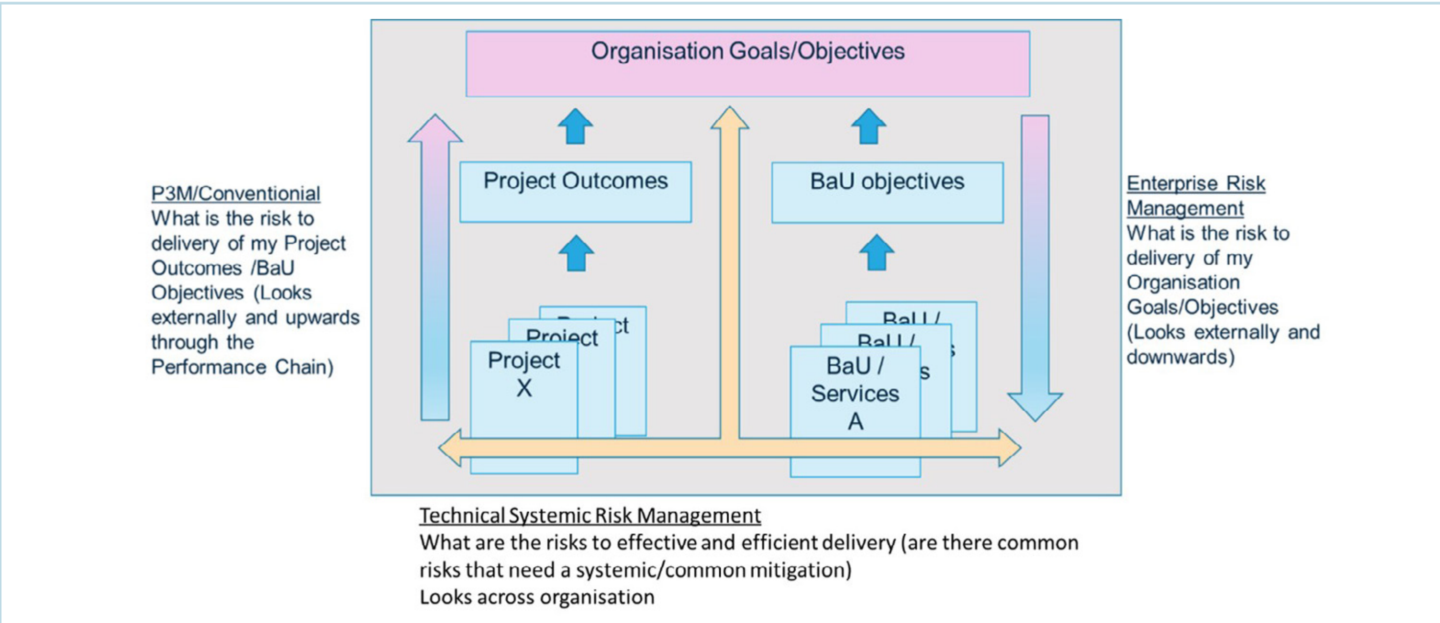
ERM sounds very similar to managing Technical Systemic Risks, but there are some key differences.

- Technical Systemic Risk management takes a purposeful and proactive orthogonal view across projects, programmes, BaU activities and functions. It is intended to operate across multiple projects, programmes and even sub-portfolios identifying and mitigating risks to technical delivery, and the effectiveness and efficiency of the business.
- Critically, whereas ERM takes a top-down perspective to identify risks to achieving the enterprise's strategic objectives, Technical Systemic Risk management extends the bottom-up traditional approach to identify technical risks which have the potential to derail multiple projects or business activities and **escalates them outside of programmes and projects for resolution and mitigation**.

As shown in Figure 3, ERM drives out risks to achieving enterprise objectives, traditional risk management drives out risk to project outcomes, and Technical Systemic Risk management drives out risks to effective solution delivery (often risks unforeseen to other projects and business units).

FIGURE 3

Comparison of ERM, TSR and P3M Risk Management



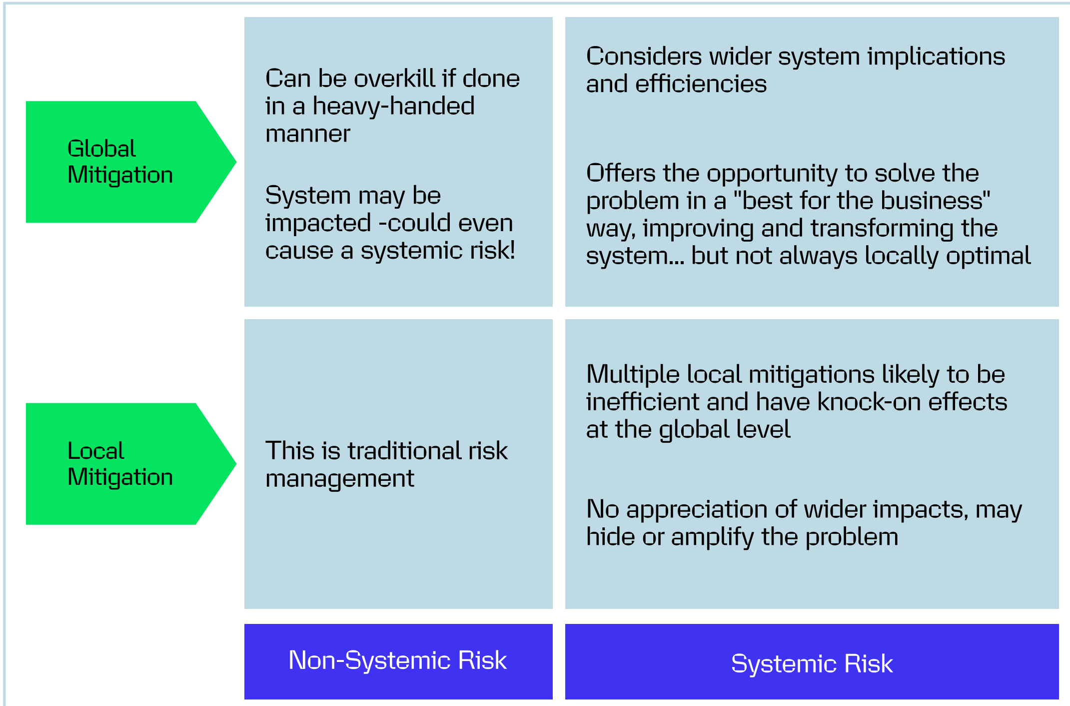
4.2 A Process vs A Way of Thinking

Importantly, traditional risk management and ERM are processes operating in the organisation. Systemic Risk management however can adapt to use existing processes and is more of a "way of thinking" to extend risk management approaches. When a risk/issue is identified, using a traditional or ERM, approach (or when an unexpected event occurs), Systemic Risk management asks the question: "Could this be occurring elsewhere in the business; will this have an adverse impact elsewhere outside of my immediate area of interest; and if so, is the mitigation or prevention of reoccurrence best handled with a cross project/BU/organisation action?"

Of course, just because a risk could be treated as being systemic, doesn't necessarily mean that it should be treated as such – and similarly for non-systemic risks. As shown in Figure 4 below, there are situations where global mitigations to non-systemic risks can be as dangerous as trying to apply a series of local mitigations to a system risk. This figure also brings out the important point that some systemic risks may require locally sub-optimal mitigations in order to serve the "greater good".

FIGURE 4

Mitigating Systemic and Non-Systemic Risks



MOD risk management policy draws heavily on advice from the Office of Government Commerce (OGC) and Association of Project Management (APM). JSP 892 (MOD 2021) provides direction and guidance on the "strategy, principles and mandatory requirements" for risk management in the MoD, however, under a delegated operating model, each constituent organisation is free to implement its own approach to governance, process and activities, providing they meet the requirements within JSP 892.

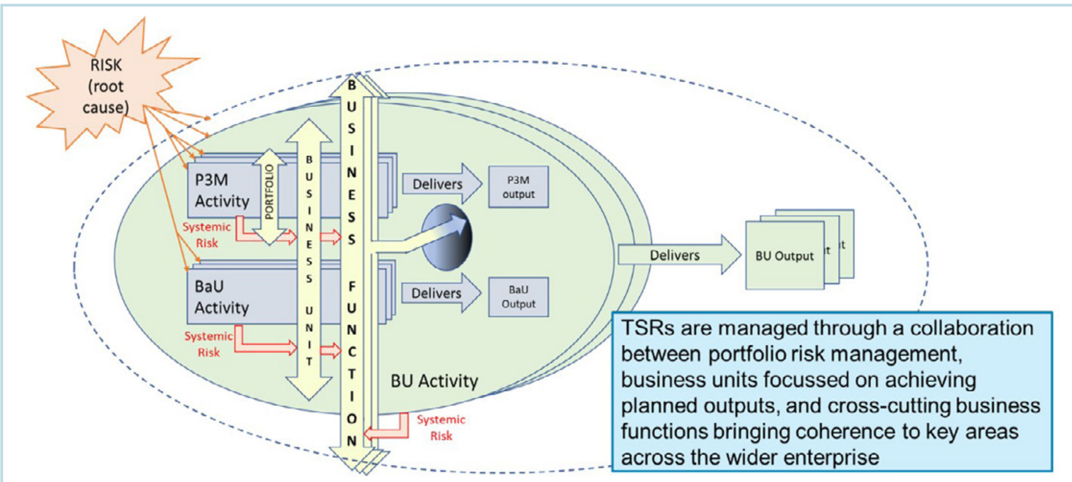
The policy currently guides organisations to identify and manage "cross-cutting risks", and Systemic Risk management provides a means to comply with this. The intent is that the Systemic Risk management approach will be adopted into Defence risk policy in the next issue of JSP 892. The approach has also attracted the interest of the Risk Centre of Excellence within HM Treasury, with some initial exploration taking place to make it part of a pan-government risk toolkit.

5. Implementation of Technical Systemic Risk Management in UK MOD

The Systemic Risk management approach is applicable to all the organisations within the MoD, and the cross-cutting nature could provide many of the "Functional Leadership" areas with improved risk information relating to their areas of responsibility. Technical Systemic Risk management is being piloted first by working with senior technical stakeholders in all MoD organisations. Significant engagement has taken place over the last 18 months with stakeholders ranging from risk practitioners within projects, technical experts and portfolio management teams. The team has provided guidance material, teaching sessions and briefings, and plans to work with existing technical governance structures to share TSRs and discuss coherent mitigation strategies. Figure 5 below shows the intended operating model for managing Technical Systemic Risks. As can be seen, the aim is to ensure that technical systemic risks are captured and managed by a combination of traditional P3M risk management activities and by activities within the business units and cross-cutting business functions.

FIGURE 5

Technical Systemic Risk within the UK MOD Acquisition Landscape



Project "Learning from Experience" (LFE) reviews are expected to provide a rich source of potential Technical Systemic Risks which could impact other projects or future business activity. Systemic Risk management provides an opportunity to capture this experience and where the potential benefits justify the resource, develop mitigations that lead to long term business improvement. Once tested in this way, the intent is to promote wider adoption of Systemic Risk in other business areas.

Three case studies emerged during the study, which are summarised below in an abstracted form.

"Consistently Recurring" Example – Learning from Experience:

During stakeholder engagement, several different organisations flagged up that they did not think that they were exploiting their lessons identified as effectively as they could be, potentially leading to recurrent problems that could be addressed by better visibility of similar risks on recent programmes.

An LFE toolset was identified that was already in use and would be straightforward to roll out across these organisations. An investigation was proposed into using data analytics on this toolset, aiming to move from cataloguing LFE to actively exploiting it.

"Interdependence" Example – Workforce SQEP Management:

Most stakeholders have raised risks around workforce planning and the need to have access to Suitably Qualified & Experienced Personnel to support their programmes and activities - noting that they are often in short supply.

Mitigations such as offering better pay and conditions would be likely to solve a local problem at the expense of creating one elsewhere in the wider enterprise.

A broader approach would be to look at creating centres of excellence for certain key disciplines (such as Quality) that can be drawn upon, changing roles & responsibilities within the processes, or taking a longer term view across the business to enable better workforce planning to meet evolving skills needs.

"Systemic View" Example – Requirements Interface:

A pattern was spotted between risks raised within customer organisations and risks raised within acquisition organisations relating to the technical requirements interface. One side felt that they didn't always get enough technical support to develop the requirements, the other felt that they didn't always get enough firm direction and scope on what the requirement was.

This is recognised as an opportunity to improve Front Door services, particularly in the Programme Definition and Concept Phases where requirements should be developed in more of a collaborative manner between customer and supplier organisations.

6. Conclusions

The following conclusions have been drawn from the transformation initiative described in this paper:

- Traditional risk management practice tends to overlook Systemic Risks, often due to lack of vision beyond project and programme focus or organisational and functional boundaries.
- Technical Systemic Risk management allows risks that may be common to, or impacting upon, several areas of the business to be identified, and managed. This will allow common and consistent risk mitigation to be applied in a "best for the business" way.
- Technical Systemic Risk management is complementary to existing P3M and ERM approaches, providing an almost orthogonal view on the same problem-spaces and solution-spaces.
- Technical Systemic Risk management is equally applicable to business-as-usual activities as it is to projects and programmes. LFE reviews are a rich source of potential Systemic Risks.
- The approach outlined above is an accessible and useful approach which risk practitioners should find easy to adopt and can be readily adapted for non-technical Systemic Risks.
- This approach should be readily applicable in any enterprise which is grappling with the issues outlined in this paper.

Acknowledgements

This paper is based upon material previously presented at the INCOSE UK Annual Systems Engineering Conference 2021 and republished with the permission of INCOSE UK Ltd.

We would particularly like to thank the Defence Risk Authority, and the wider stakeholder group, for their help and support in developing the approach outlined in this paper.

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Lessons from Experience – 25 Years in Acceptance Planning for Defence Customers

Abstract

An integrated systems engineering approach aligned to ISO 15288 goes a long way towards securing delivery of assured capability. A 'customer' perspective on Integrated Test, Evaluation and Acceptance (ITEA) is presented based on 25 years' experience of applying the ITEA planning process with the UK Ministry of Defence. The pros and cons of prescriptive vs collaborative approaches are discussed, along with commercial considerations and balancing 'the risk of not knowing' against 'the cost of finding out'. The practicalities are considered of managing 'planning' and then 'implementation' of ITEA, not just of new systems, but of Capability in the round.

Keywords

Integrated Test, Evaluation and Acceptance (ITEA); Systems engineering; Defence

Introduction

ISO 15288[1], the international standard for Systems Engineering, provides guidance on best practice and advocates systematic verification and validation. In layperson's terms the author would say that this standard simply advocates 'applied common sense', suggesting a systematic approach to writing down Requirements and, as an integral part of expressing those requirements, defining measurable effectiveness for User Requirements (URs) and measurable performance for System Requirements (SRs).

However, having defined measures of effect or performance to be achieved (where a measure comprises both metric and a standard to be achieved) is not the same as having a clear understanding of 'what good looks like' and 'how you will know when you've got there'.

For example, the UR might call for the ability to 'project power globally' and SR might for require 'global range' with the Measure of Performance (MOP) defined as 'able to reach India without refuelling'. However, sailing or flying to India might not be the best way to establish confidence that the solution satisfies this requirement. It might be better to measure specific fuel consumption in the cruise and useable fuel capacity, the latter obtained by calculation from drawings of the fuel tanks (ie analysis) perhaps, and then extrapolate.

A number of fundamental tenets have emerged from 25 years' experience in the planning and implementation of Integrated Test, Evaluation and Acceptance (ITEA) across a wide variety of UK Defence projects in the Land, Sea, Air, Weapons and C4I domains. Fundamentally, ITEA is a process of developing an argument, supported by evidence, in support of one or more important decisions, through life.

The more thought that is put into answering the question 'What would I like to know when I have to decide', the more likely that information is to be available when you need it. The author would like to offer his 'Top 10' thoughts for your consideration and hope this helps you achieve a better outcome for your project or programme.

Ten Thoughts on Integrated Test, Evaluation and Acceptance (ITEA)

1. Begin with the End in Mind

1.1 Acceptance Strategy

The starting point should be the development of a clear Acceptance Strategy. This means identifying and defining the key 'Decisions' that ITEA needs to inform. This sounds simple, but rarely is.

1.2 Identify Capability Milestones

At a fundamental level the most important decisions in UK Defence are 'Capability Milestones' (CMs) – the declaration that a usefully deployable capability increment has been achieved. Initial Operating Capability (IOC) is defined as the minimum usefully deployable capability. This matters legally because, in Defence, a senior officer is 'Accepting' that the capability is ready to be used in anger and could then accept the risk of placing people in harm's way on operations.

1.3 Define Capability Milestones

CMs are about the ability to deliver a defined military effect; they are not solely about equipment functionality or the availability of a given number of items, but about readiness across the enabling- systems that you need to support the primary (or operational) system during the operational stage of the system lifecycle; in UK Defence these are referred to the Defence Lines of Development (DLOD) identified in the MOD Knowledge in Defence (KiD)[2] guidance. A CM needs to be defined, and evidence gathered of readiness, across each and every DLOD - Training, Equipment, Personnel, Information, Doctrine & Concepts, Organisation, Infrastructure, Logistics - represented by the mnemonic 'TEPIDOIL'. Undue focus on Equipment, and attendant failure to establish appropriate projects and accountability across the other DLODs, can lead to significant delays in achieving CMs. Other aspects which may merit special consideration and monitoring include:

i. Interoperability.

ii. Safety and Environmental protection.

iii. Security.

iv. Sustainability/Carbon Net Zero.

2. Informing Other Decisions

When ITEA planning there is a tendency to focus on the final 'Acceptance' decision for the roll-out of a defined capability increment. But there are other decisions along the way which would benefit from being 'informed' by 'evidence' and supported by a robust evidence audit trail.

2.1 A Legal Analogy - Arguments

A decision is the outcome from a review where an 'argument' is considered. The person presenting the argument may appeal to evidence to support their assertion. An information-item can only be considered to be evidence if it is used to support an argument. In her 1986 book on W Edwards Deming[3], Mary Walton cited the following quote, often attributed to Deming - "In God we trust. All others must bring data". As in a court of law, admissible evidence may be:

i. Factual (test-reports).
ii. Testimony (expert-witness).
iii. Exhibit (physical item).
iv. History /Precedent (every rainbow that we have ever seen has been preceded by rain).

2.2 Other Types of Key Decision

For every Defence Acquisition project in the author's experience there have been a multitude of important decisions made prior to 'Acceptance'. These may include, but not be limited to:

2.2.1 Bid Phase Decisions

i. Candidate Option Down-selection.
ii. Preferred bidder selection.
iii. Contract Award.

2.2.2 Design Phase Decisions

i. Preliminary Design Review (PDR).
ii. Critical Design Review (CDR).
iii. Final Design Review (FDR).
iv. Trials Readiness Review (TRR) (likely to be multiple events!) .

2.2.3 Key Programme Milestones

i. Logistic Support Date (LSD) (both developmental (for trials) and in-service).

ii. Release-to-service (RTS - safety clearance).

iii. Ready for Training Date (RFTD).

iv. Contract Acceptance (CA).

v. System Acceptance (SA).

vi. In Service Date (ISD).

2.2.4 Subsequent Capability Milestones

Once an IOC has been achieved and declared available at ISD, further increments are likely driven by considerations which may include:

i. Day, Night, Poor Weather clearance.

ii. Temperate vs Arctic or Tropical Environments (hot/high/cold)

iii. Benign vs High Threat Environment that requires defensive aids etc.

iv. 'Standard' vs 'Special' Operations.

For a full 'default' list see IEEE Std 15288.2 - IEEE Standard for Technical Reviews and Audits on Defense Programs[4].

It is an unassailable fact that, if you identify all these decisions, contemplate what you'd like to know to give you confidence you've made the right decision, and then systematically set about collecting it, you are much more likely to have the information available to make a good decision. To understand what information you would like to have to hand, you need to develop the basis of your argument – the Acceptance Case.

3. Evidence Gathering Opportunities

Having identified and defined the 'decisions' requiring 'evidence' in support, the next logical step is to identify where that evidence could be obtained.

3.1 IDAT – Possible Methods

ISO 15288 presents a basic taxonomy of methods for generating 'evidence' to support your 'argument', often known by the acronym 'IDAT':

i. Inspection – take a close look
ii. Demonstration – show me it working
iii. Analysis – do some calculations
iv. Test – make objective measurements

Any other 'method' can usually be considered a specific sub-set thereof.

3.2 Exploit Existing Data

The key point here is to evaluate, in the first instance, what existing qualification data (EQD) is available and can usefully be read across, to avoid the need for further testing; confining evaluation to data gathered exclusively for 'qualification' purposes may be unhelpful here, although it implies a certain degree of rigour and controlled conditions. It is important to explore the utility of all available information. The challenge lies in determining or justifying whether read-across is valid; were the conditions adequately controlled and what may have changed?

3.3 Avoid the Unnecessary

Here, the focus needs to be on avoiding the time and cost penalty associated with conducting unnecessary trials. This is particularly pertinent to expensive flight trials in the Air domain. This can happen for a number of reasons:

i. Failure to adopt an Integrated approach to ITEA, combining Developmental and Operational T&E as far as is practicable.
ii. Not taking a risk-based approach to balance, carefully, the 'risk of not knowing' against the 'cost of finding out'.
iii. Lack of innovation – failure to exploit new ways of working by making greater use of 'digital twins', synthetic environments, modelling or simulation.

3.4 Take a Risk-based Approach

Inevitably, there is a cost attached to every potential activity to gather data, and both time and resources are limited. So having rationalised any duplicated activities, the next step is to rationalise further to bring the T&E programme within affordability limits and time constraints – considering "what are we really worried about - how likely is it that the solution will not satisfy this requirement and ...what would be the impact?" We should then prioritise activities that will give us confidence in those areas.

3.5 Progressive Assurance

Next the author would advocate looking at the opportunities between each decision point to learn more about the capability. Joint customer-supplier forums are required to explore and identify opportunities to increase confidence, over time, that the solution will satisfy the requirement by providing 'progressive assurance' that things are going well or early warning of possible issues ahead. In most projects there is a logical progression through a series of events, each of which may be further sub- divided, such as:

i. Bid reviews
ii. Design reviews
iii. Bench testing
iv. Rig Testing
v. Integration testing on the platform
vi. Static Testing
vii. Dynamic Testing
viii. Operational Evaluation
ix. Warfighting exercises

While testing 'products' is important, it could be argued that testing 'process' (how you interact with the product) is even more insightful. Additional specific trials or testing in specialist areas may be required, such as:

i. Human Factors Integration (HFI)
ii. Logistics Demonstration
iii. Electro-magnetic compatibility (EMC)

3.6 Rationalise

Identifying and agreeing the identity of each phase of 'evidence gathering' and who is 'leading' on planning and implementation, allows the wider stakeholder community to get involved in a process of rationalisation, upholding the tenet 'Test Once, Use Many Times'.

3.7 Early User Involvement

Early involvement and oversight of contractor developmental activity by the end user benefits both parties; the contractor potentially benefits from 'free' consultancy. If this 'advice is followed, it is likely to result in increased user satisfaction and better follow- on sales prospects for the supplier while the end user gets a better product more suited to an emerging operational environment the contractor may not fully understand. There are potential downsides though; requirements creep, differing opinions and negative impressions of immature developments may arise so this needs to be managed carefully.

3.8 Choose the 'best athlete'

Once a defined set of 'opportunities' have been identified in which to conduct test and evaluation activities, then stakeholders can get down to the detailed business of allocating conduct of a particular activity to a given 'opportunity'; finding the 'best athlete' for the task in hand.

4. Commercial Practicalities

It is important that the Programme and Technical Management have a shared perspective on everything from 'Bid Development' to 'Acceptance', particularly with regard to the contract and commercial aspects. Among things to consider are:

4.1 Existing Qualification Data?

The invitation to submit proposals and/or the contract should make explicit provision for the supply of the EQD required to support decisions; for a mature 'Commercial-off-The-Shelf' (COTS) product this may even be sufficient to support acceptance without further trials. Review and evaluation of available EQD during solution down-selection should allow better quality decision making and substantiate 'marketing claims' made in brochures.

4.2 Developmental Programme?

Does the programme necessarily involve development? Where development is involved, and the solution will not be designed until after contract award, the approach to ITEA needs to acknowledge this and, rather than contracting for 'specific evidence' might be better off contracting for 'ways of working'; for example, agreeing a joint approach to defining what evidence will be provided.

4.3 Prescriptive vs Collaborative?

While it would be nice to have a calibrated crystal ball with which to see the final design solution and contract for specific evidence at the outset, this is rarely practical. The customer rarely has the detailed technical knowledge nor the capacity to develop exhaustive lists of evidence and criteria against each of their requirements. Criteria used to determine if the solution satisfies the requirement are expressed as 'measures-of…' and stipulated/agreed by the requirement owner, preferably after they have consulted the solution provider to determine the art- of-the-possible. There is an attendant risk that, by demanding specific evidence, the customer inadvertently drives additional cost into the programme. Every request for information comes with a cost and customers shouldn't expect a supplier to provide 'free' information. If you want something, contract for it and pay for it. As a general rule, things seem to work best when the supplier is responsible for proposing how they intend to demonstrate compliance, and the customer has a 'right of veto' that they can exercise if supplier proposals fall short of expectations. This is sometimes referred to as the 'show and find' approach; it is for the supplier to 'show' and the customer to 'find' compliance with the contract and satisfaction of the requirements; it should be in the supplier's interest to help them do so.

4.4 Specific Deliverable Documents

It is important to make customer expectations, with regard to ITEA, explicit in any 'Requests for Proposals' and subsequent 'Contract' documents. These should require the supplier to present a Compliance Demonstration Plan (CDP) outlining:

i. Their approach to ITEA implementation.

ii. How they intend to interact with the Customer to agree an 'Acceptable Means of Compliance'.

iii. How joint working will be effected to provide the customer with visibility of activities throughout the project lifecycle, providing progressive assurance.

iv. The measurement activities that they will conduct to determine that their solution satisfies your requirements.
v. The information-items that they will use to support their argument.

To ensure these documents are 'suitable', the customer should issue clear information product descriptions or 'Data Item Descriptions' (DID), listing the expected content and structure, and make them explicitly deliverable items as part of the bid response or contract, by allocating a unique DID or Contracted Document Requirements List (CDRL) serial number.

4.5 Link Contract and System Acceptance

An integrated approach is one of the fundamental elements of ITEA. To that end, Contract Acceptance should be contingent on System Acceptance. The supplier will not like this, because User evaluation of the system effectiveness as an integrated whole in the operational environment is inherently more subjective, and therefore fraught with risk from a supplier perspective. This makes it important to present the supplier with customer proposals for User validation of the system at an early stage, showing that there are fair and reasonable objective measures of effectiveness. It is important to secure mutual agreement on what constitutes acceptable system effectiveness in the operational environment and how this will be demonstrated for System Acceptance, as an essential precursor to Contract Acceptance.

4.6 A Pragmatic Approach.

While contract acceptance should be dependent on system acceptance, which in turn should be conditional upon user acceptance, the pragmatic approach is to accept the design, based on the argument presented, but reserve the right to change amend your decision if evidence to the contrary is later exposed that rebuts the earlier argument. In practice, Contract Acceptance is unlikely to be a 'one shot' event, but to comprise a series of milestone payments. As it is likely that the appetite to claw back any milestone payment would be poor, consideration should be given at the outset to what proportion of the total milestone payments to attach to each milestone up to and including User acceptance.

4.7 Contract Requirements Specifications

A contract to design, build, and support a product should comprise three requirement specifications for:

i. Design
ii. Support specification
iii. Data specification – often called a CDRL.

The contract may also include a statement-of-work (what they are going to do), where the output from each activity is either a product (listed in the delivery schedule) or data (listed in the CDRL). 'Ways-of- working' are typically expressed in a Memorandum of Understanding (MoU) rather than a contract.

5. Validation and Verification

In UK Defence terminology System Acceptance should be conditional upon both Verification against System Requirements, led by the supplier, and appropriate Validation against User Requirements, led by the User. Otherwise, undue reliance is placed on the veracity of any mapping between User and System requirements, and their subsequent decomposition into design requirements for each system element. Before accepting the system, the User should evaluate whether the system delivered meets the endorsed User Requirements specification, by conducting appropriate evaluation involving system use in representative scenarios which include realistic operating environments. All too often, User trials are not planned or completed until after Contract Acceptance is complete, when any leverage to secure remediation against perceived shortfalls has been lost.

6. Stakeholder Engagement

The Association for Project Management (APM) cites 10 Key Principles for Stakeholder Engagement[5], with 'Communicate' heading the list. However, it is not unusual to find programmes where key stakeholders have not been engaged at an early stage! Examining three key groups could explain why:

6.1 Users

The term 'User' can be quite broad; there is a danger of consulting, for example, only the principal operator of a system, but maybe neglecting to consider the wider 'User' community. For example, with an airborne early warning or reconnaissance aircraft, 'Users' could be construed beyond the immediate crew of the platform to include everyone that uses the information products it generates, which might range from operators of other assets being directed, to the battle commanders in headquarters, to intelligence analysts to air traffic management staff.

6.2 Maintainers

Generally, maintainer interests are reasonably well considered under the banner of Integrated Logistics Support (ILS) in accordance with Defence Standard 00-600, which generally includes maintainer training, documentation, spares and repairs. However, it is increasingly rare to see the full Logistic Support Analysis (LSA) processes followed. As a minimum, UK MOD KiD guidance advocates completion of a spreadsheet known as the Support Solution Development Tool (SSDT) as a vehicle to ensure adequate consideration of the 'Support Solution Envelope' (SSE).

6.3 Regulators and Specialists – Red Card Holders

There almost seems to be a reluctance to engage certain regulators and specialists, sometimes termed 'Red Card Holders', that have the potential to really 'throw a spanner in the works' at a later stage. To reduce risk to the programme, these stakeholders should be consulted from the outset to ensure their specialist requirements are captured and their advice sought on the level of evidence required from the supplier to support 'sign off' by the relevant authorities. Areas which frequently would have benefitted from earlier consultation include, but are not limited to:

i. Safety certification.
ii. Security including Physical, Cyber and Emission Control (TEMPEST).
iii. Human Factors.
iv. Electromagnetic Environmental Effects (E3) including Spectrum usage and EMC.
v. Interoperability and Networking.

7. Resources and Responsibilities

There is a tendency to underestimate the resources required to implement ITEA. This is driven, in part, by a reluctance to disclose the full costs which are likely to be incurred when seeking funding approval. This makes it difficult from the outset because the customer is likely to be under-resourced when they come to oversee supplier activity. Resources tend to come under two main headings:

i. Human Resources - People

ii. Equipment and facilities

7.1 People - Requirements

There are generally two challenges with identifying people; the first is understanding your requirements for support – all the ITEA roles which need to be fulfilled by someone. It is easy to underestimate the human resources required to support the ITEA process from initial requirements capture through trials conduct to evidence evaluation and finally decision making. At a working level, there is likely to be a requirement for members to support a full-time Joint Evaluation Team (JET), working alongside the supplier to plan T&E and then overseeing and witnessing activity during implementation. At higher levels, although not likely to be involved full-time, others are going to be required to participate in the hierarchy of meetings necessary for effective governance of the programme.

7.2 People – Solution

As a minimum, the ITEA Information Management System should aim to capture who will test the solution, who will evaluate the data generated, and who will decide an appropriate 'sentence' against each requirement – the latter normally known as the 'requirement owner' – the arbiter of success. It is an important exercise to get 'names in the frame' for each and every requirement, not least because the stakeholders which emerge may not necessarily be suitably qualified and experienced persons (SQEP).

7.3 Subject Matter Experts

Where the 'requirement owners' don't consider themselves SQEP, then the customer probably needs to engage a 3rd party to provide SQEP specialist Subject Matter Experts (SME) who can give independent advice in support of sentencing requirements.

7.4 Equipment

Surprisingly, it is easy to overlook fundamentals like the equipment required for testing. This tends to be less of a problem where a new platform is being introduced. It can be more of an issue with upgrade programmes, which depend on taking in-service platforms out of circulation. Similarly, 'commodity' programmes, which span multiple platform types, tend to think the 'world revolves around them', when actually 'Platform Primacy' tends to prevail and they may have to wait their turn for embodiment at the next maintenance opportunity, alongside other upgrades and modifications.

7.5 Consumables

Consideration needs to be given to consumables required to support trials, particularly User trials. This is particularly true of weapons or stores that need to be fired or dropped; how many rounds will be required for test purposes, if only to validate models, including 'space models' for 'fit' or 'platform release' tests, guided inert rounds for accuracy assessment and live warheads for blast, fragmentation or penetration tests? And what about representative 'multi-spectral' targets?

7.6 Ranges

Besides the equipment under test, consideration should be given to what Ranges may be required to support the T&E programme. With any kind of weapon evaluation, consideration will need to be given to where they can be fired – it is easy to exceed the safety limits for many UK ranges, necessitating expensive overseas trials in places like the US and Australia where larger ranges are available.

7.7 Instrumentation

Consideration also needs to be given to the availability of suitable instrumentation. While there is increasing scope these days for extensive data capture from digital systems for subsequent analysis, there may be a requirement to capture additional data. This may involve the development and integration of additional specialist instrumentation and sensors such as high-speed cameras, precision navigation systems, strain gauges or temperature sensors. All of this has attendant costs and can create a dependency on one or two specially instrumented assets.

7.8 Facilities

A wide variety of specialist T&E facilities may be required to support a programme, ranging from the relatively simple but often overlooked requirement for suitable secure and environmentally controlled storage for equipment under test (EUT) to specialist facilities such as:

i. Open site Electromagnetic Compatibility (EMC) testing.
ii. Environmental Test Chamber.
iii. Radio Frequency Anechoic Chamber.
iv. Vibration testing.

7.9 System Rigs

A great deal can be learned from having a representative full systems rig which replicates that which is embedded in a platform but allows ready access to system components in a laboratory environment. Investment in a rig during development may provide an asset which subsequently supports the capability through-life – providing an environment where line replaceable units can be run to trace faults or eliminate 'no fault found' arisings and returned to use or used for ongoing development and test of bug- fixes and upgrades. Projects often acquire a test-rig and a separate training-rig. Consider both requirements before settling on a solution, as one rig may satisfy both requirements.

7.10 Digital Twin

The term 'digital twin' can mean many things, ranging from a 3-Dimensional Computer Aided Design (CAD) drawing set to a functioning software model of the system. Increasingly, the term 'digital twin' is used to describe a systems rig where some or all of the system is replicated virtually, or emulated, rather than necessarily using the operational hardware/software manifestation of the system, to allow development and test against representative stimuli. While the supplier may themselves develop some form of 'digital twin' for development purposes, consideration should be given to whether the customer would benefit from having access to their own 'digital twin', as a cost-effective vehicle for some aspects of T&E as well as for retention as a through-life support tool.

7.11 Simulators and Synthetic Environments

Similarly, consideration should be given to what opportunities exist to exploit modelling and simulation as a vehicle for providing evidence to support decision making. There are issues associated with establishing the validity of evidence gathered by synthetic means, but conversely the use of modelling and simulation offers many potential advantages, particularly in the air domain, which include:

i. Reduced cost compared with live flight trials.
ii. Gathering more evidence early on before flight clearance is available for live flight testing.
iii. Running many more scenarios and conditions, gathering far more data than would be practicable or affordable with live testing.
iv. Completing actions, drills or scenarios that might be unnecessarily/unacceptably risky to complete during live testing.
v. Using a blend of live and synthetic to explore constructive scenarios that would be impracticable to reproduce through live testing alone.
vi. Avoiding your activities being monitored by an adversary.

8. Governance Organisation

The governance organisation established to oversee a programme obviously plays a key role. Often, meetings and working groups can proliferate, with poorly defined Terms of Reference (TOR) and limits of authority, leading to duplication, confusion and lack of clarity. A hierarchy of forums has emerged to support the ITEA process, which generally needs to comprise the following:

8.1 Programme Board

The Programme Board is the high-level forum in which the Senior Responsible Owner (SRO), charged with delivering the change programme by the Sponsor, makes the high level decision against a defined capability milestone, when presented with a comprehensive Acceptance Case Report (ACR), previously reviewed and endorsed by the sub- ordinate Capability Integration Working Group (CIWG).

8.2 Capability Integration Working Group (CIWG)

The CIWG is a management forum established within the User organisation to oversee the integration of the capability across all DLODs (see above). The CIWG should be the forum to establish and run any projects necessary across the other DLODs and make sure all necessary provision is in place to embrace and field effectively the system being acquired. The CIWG should have representatives for each DLOD, plus areas like Safety, the Environment and Security, reporting on readiness in their area. Prior to a Capability Milestone, the CIWG will review the Acceptance Case Report (ACR) developed in the ITEA WG (see below), focussing on any 'exceptions', and making recommendations to the Programme Board as to whether, collectively, these exceptions are tolerable or otherwise.

8.3 ITEA Working Group

The ITEA WG is an intermediate forum, usually comprising the same persons as were previously the Requirements Working Group, who naturally move on from asking 'What do we want?' to asking 'How will we know when we have it?'.

8.3.1 Planning Phase.

Depending on the nature of the programme, which may include varying complexity, novelty, or customer SQEP, during the 'Planning Phase' the ITEA WG may develop a VVRM against the Requirements Set as the proposed basis for 'Acceptance' either by:

i. Defining the evidence it expects to see provided, with criteria to be achieved (Prescriptive).

ii. Reviewing and agreeing supplier proposals (Consultative).

8.3.2 Implementation Phase

During the implementation phase the ITEA WG will then review the evidence presented and the sentencing proposed by the JET, developing the VVRM to present an argument, presented in an ACR, against a given Milestone.

8.3.3 The Acceptance Case Report

The ACR will effectively be a database export, with covering recommendations, highlighting which requirements have been met and any 'exceptions'.

8.3.4 Exceptions or Issues

Exceptions arise where confidence in the satisfaction of a given requirement has not been established, which may be due to either:

i. An issue with the solution – a system performance shortfall.

ii. A weak argument – eg evidence shortfall.

An issue is a risk that has materialised; the governance forum serves to place actions on stakeholders to resolve issues.

8.3.5 Sentencing Options

The following 'sentencing' options seem to cover every eventuality:

i. **Accept Outright** – the solution meets the requirement.

ii. **Accept with Proviso** – The requirement remains unchanged; there is a temporary relaxation of the requirement, pending completion of defined remedial action. A proviso should define what remedial action is to be taken and by when, which may involve just re-test, or re-work and then re- test. The only thing that really changes is the timeframe in which you expect the solution provider to satisfy the requirement.

iii. **Accept with a Concession** – there is an exception which can be accepted permanently; no remedial action is anticipated, although a price reduction may be sought. Effectively, the requirement is permanently relaxed.

iv. **Accept with a Proviso and a Concession** – where it is recognised that perhaps the requirement was unrealistic and could not be achieved in full, but higher performance than has been demonstrated is required as a minimum. In this case a temporary relaxation of the requirement may be granted pending a further improvement, which it is acknowledged will still fall short of the original MOP or MOE.

v. **Reject** – This aspect of the capability is unacceptable and therefore the Capability as a whole should not be accepted. This should be used very rarely. If the intention is to introduce the capability regardless, one of the above (ie proviso/concession) should apply.

8.4 T&E Working Group

The T&E WG sits below the ITEA WG which does not generally have the appetite for detail necessary to review each and every requirement. The T&E WG is where most of the detailed work of T&E Planning and Reporting is carried out to:

i. Propose detailed activities and success criteria.
ii. Allocate individual activities to the most appropriate evidence gathering opportunity.
iii. Develop a detailed 'trials plan' against each 'evidence gathering opportunity'.
iv. Review test scripts and check all necessary test points have been included.
v. Produce reports, with sentencing recommendations

The T&E WG would normally comprise both customer and supplier representatives and meet periodically, as required, to develop and agree trials plans and the subsequent reports.

8.5 Joint Evaluation Team (JET)

The JET is more of a 'way of working' than a forum. The term JET is preferable to terms like Combined Test Team (CTT), which unduly emphasise Test, which is just one means of gathering evidence. Evaluation better describes the role – evaluating whether the solution meets the requirements, gathering evidence through testing if necessary. The JET normally comprises the supplier team leading the conduct of most verification T&E, with customer representatives on site to agree proposals, witness testing and agree outcomes. This enables the presentation of reports by the supplier which have been 'vetted' by customer SME representatives on the ground. Roles may be reversed, although the same people may be involved, following any transition to User validation activity. Ideally the JET will comprise appropriate SQEP SME from the customer including technical specialists, independent 3rd party evaluators and the end User.

9. Validation and Verification Requirements Matrix (VVRM)

The VVRM is just one name that can be given to an ITEA Information Management System, developed from the requirements specifications. Other names often used include, but are not limited to:

i. Verification Cross Reference Index/Matrix (VCRI or VCRM) – usually used to describe a lower-level supplier verification matrix against the design specification.

ii. Acceptance database.

iii. Acceptance Case

iv. ITEA database

Once populated with outcomes, the database can be used to present a summary of the evaluation process outcomes including recommendations for sentencing each requirement. This is known as the Acceptance Case Report or ACR. This is an extension, of the long-established approach to presenting 'safety' arguments through Safety Case Reports, extended to include 'suitability'. A coherent argument, supported by an evidence audit trail, is presented that the capability meets the defined requirement.

9.1 Hosting the VVRM

For a simple project, the VVRM may be manifest as a relatively simple spreadsheet with the requirements, measurement activities, and evidence managed in linked worksheets. This has the advantage of ease of use and transmission between stakeholders but does not readily support rigorous configuration control or the more complex cross referencing needed for a large project. Requirements management tools like IBM DOORS™ may offer better solutions but come with some limitations; access can be problematic, licences expensive and specialist knowledge is required to customise the tool using the DOORS extension language (DXL) to fully exploit the tool's potential. More recently, tools like Polarion, Dimensions RM and Jama have begun to supersede DOORS as the tools of choice.

9.2 Developing the VVRM

There are two main phases to developing the VVRM:

i. **Planning** – during which the Requirements specifications are developed to identify not only MOP and MOE but also specific activities and criteria, to establish where evidence will come from, when, and who is responsible for conducting activities, presenting evidence, evaluating compliance and making recommendations and finally deciding whether to accept.

ii. **Execution** – during which evaluation is carried out, evidence outcomes are recorded and sentencing recommended for each requirement accordingly. Once every applicable requirement has been addressed an ACR can be extracted from the database which reflects these outcomes.

9.3 VVRM Structure/Granularity

There is a tendency to develop the VVRM with a 'one shot' mind-set – setting one value for 'evidence' and 'criteria' at [final] 'Acceptance'. There may be value in supporting incremental acceptance by developing a more complex VVRM which sets values for 'evidence' and 'criteria' against other milestones and decision points, recognising the need for progressive assurance. In that way the VVRM could be used to support decisions throughout the programme from preferred bidder selection and contract award through design reviews to progressive roll-out of the capability in increments, not just across successive capability milestones lying between Initial and Full Operational Capability.

9.4 Acceptance Case Report (ACR)

In its crudest form an ACR could be just a raw database export of the outcomes against each requirement. In practice, the ACR usually comprises 4 elements:

i. **Summary Letter.** A summary letter from the CIWG Chair to the SRO presenting an overall acceptance recommendation for the capability. This will normally identify whether there are any exceptions and, if so, the number of Provisos or Concessions, the aggregate impact these are considered to have on the capability delivered, along with the proposed plan for clearing any Provisos.

ii. **DLOD Statements.** A set of letters, one from each DLOD owner, providing specific assurance to the SRO that each DLOD has achieved the necessary state of readiness.

iii. **Exceptions Report.** An appendix containing a summary listing of all the proposed exceptions, including impact statements for each.

iv. **Full database Listing.** A complete database listing comprising a summary page per requirement detailing the outcome and allowing the SRO to drill down for more detailed information if required.

9.5 Dimensions of ACR

Typically, at least 3 separate ACRs are required, one for each of the following dimensions:

i. **Contract ACR** – An ACR that establishes the level of compliance of the supplier with their contractual obligations, the enabling acquisition organisation to support their contract acceptance decision and justify any remediation sought through the contract with regard to any performance shortfalls in the system delivered. This should address not just delivery of the 'design', but also 'support' and 'data'.

ii. **Safety ACR** – An ACR which presents evidence in support of the safety case argument and is supported by appropriate independent 3rd party advice. In the Air domain this specifically supports Release-to-Service and authorisation of the commencement of Service flying within defined operating limits. That is necessary to begin training and work up to an effective operational capability.

iii. **Capability ACR** – this presents a picture of pan- DLOD readiness and may not be delivered for some time, maybe months or even years, after the Contract and Safety ACRs, once the equipment has been fielded, supporting infrastructure established, and training completed such that there are sufficient Force Elements at Readiness (FE@R) for operational deployment and IOC, or any subsequent CM, has demonstrably been achieved.

9.6 Operational Risk.

Ultimately, the Acceptance Authority must decide whether to accept the Operational Risk, which is effectively the sum of:

i. safety-risk

ii. environment-risk

iii. security-risk

iv. DLOD-risk.

Even if all the DLODs are ready, the operational risk may not be As Low as Reasonably Practicable (ALARP) and/or tolerable. Therefore the CM acceptance case argument should discuss both readiness AND operational risk.

10. Pan-DLOD Approach

While the new platform or equipment may be central to the delivery of a new military capability through a change programme, effective fielding of that system as an effective military capability requires the other DLODs to be developed in parallel.

10.1 Capability Integration Plan (CIP)

The default 'setting' seems to be that there is little or no impact across the DLODs, leading to complacency and then last-minute realisation that more should have been done. To prevent this, the User organisation should develop and implement a comprehensive Capability Integration Plan, identifying what needs to be done and setting out the path to an integrated military capability.

10.2 DLOD Requirements?

In an ideal world, the System Requirements Document would be a pan-DLOD expression of the requirements. The flaw in this approach is that the DLODs are largely part of the solution, driven in many areas by the emergent equipment system design.

10.3 DLOD Goal Elicitation

In practice, identification of DLOD impact and setting up associated DLOD projects is an iterative, recursive activity which must continue throughout the programme, as the equipment solution emerges and the implications are understood. There are various ways in which the true extent of DLOD 'goals' can be identified and managed:

i. Stakeholder workshops – at regular intervals, stakeholders can be brought together for facilitated workshops to effect a 'brain dump' of their 'worry beads'. Simply gathering people in a room and getting them to write their fears and concerns on sticky notes and then put them under the appropriate DLOD area on a whiteboard can be very effective in identifying issues, risks and opportunities throughout the lifecycle/programme'.

ii. Lessons from experience (LFE) – every project has some similarities with projects which have gone before. Much can be learned from other peoples' mistakes, ruthlessly exploiting their LFE workshops and wash-up meetings to identify the things they wish they had known at the outset and done something about sooner.

iii. DLOD by DLOD analysis. This is a process whereby each DLOD is systematically analysed for its impact across other DLODs. So the Training DLOD may be examined to see what Training the Trainers require, what Infrastructure is required to house the training for maintainers or operators, what Information is required to develop training material, what Personnel are required to staff or support the training facility, what dedicated assets and Equipment are required for training etc.

iv. Systematic Structured Analysis. It may be very helpful to use a structured approach like 'Mind Mapping' or the more formal 'Goal Structuring Notation' (GSN) to systematically map out everything which needs to be done on each DLOD. Experience has shown that a hierarchical, graphical representation is easier to assimilate than large tables of data or a 'to do' list. Presented with a map of 'things to do', it becomes much easier to 'see' omissions or navigate to and scrutinise areas of potential concern.

v. Pan-DLOD Acceptance Case. Once the 'goal structure' is complete, the 'goals' can be treated as a 'requirement set' and similar attributes developed against them to capture responsibilities for delivery, evidence and criteria, due dates and other information.

10.4 Provider vs Decider

To prevent the 'poacher' and 'gamekeeper' being one and the same, it is desirable to identify at least two different persons for each DLOD, one responsible for delivery and the other to hold them to account (H2A), otherwise there is a tendency for the 'deliverer' to set the bar low and to be their own arbiter of success. Clearly, a measure of independence between delivery and assurance is preferable. This is perhaps best achieved by having a 'desk officer' responsible for day-to-day delivery who is then H2A by a senior officer responsible for issuing an explicit statement of DLOD readiness to the SRO at each CM.

10.5 DLOD Projects

Where there is a significant change project associated with a particular DLOD, which falls outside the acquisition project for which funds are transferred to an enabling 'procurement' organisation, then the Lead User organisation is responsible for establishing and running that project, through the CIWG.

10.6 DLOD Working Groups

Where there is a significant change project to be run within a particular DLOD, then a dedicated DLOD working group may be established. Often, DLODs like Organisation, Training and Personnel are managed in a joint working group because of their myriad inter- dependencies.

Summary and Conclusion

The ITEA Process is a matter of applying common sense to develop a robust argument, supported by an evidence audit trail, which is available in time to support each key decision. You are much more likely to have the information needed to support that argument and to make informed decisions if you start planning early and systematically collect it; if this approach is applied through-life, risk will be reduced.

The idea is simple. Execution is a little more difficult. It is hoped that some of the ideas outlined above will enable those responsible for acceptance of future projects to benefit from the author's experience supporting 'Acceptance' planning for the UK MOD over the last 25 years.

Acknowledgements

Mr. Ian Dodd, QinetiQ and Mr. Barrie Horton, BMT who conducted peer review.

This paper was previously presented at the Society of Flight Test Engineers European Chapter Symposium (Rome, May 2023) and the Aerospace Test & Development Show (Toulouse, September 2023)

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Abbreviations and Acronyms

ACR	Acceptance Case Report
ALARP	As Low as Reasonably Practicable
C4I	Command, Control, Communications, Computing and Intelligence
CA	Contract Acceptance
CAD	Computer Aided Design
CDR	Critical Design Review
CDRL	Contracted Documents Requirements List
CIP	Capability Integration Plan
CIWG	Capability Integration Working Group
CM	Capability Milestone
COTS	Commercial Off-The-Shelf
CTT	Combined Test Team
DOORS	Dynamic Object-Oriented
DID	Data Item Description
DLOD	Defence Lines of Development
DXL	DOORS™ Extension Language
E3	Electromagnetic Environmental Effects
EMC	Electro-Magnetic Compatibility
EQD	Existing Qualification Data EUT Equipment Under Test
FDR	Final Design Review
GSN	Goal Structuring Notation H2A Held to Account
HF	Human Factors Integration
IBM	International Business Machines™
IDAT	Inspection, Demonstration, Analysis, Test
ILS	Integrated Logistic Support
ISD	In-Service Date
ISO	International Standards Organisation
IOC	Initial Operating Capability
IEEE	Institute Of Electrical and Electronic Engineering
ITEA	Integrated Test, Evaluation and Acceptance
JET	Joint Evaluation Team

KiD	Knowledge in Defence
LFE	Lessons From Experience
LSA	Logistic Support Analysis
LSD	Logistic Support Date
MOD	Ministry of Defence
MOE	Measure of Effectiveness (against a UR)
MOP	Measure of Performance (against an SR)
PDR	Preliminary Design Review
RFTD	Ready for Training Date
RTS	Release to Service
SA	System Acceptance
SME	Subject Matter Experts
SQEP	Suitably Qualified and Experienced
SSDT	Support Solution Development Tool
SSE	Support Solutions Envelope
SR	System Requirement
SRD	System Requirements Document
SRO	Senior Responsible Owner
T&E	Test and Evaluation
TEPIDOIL	Training, Equipment, Personnel, Information, Doctrine and Concepts, Organisation, Infrastructure , Logistics (and Interoperability)
TOR	Terms of Reference TRR Trials Readiness Review
UR	User Requirement
URD	User Requirements Document
VCRI	Verification Cross-Reference Index
VCRM	Verification Cross-Reference Matrix
VVRM	Validation and Verification Requirements Matrix
UK	United Kingdom
WG	Working Group


Stansted
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M11

Durable Enhanced Asphalt Surfacing for the M25

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Abstract

There have been a number of developments in more durable surfacings in the UK in the last 10 years that can help drive a move to longer lasting surfacing materials. The paper describes the development of a new surface course specification for the M25 (London's orbital motorway) in collaboration with all parties in the M25 Design Build Finance and Operate Community and National Highways These materials are high bitumen content and low voids and use texture as a surrogate for skid resistance as required by National Highways.

The development of more durable surfacing materials by suppliers, and their initial performance on the English strategic road network is described. The materials have been assessed for skid resistance, noise, texture on the network and performance is compared with a control material.

Keywords

Durability; Sustainability; Collaboration

1. Background

There have been a number of developments in more durable surfacings in the UK in the last 10 years including: TS2010, which is now the material of choice on the Scottish trunk road and motorway network and has shown clear benefits in terms of durability and surety of performance; and W2020 in Wales which is a similar material to TS2010. The specifications for TS2010 (Transport Scotland, 2018) and W2020 (Welsh Government, 2020) use skid resistance as the performance criteria rather than the surrogate of texture which has been used historically on the English trunk road network.

TS2010 was developed using a similar approach to that used in Germany, where Stone Mastic Asphalt (SMA) has been the material of choice since 1984. Annual reporting of the Scottish Inspection Panel (SIP) in 2018 concluded " The data collected on older TS2010 sites suggests that the average service life of TS2010 could achieve double the service life of previous estimates for Scottish Clause 942 mixtures" (McHale and Martin, 2019).

The expected life of this type of material in Scotland and Germany, where there is a much longer experience, is 16-20 years. Scottish experience with TS2010 has shown that good early life performance and visual condition can be a reliable indicator for long term performance. Waiting for 16 years+ is not necessary.

Cl.942 Thin Surface Course Systems (TSCS) materials on the M25 Design, Build, Finance and Operate (DBFO) network are typically lasting 9-12 years. The programme to move to more durable surfacings has the potential to save future interventions during the remainder of the M25 DBFO concession period. Fewer interventions will have a significant impact on the DBFO's carbon reduction targets as they aim to reduce greenhouse gas emissions in line with National Highways net zero plan. The performance of these products could also assist National Highways in developing a specification for the use of more durable surfacing materials more widely.

At the outset of the programme to introduce more durable surfacings, a draft National Highways (NH) Cl.941 specification was in circulation[1] and being discussed with the Mineral Products Association (MPA). This was developed and enhanced by the project team to produce a specification that was more suited to the high stress conditions on the M25. The resulting AR Clause was titled "Durable Enhanced Asphalt (DEA) Surfacing System for M25". The specification maintains the requirement for surface texture.

1 The NH draft Specification has since been withdrawn and is expected to be replaced with a specification more suited to high stress locations.

2. M25 Innovations Group

Connect Plus and Connect Plus Services, responsible for the management of the M25 DBFO, have innovations teams for Pavements and Structures which meet regularly to discuss new ideas, materials, and approaches to provide operational efficiencies in the maintenance and running of the M25 DBFO network. The Pavements innovations team consists of members from AtkinsRéalis, Connect Plus services, Milestone Infrastructure, Skanska, and Tarmac. This approach has led to good collaboration and knowledge sharing across the group and the supply chain.

The development of the AR DEA Specification also included consultation and collaboration with National Highways (NH), F M Conway and Toppesfield as well as the Innovations Group.

2.1. Aims and Objectives

Use of this specification should provide benefits in both serviceability / durability and whole life costs. This DEA material has higher binder content and lower initial texture requirements than conventionally used Cl.942 materials. The minimum level of texture is still maintained and consistent with the requirements of Cl.942. DEA provides the added potential benefit of low rolling resistance and, with the low air voids content of the mixture, it can also be used for surfacing bridge decks.

The initial costs will be higher due to the premium nature and higher volume of binder required, but the benefits are realised with fewer interventions and the resulting positive impact this will have on the DBFOs carbon reduction strategy.

More durable = More sustainable.

Enhancements made to the draft National Highways 941 *draft* Specification included a higher minimum binder content, lower air voids content and an optional gritting clause during the laying operation. The specification also included a staged approach to materials approvals with approval of a laboratory design and Plant Mix Trial (PMT) to demonstrate material compliance before proceeding to the Network.

The main objectives are to provide more durable surfacing materials that would lead to clear benefits in terms of:

- increased service life;
- network reliability/availability;
- reduced future interventions and worker exposure;
- reduced use of resources;
- reduced whole life carbon and whole life costs;
- lower rolling resistance (leading to lower emissions and carbon savings);
- more resilient to climate change; and
- slower rate of deterioration allowing more time to plan maintenance interventions

The lower air voids content of this material should also lead to reduced Cat 1 / Ca 2 defects as the material will be less prone to ravelling and sudden failure towards the end of life.

2.2. Materials Development

The team worked closely with the two framework suppliers, Tarmac and F M Conway, on the specification development and for the trial it was agreed that both would develop a 10mm DEA material using Polymer Modified Bitumen (PMB) and that these should be trialled in a single Network trial with both gritted and un-gritted options included.

An optional gritting clause was added to the DEA Specification together with some alternative tests to gain additional knowledge from the programme. Torque Bond and Wheel Tracking using the small device were the mandatory specification requirements with Leutner Shear and Large Wheel tracker also added to gain further information.

The key parts of the specification for a 10mm material are higlighted in Table 1:

TABLE 1

Specification for a 10mm material

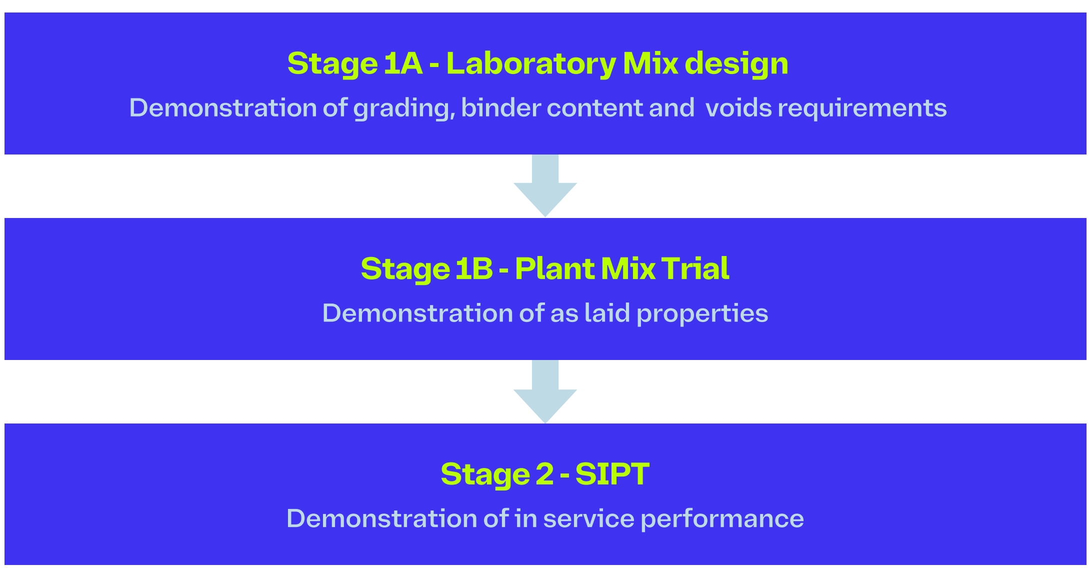
Minimum binder content	6.2% Mixture types: BS EN13108, Parts 1 and 2 (AC & BBTM with PMB to BS EN 14023)	6.4% Mixture types: BS EN 13108 Part 5 (SMA – paving grade bitumen to BS EN 12591 or PMB to BSEN 14023)
Voids	3-4% at laboratory (stage 1A) 2-5% at PMT (stage 1B) and Network (stage 2).	
Texture (initial and retained)	0.8mm - 1.3mm	
Note: PMB required for heavily trafficked roads (BS EN 14023 Pen Class 7; SP Class 3)		

The key concern from both suppliers was meeting the voids requirement and it was reported that the results indicated by the gyratory compaction in the laboratory stage did not necessarily match the reality when testing compacted material from site.

The PMT was therefore considered a useful stage for all parties to demonstrate performance and compliance with the specification and reduce risk when moving on to the Network Stage 2 System Installation Performance Trial (SIPT). The aggregate assessed at Stage 1A and 1B (see Figure 1) needs to be retained for Network use. A change in aggregate type requires a new mix design.

FIGURE 1

Material approval process



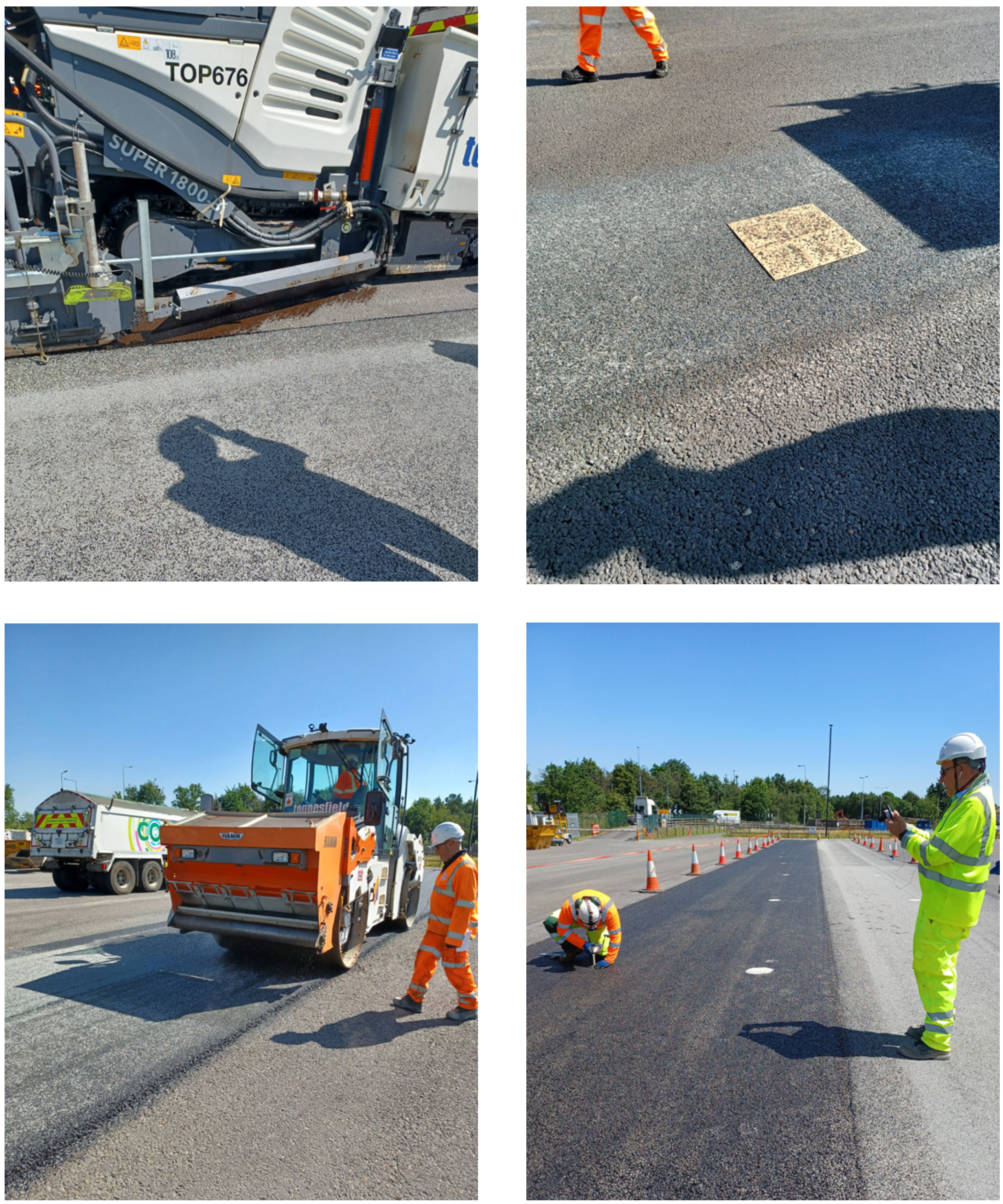
2.3. Plant Mix Trials

The network trial was to include both gritted and ungritted sections from both suppliers with a Cl.942 control section included for comparison. The PMT also included a gritted section so that experience of the process could be gained. There is always the pressure to minimise the extraction of cores from the network for newly laid material so the PMT has the advantage of ease of access and that numerous cores can be extracted for assessment. This avoids the Network trial looking like a Swiss cheese.

The F M Conway PMT was laid at the Milestone Office compound at J25 on the M25 on 16 July 2021. Figure 2 shows the FM Conway PMT.

FIGURE 2

F M Conway PMT showing Integrated paver, calibration of grit spread rate, compaction with gritting and completed surfacing assessed for texture



This consisted of two rips each 3.8m wide by 56m long with one gritted at 0.75kg/m^2 and one ungritted. The joint was cut back and sealed prior to laying the second rip and this allowed for extraction of samples to assess the integrity (i.e. voids) at the joint. The material was laid onto an existing surface utilising a Colbond 50 bondcoat applied at 0.65 L/m^2.

Tarmac undertook a number of PMTs, the first two were on the access road at their Snodland Plant, and the third at their Harper Lane plant. The material was laid onto a planed surface utilising a Colbond 50 bondcoat applied at 0.7 L/m^2.

The first Tarmac PMT on the access road to their Snodland plant in Kent took place on 3rd August 2021. Two rips approx. 3.5 to 3.6m wide by 93m long with one gritted at 0.5kg/m^2. The spread rate was reduced following the experience at the F M Conway PMT with 'lessons learned' being shared with all parties as part of our collaborative approach. Views from this PMT are shown in Figure 3.

FIGURE 3

First Tarmac PMT undertaken at Snodland and the lower spread rate selected for the application of grit is clearly noticeable when compared with the F M Conway PMT.

Some issues occurred during the first two PMT's that led to excessive variation in the voids in the mix. A step back approach was taken by Tarmac and some changes to the mix design were made prior to a further PMT at Harper Lane which was constructed on 22nd November 2021.

A visit to the site was made the day after construction during the coring operation for retrieval of test samples. Figure 4 shows the Harper Lane PMT during the coring. It was noticeable how quickly the DEA surfacing dried out indicating that any voids present were not interconnecting.

FIGURE 4

Tarmac's Harper Lane PMT

The main purpose of the PMT is to demonstrate compliance with the specification of plant mixed materials prior to laying in the field. This process allows for extensive material sampling prior to the main works and significantly reduces the risk of problems occurring in the field. This has been demonstrated by changes to mix designs made during the process undertaken here to get the mix design right before proceeding to the Network. A summary of results for stage 1B plant mix trials from F M Conway and Tarmac are shown in Table 2.

TABLE 2

Summary of Stage 1B results from PMTs

Property	Test Method	DEA Spec. limits	F M Conway (65 psv Conexpo)	Tarmac (65 psv Bremangar)
Air Voids	BS EN 12697-8	2-5%	5.0%	3.5%
Grading and binder content*		6.4% min	Within limits	Within limits
Macrotexture	BS EN 13036-1	0.8mm – 1.3mm	1.0mm	1.0mm
Torque bond		≥400kPa	1167kPa	700kPa
Wheeltracking (small device) @ 60oC	BS EN 12697-22 Procedure B	Class 2	0.04mm/10^3 load cycles	0.09mm/10^3 load cycles
Leutner Shear, Peak shear stress	SHW Cl 954	NR	0.99MPa	0.8MPa
Wheeltracking (large device) @ 60oC	BS EN 12697-22	NR (Pmax = 5.0% preferred)	2.95%	4.4%

Note: Results shown in italics are for information only; NR = No requirement

* Both materials are SMA to BS EN 13108-5. Target gradings selected by the suppliers (within the limits of BS EN 13108-5). Binder content by Ignition to BS EN 12697-39.

3. Network Trial Site

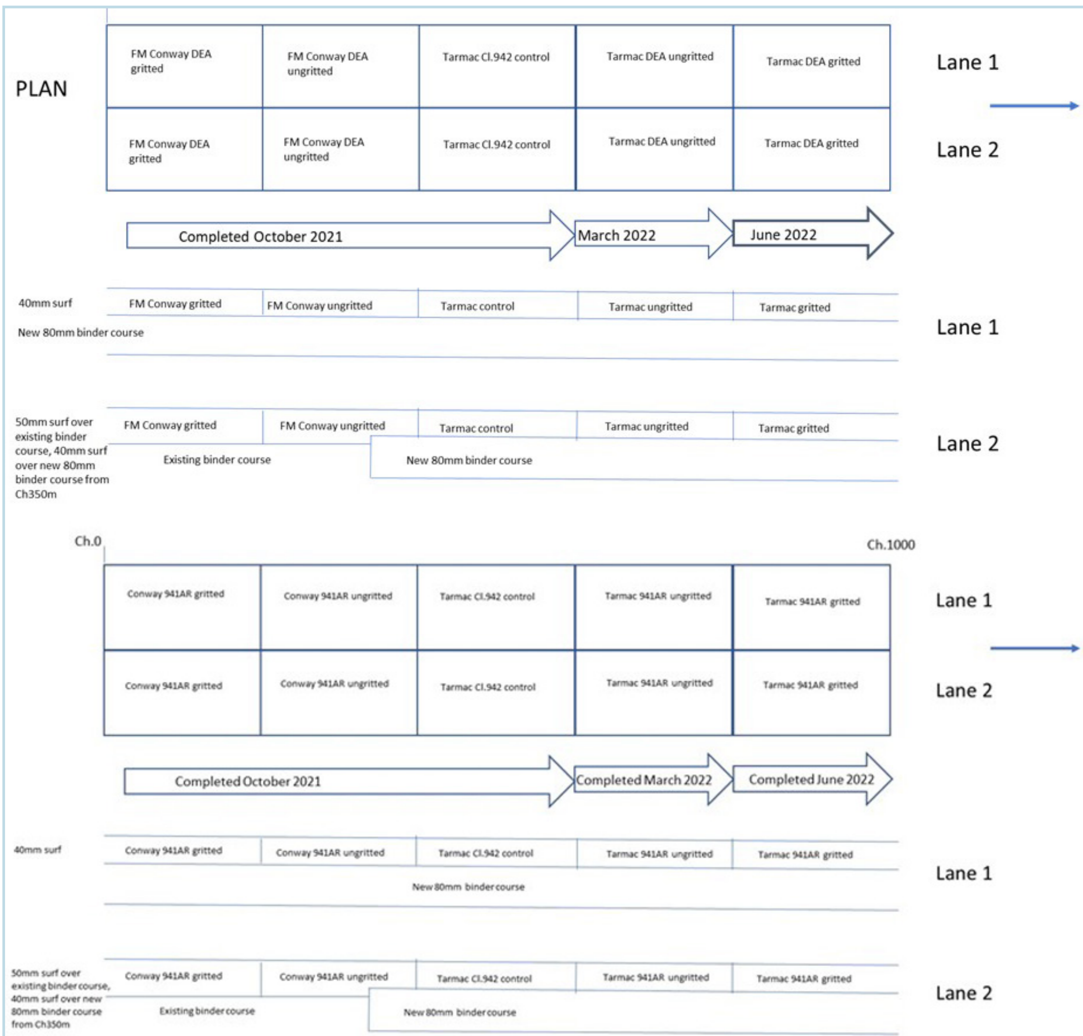
Selection of a trial site location always presents problems with the priority to try and fit the trial into a pre-existing scheme. The site selected was in Lanes 1 and 2 on M25 clockwise carriageway between J27 and J28. The site trial was carried out under a Departure from Standard (Departure ID: 102812).

Visual inspection and coring of the existing pavement showed that there was significant rutting in both lanes (and the latest TRACS data showing increases in deformation since the previous year bringing some locations into Cat 3). Materials testing indicated that the binder course was susceptible to deformation.

It was, therefore, decided to replace all of the binder course in Lane 1 and the majority of the binder course in lane 2. A schematic of the as built trial is shown in Figure 5.

FIGURE 5

Schematic of as built trial



3.1. Assessment of Network Trial Site

The network trials are being assessed for basic materials properties (texture, density, voids, Wheel Track Rate (WTR) etc.) and in service performance for skid resistance (GripTester, Pavement Friction Tester (PFT), Sideway-force Routine Investigation Machine (SCRIM), noise (CPX method), and visually using the Inspection Panel marking system given in TRL Report 670 (McHale et al, 2011).

The aim, subject to specification compliance, is to give Interim approval of the DEA materials after 6 months service and full approval after 2 years satisfactory performance.

The installed texture measured using volumetric patch method (BS EN 13036-1, BSI 2010a) for all DEA materials were within the specification requirement of 0.8-1.3mm.

3.2. Interim Approval of FM Conway Material

In situ air voids (BS EN 12697-8, BSI 2019) from the as laid DEA material were measured giving an average of 4.7% (specification range 2-5%). WTR (BS EN 12697-2, BSI 2015) was measured as 0.04 mm/1000 load cycles. These results showed compliant levels of voids, good deformation resistance and good comparison with data from the PMT.

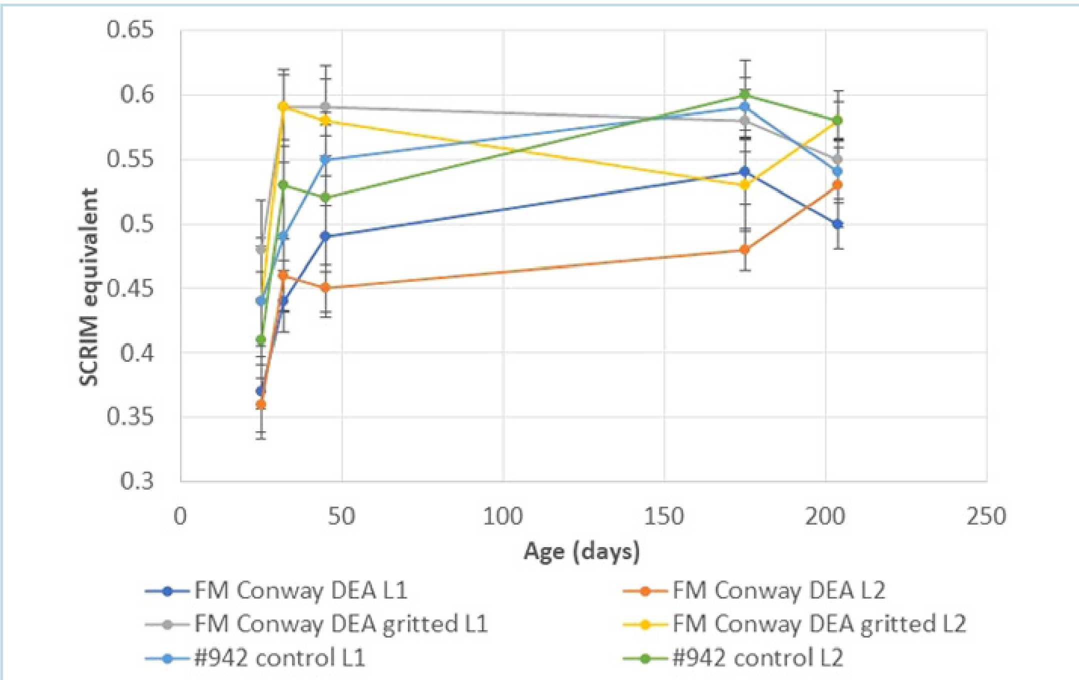
3.3. Skid Resistance

GripTester measurements for skid resistance were made at various intervals after construction to determine any changes over time and differences between gritted and un-gritted variants. DEA materials have a high binder content with a 75/130-75 polymer modified bitumen (BS EN 14023, BSI 2010b) and the binder film will take time to be removed under trafficking exposing the natural microtexture of the aggregate surface.

GripTester runs were undertaken on 1st, 8th and 22nd November 2021, and 1st and 29th April 2022. The mean results adjusted to Sideway force Coefficient Routine Investigation Machine (SCRIM) equivalent values, using a conversion factor of 0.89 x GT number are shown in Figure 6. The SCRIM investigatory level for this (non-event) site is 0.35.

FIGURE 6

GripTester measurements over first 6 months for FM Conway DEA and Control 942 materials (shown as SCRIM equivalent)



The initial GripTester measurements for the non-gritted DEA were just above the intervention level of 0.35 on the 1st November 2021 survey, circa 2-3 weeks after installation. An increase in skid resistance was noted in subsequent GripTester surveys on the non-gritted DEA section in keeping with the gradual removal of the binder film from the aggregate surface.

The results show the benefit of gritting with higher initial values, and higher levels of skid resistance in the medium term. The grit is applied with the first roller pass which leads to a level of grit being retained in the surface over the longer term. However, all results, including un-gritted, were above the SCRIM investigatory level of 0.35 for all materials indicating that for non-event sites the ungritted DEA option is acceptable. The gritted option would have merit in safety critical locations; that is, with higher SCRIM investigatory levels specified.

3.4. High Speed Friction

For this study, high speed friction measurements were made with the Pavement Friction Tester (PFT) using a smooth ASTM tyre in wet conditions at 90 km/h, presented as P-Fn90 and L-Fn90, representing peak and locked-wheel friction respectively. High speed friction measurements do not have a standard with which they can be compared. To add context to the results, high speed friction results are presented with reference to the typical performance ranges expected for the material being tested, usually obtained from historical measurements.

During testing, the tyre contact patch slides over the surface at the same speed as the towing vehicle (i.e. test speed is the same as slip speed). During testing, the load and drag forces on the tyre are measured every 0.01 seconds throughout the braking cycle and from this the peak[2] and locked-wheel friction[3] are determined.

PFT measurements were undertaken by TRL Ltd in March 2022 and demonstrated that both locked and peak friction to be within the normal range expected for the FM Conway DEA and Cl#942 control materials. The results for locked wheel friction are shown in Figure 7 and peak friction results in Figure 8.

2 Peak friction is the maximum friction value reached as the test wheel begins to slip.

3 Locked-wheel fiction is the friction generated between the surface and test tyre when the wheel is locked.

FIGURE 7

PFT locked wheel friction (March 2022) - from TRL Client Project Report (unpublished)

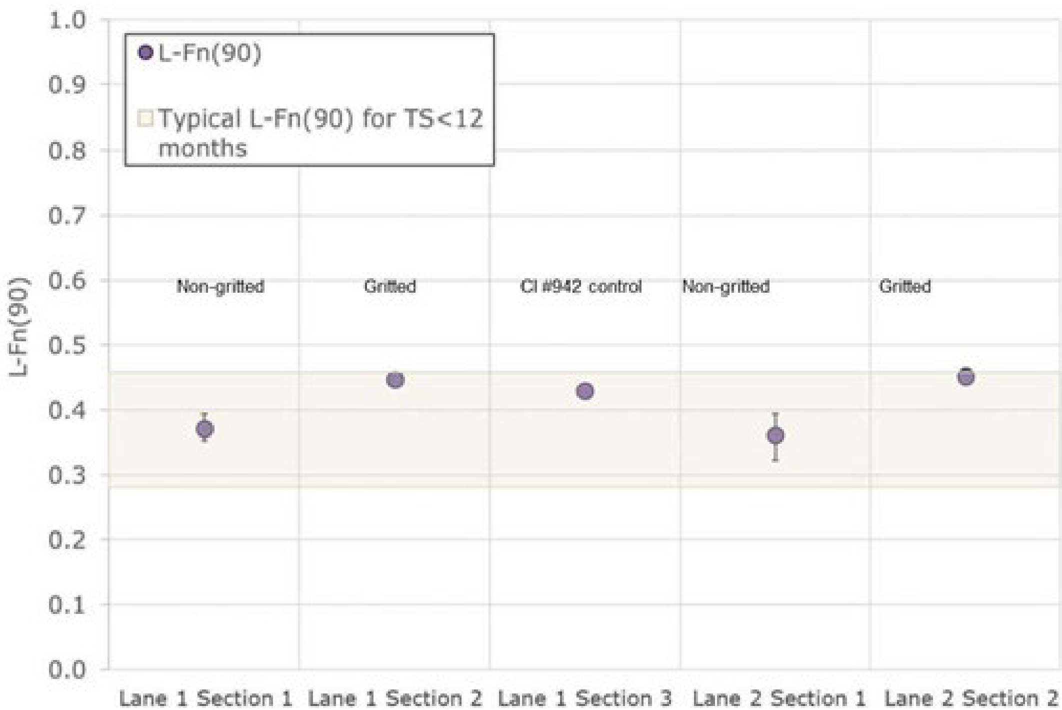
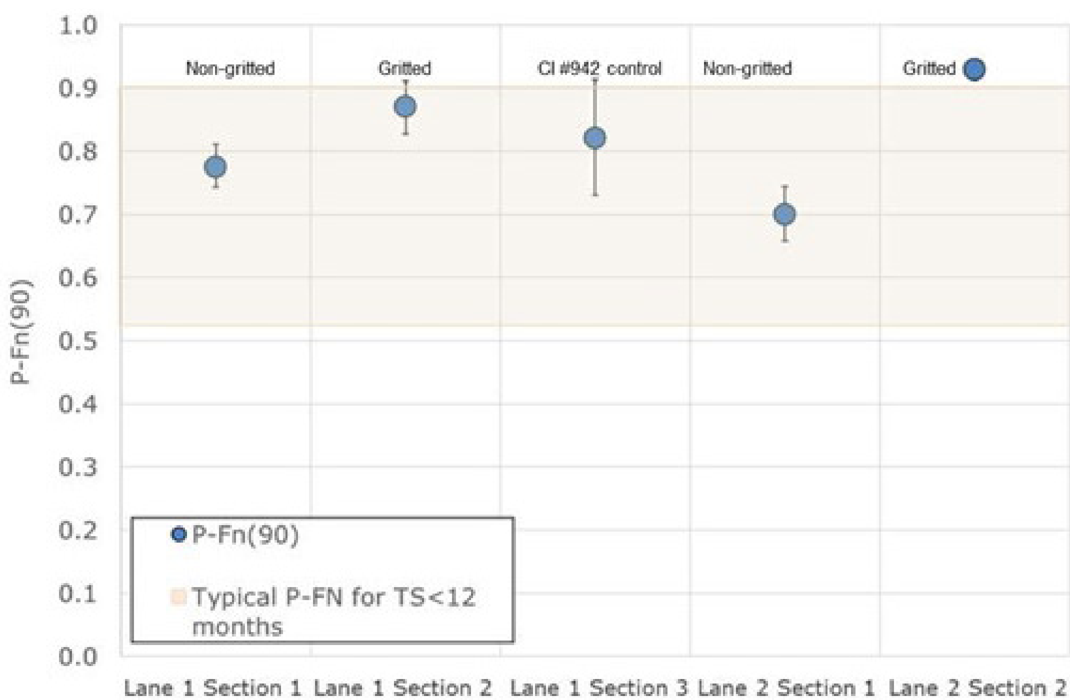


FIGURE 8

PFT Peak friction (March 2022) – from TRL Client Project Report (unpublished)



4. Road/Tyre Noise

Road-tyre noise is an important consideration when investigating a new material to make sure that unaccetpable levels of noise are not generated.

Noise measurements were made along the site, on 3rd February 2022 using the Close Proximity (CPX) method, to assess how the noise levels compare with Cl.#942 materials and/or if gritting has any impact on the noise levels.

The CPX method is designed to assess the acoustic properties of road surfaces by measuring the rolling noise of a standard reference tyre at two microphone positions located close to the tyre/road contact patch. Measurements are performed at a range of specified reference speeds; on high speed roads the reference speed is commonly 80 km/h.

The sound level close to the tyre is measured with two microphones over the length of a road section. The CPX measurement is performed in both wheel tracks simultaneously.

These results, shown in Table 3, indicate that there are no noise issues with the DEA material, either gritted or ungritted, compared with Cl.#942. The noise levels between the various DEA materials were comparable. In addition, all of the noise levels measured were lower on the newer materials compared with the existing Cl. #942 (section 4). Section 4 has since been replaced with Tarmac's ungritted DEA material laid on 28th and 29th March 2022.

TABLE 3

CPXP - levels (Feb 2022)

Section	**CPXP-level [db(A)]**	
	L1	L2
1. DEA ungritted	97.9 (0.4)	97.9 (0.6)
2. DEA gritted	97.8 (0.2)	98.2 (0.5)
3. Cl.#942 - new	98.2 (0.8)	96.7 (0.5)
4. Cl. 942 (existing)	99.9 (0.2)	99.5 (0.5)

Note: Section lengths nominally 200m. Figures in brackets denote the standard deviation.

5. Visual Assessment using an Inspection Panel System

The Network site was assessed visually, using the panel method described in TRL Report 670 (McHale et al, 2011) and referred to in the DEA for use on the M25 Specification) on 22nd April 2022 by a panel of 4 pavement engineers.

The appearance of the 'as laid' materials was very consistent across the mat. All sections (which included Tarmac's ungritted DEA material laid on 28th and 29th March 2022) in both lanes L1 and L2 were assessed as being Excellent (E).

6. Conclusions and Recommendations

The development of a new surface course specification has the potential to provide durability and sustainability benefits compared with Cl.#942 material and save an intervention during the M25 DBFO concession period. The appearance of the as laid materials were very uniform. Measurements for as laid texture, air voids and in service skid resistance were compliant with the specification. No changes in texture have been measured over the first nine months service.

Longer term, the new specification could potentially deliver durability improvements across the NH strategic road network.

- The data assessed for FM Conway's DEA 0/10mm materials (gritted and ungritted) incorporating Conexpo coarse aggregate have demonstrated compliance with the Specification over the first 6 months of monitoring including good in-service skid resistance.

Further use of the FM Conway DEA materials is recommended subject to approval of the required Departures from Standard.

Gritting could be beneficial in safety critical areas with higher levels of skid resistance are required.

There are no noise issues associated with the use of DEA compared with Cl.#942 materials.

Throughout the specification development, lab mix design and plant mix trials, there was good collaboration and knowledge sharing. Lessons learned were quickly shared across the M25 Consortia and supply chain.

The use of PMT in materials development has benefits in providing confidence before proceeding to network trials and reduces the risk of failures on the network.

7. Next Steps

- Further use of FM Conway's DEA materials on the M25 DBFO in the 2022/23 programme.
- Continued monitoring of the trials with further GripTester and PFT surveys and the addition of routine SCRIM survey data to assess skid resistance.
- Regular ad hoc assessments of visual condition. Demonstration of trend line is likely to be the first indicator of improvement compared with historic trends for Cl.942 materials.
- Interim approval of Tarmac's DEA after demonstration of performance compliance after 6 months service.
- Confirmation of longer term texture compliance.
- General use after demonstration of 2 year SIPT properties (with DfS).
- Development of WMA variants.

Acknowledgements

Originally published as a technical paper on the Institute of Asphalt Technology web site.

The development of the specification; materials development and network installation required significant collaboration across many organisations. The authors are grateful to the following for their contribution and support:

Mark Flint (F M Conway); Frank Haughey (Tarmac); Arash Khojinian and Matt Wayman (SES - National Highways); Nick Mills and Sivarajasingam Shanthakumar (Milestone Infrastructure); Paul Phillips and Kevin Collins (Toppesfield); Andy Simms (Skanska); Elsie Twumasi-Mensah (Connect Plus); and. Michael Wright (AtkinsRéalis).

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Pressure monitoring and transient modelling: A diagnostic overview of failing operating state

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Abstract

Water companies can incur significant repair and Public Relation costs due to frequent bursts of sewage rising mains. Considering both the environmental and economic impacts of bursts, minimising their occurrence is becoming ever more important to asset operators. To better understand the patterns associated with bursts, high frequency pressure sensors were installed on several sewage rising mains which based on their burst history were known to be at a higher risk of failure. To complement the measured data, a transient hydraulic model was built and calibrated for each pumping system. The investigated systems varied in pipe size, material, profile, pump type and capacity. This paper presents the methodology followed to interpret the data obtained from site measurements and to validate the hydraulic models. Moreover, it provides a diagnostic overview of a wide range of failure mechanisms such as air valve with reduced capacity, Non-Return Valve leakage and slam. The outcome is predictive capabilities for asset owners to address underperformance prior to failure and to develop proactive planning for investment, replacement, and rehabilitation strategies.

Keywords

Pressure monitoring; Transient modelling; Pump operation; Pipeline analysis

1. Introduction

Many of the UK's sewage pipes today were installed in the second part of the 20th century. The condition of aged rising mains is deteriorating rapidly due to corrosion and mechanical stresses which has resulted in an increasing number of pipe bursts. In line with Environment Agency and Ofwat expectations of more action, there is a mounting pressure on water companies to achieve zero pollution events. Although proactive maintenance has helped water companies reduce pollution caused by pipe bursts, further improvement is urgently needed to minimise costly clean-up operations, financial penalties, prosecutions, and long-term reputational damage.

In order to minimise pollution, it is vital to isolate and repair damaged pipe sections as quickly as possible. Most bursts are easily detected due to water pooling at ground level and are often reported by a member of the public. However, for mains in remote locations including beneath rivers, railways, and roads, it might take hours or even days before the asset owners are alerted of a burst which therefore has the potential to cause a catastrophic ecological impact. Hence, there is a need to monitor the system continuously for fast detection of bursts and more importantly their underlying causes.

From the literature review, it can be concluded that there are a large number of techniques that deal with faults and leak detection in pipelines (Ferrante & Brunone (1), Covas et al. (2), Wang et al. (3), Lee et al. (4), Shamloo & Haghighi (5), and Taghvaei et al. (6)). Considering sewage pumping stations are not well instrumented, a simple technique deploying a single pressure measurement was deemed most suitable. This paper investigates the capability of single point pressure monitoring to identify a wide range of failure mechanisms such as air valve with reduced capacity, Non-Return Valve (NRV) leakage and slam. High frequency sensors were placed on poorly performing assets which were known to be at higher risk of failure. The intention behind monitoring these assets was to generate reference data which would allow for the understanding of patterns associated with poor performance and bursts.

The main objective of the paper is to provide a diagnostic overview of the most common failure mechanisms occurring in sewage rising mains. This will allow asset owners to deploy strategies aimed at extending the life of the rising main and to minimise the number of bursts and hence pollution.

2. Methodology

Numerous Anglian Water rising mains have been equipped with high resolution pressure sensors, developed by Syrinix (7), often installed downstream of NRVs in the pumping stations. The sensors collect 128 samples per second and provide one-minute summary data intervals i.e., average, minimum and maximum values. The summary data is transmitted every six hours to a cloud-based platform. The sensor and transmitter are powered by a dedicated battery. The high frequency data are only transmitted when a pressure sensitivity threshold, known as Syrinix Severity Score S3 is exceeded. The S3 score is calculated within Syrinix devices and is used to score the level of transient activity in the 128 Sample/s data stream. This score is calculated multiple times per minute on a two-minute sliding window where large deviations from the mean result in a high score and small deviations result in a low score. The score broadly reflects the energy in the waveform and is used in the devices to identify transient events for immediate transmission. The highest S3 score in each minute is summarised in the 1-minute summary data stream. The high frequency data can also be transmitted to the cloud platform upon user request. This approach is intended to maximise the battery life.

A thorough site survey was carried out to identify key parameters such as pump start/stop levels, sensor elevation, pump hydraulic characteristic, NRV type/size, and rising main profile, diameter, material and pressure rating. Moreover, in the absence of flowmeters, drop tests were performed to measure the pumping capacity which combined with the pressure monitoring defines the actual operating duty point of the pumps.

Using the survey data, hydraulic models of the pipeline systems were created in water hammer software Wanda 4.6 (developed by Deltares) and relevant transient scenarios were simulated. The pressure time series from the simulations were compared to the recorded data and if required the model was calibrated by adjusting parameters such as pipe wall roughness, local losses and wave speed to obtain a close match. Conclusions were made regarding the system performance and recommendations were provided to optimise the system operation. The below sections describe the steps which were taken to assess system hydraulic performance.

3. Pressure Monitoring

3.1 Analysing Recorded Pressure

The following information can be extracted from the one-minute summary data:

- Average value (Figure 1): Pumping pressure
- Average value: Static head (pressure during off-cycle)
- Minimum and maximum transient pressures (Figure 2)

The summary data allows the user to obtain key information regarding the system performance. High frequency data can be used to further investigate the dynamic behaviour of the system especially during critical transient events such as start-up and shutdown (Figure 3). Among the studied rising mains, which based on their burst history were known to be at a higher risk of failure, several patterns have been identified.

FIGURE 1

Average pressure - MIHOSM PS

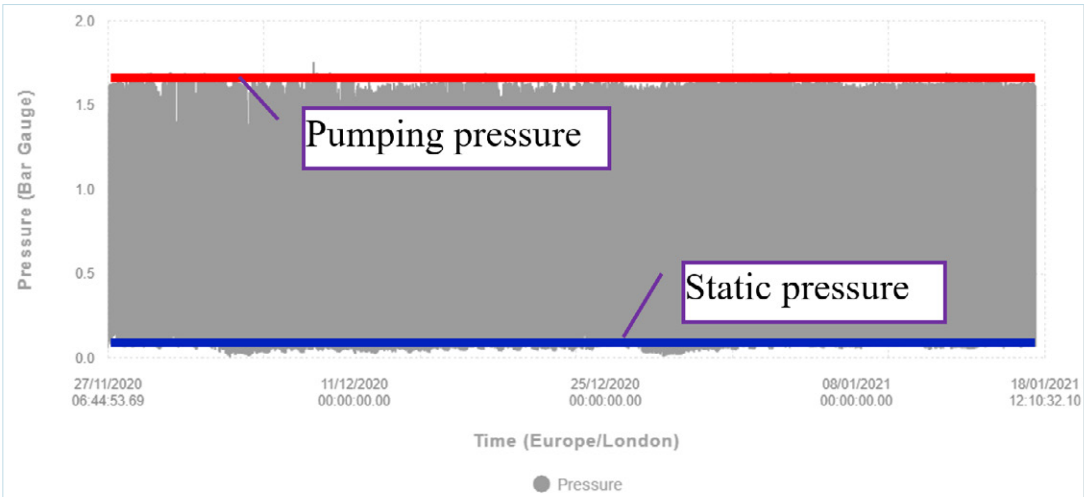


FIGURE 2

Minimum and maximum pressure - MIHOSM PS

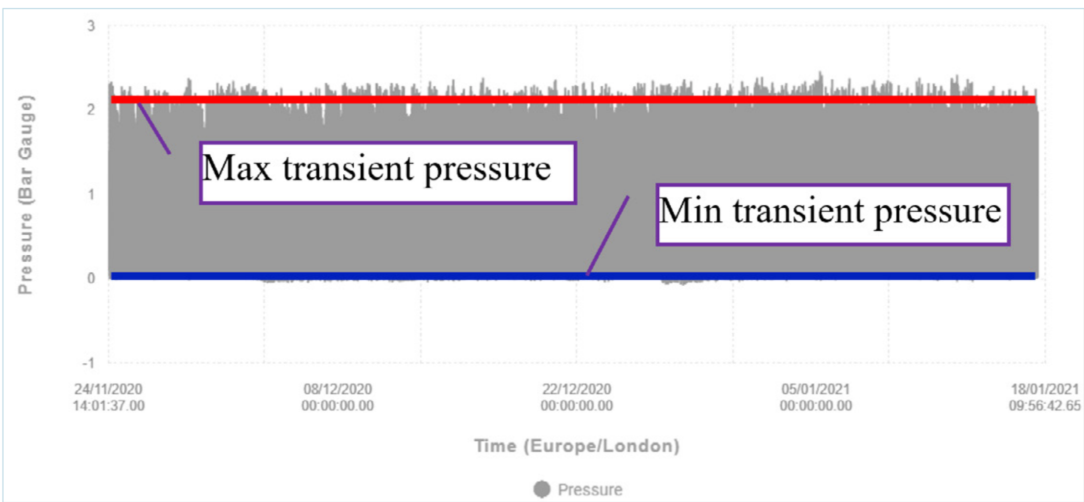
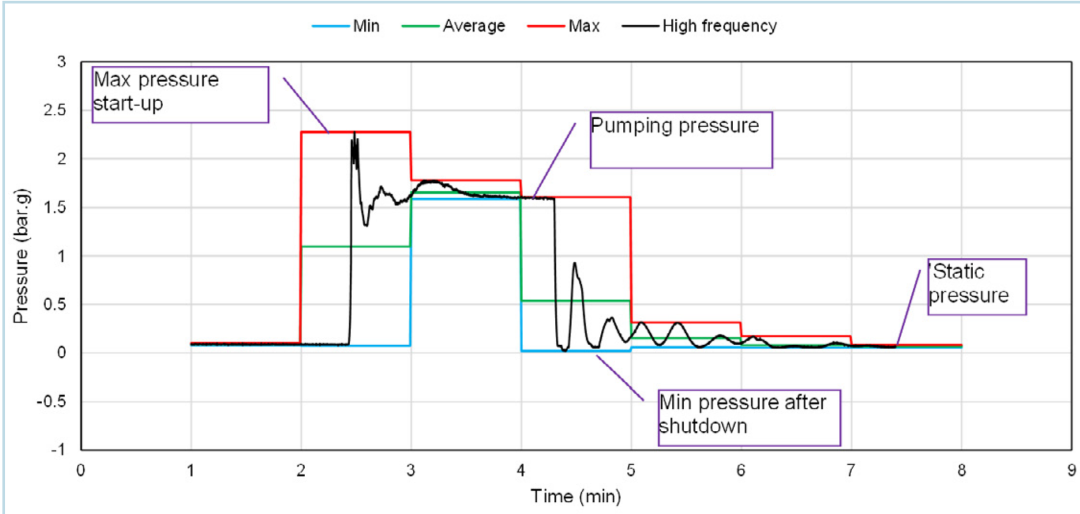


FIGURE 3

Recorded data 02/01/2021 00:30:54 - MIHOSM PS



3.1.1 Uncontrolled Start Up and Shutdown

None of the pumps in the investigated pumping stations were equipped with a Variable Frequency Drive (VFD) or Soft-starter. The pumps were Direct On Line (DOL) and reached their rated speed after a short period of time when switched on. This resulted in a significant pressure spike (Figure 4). Similarly, shutdown was triggered by cutting the power to the motor and hence results in a sudden drop in the pump speed and consequently pressure. For pumping stations with slow acting NRVs (old swing type with no lever), the combination of rapid flow deceleration and large reverse flow led to considerable NRV slamming (Figure 5).

FIGURE 4

High frequency HBWGSP PS – before (23/02/2021 00:05:35) and after VFD installation (06/11/2021 00:05:04)

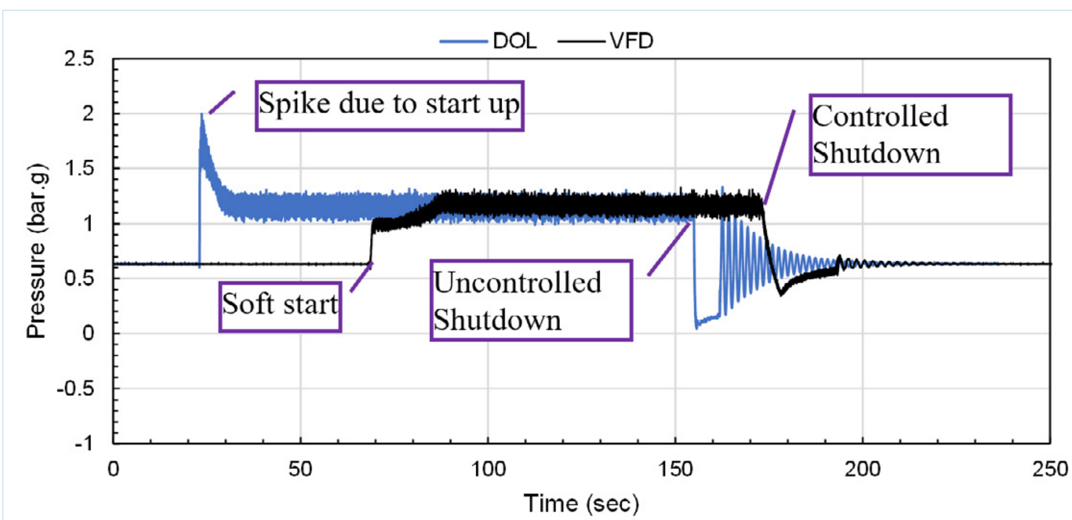
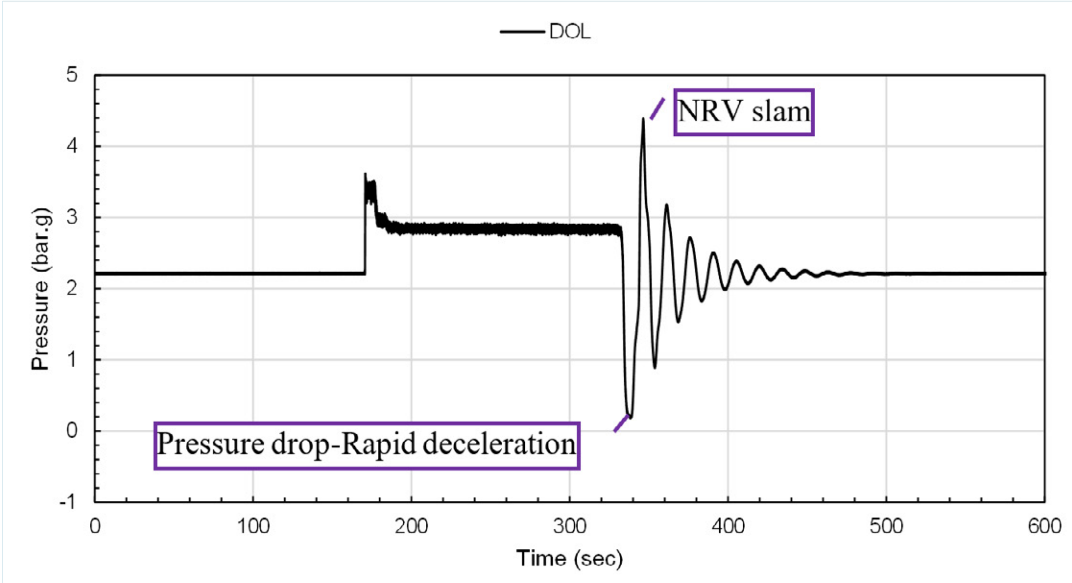


FIGURE 5

High frequency NLOWSP PS - 12/07/2021 13:44:57



3.1.2 NRV Leakage

Another commonly observed problem was NRV leakage. In each off cycle, part of the rising main drained back into the sump which resulted in a premature start of the duty pump. This can be seen in Figure 6 where there is continuous decrease in pressure after pump shutdown until the duty pump starts (two pumps with alternating configuration). The continuous operation of the pumps, even during dry periods, will reduce the lifetime of the asset. After the replacement of the leaking NRVs, the number of pump operating cycles was reduced by half (Figure 7).

FIGURE 6

Average pressure - SWANSP PS with alternating duty pumps

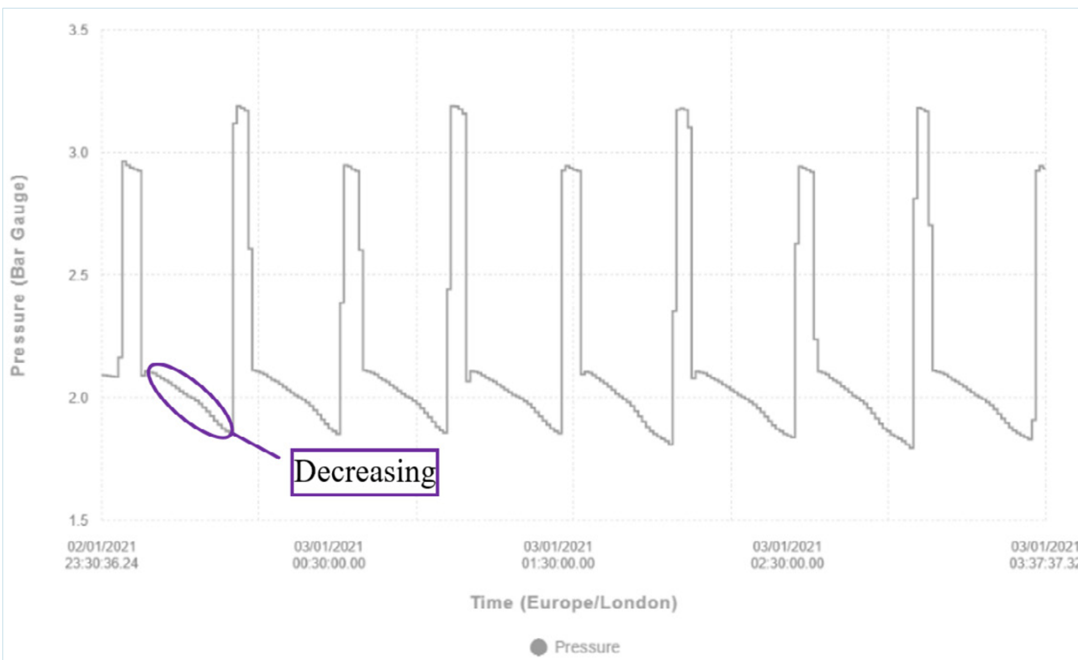
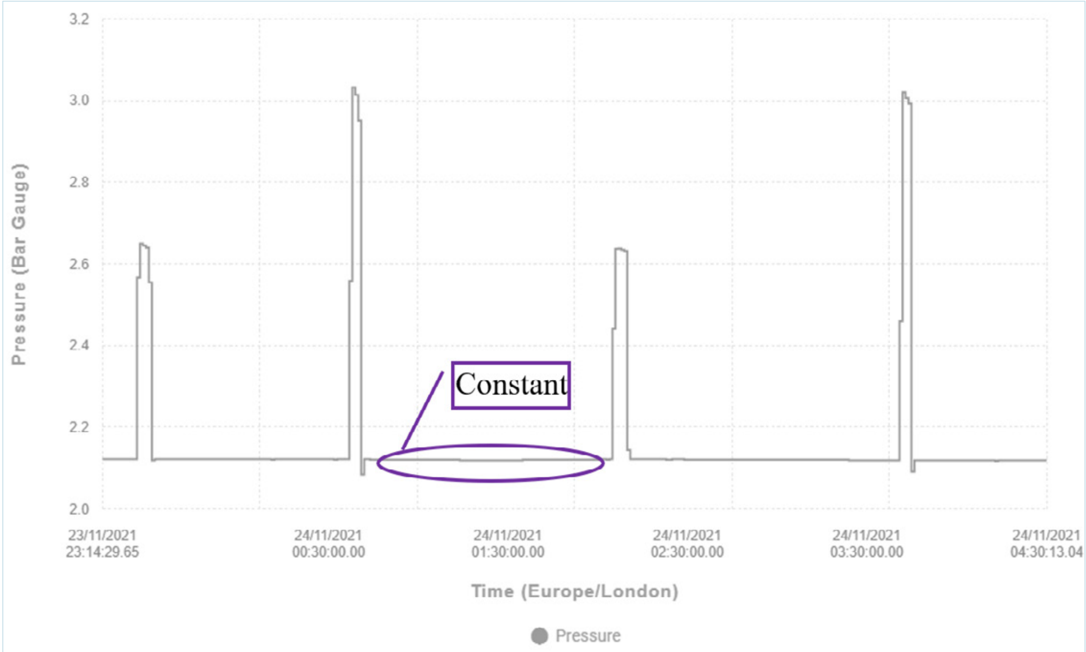


FIGURE 7

Average pressure - SWANSP PS after NRV replacement



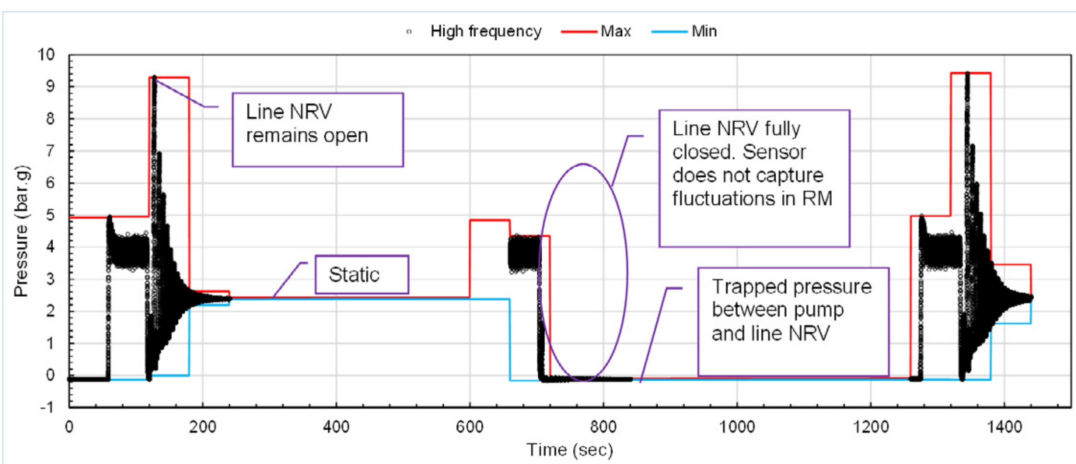
3.1.3 Line NRV, Sensor Location, and Missing Data

Some of the studied rising mains were equipped with a line NRV installed outside of the pumping station in a valve chamber. This was in addition to the individual pump NRV and provided a double protection against draining the rising main back into the sump. Closure of the latter after pump shutdown blocked the ensuing pressure transient from reaching the sensor.

This is illustrated in Figure 8 where no pressure fluctuations have been captured by the sensor during the second shutdown event (time = 710sec). The missing data might result in misleading conclusions with respect to the transient behaviour of the system. The maximum transient pressure is over 9barg due to NRV slam as captured in the first and last event. This is approximately twice the figure recorded in the second event.

FIGURE 8

High frequency LHARSP PS – Time zero is 25/11/2021 00:10:01



3.1.4 Air Valves with Reduced Capacity

For undulating pipelines with intermediate peaks higher than the discharge point, air valves are required at peak points to release air during start-up (re-priming) or admit air into the pipeline after shutdown (draining period). Many of these air valves are installed in remote locations and hence difficult to maintain regularly. Reduced air release capacity of the air valves can lead to a longer priming time (Figure 9).

As demonstrated by Alidai et al. (7), during the priming there might be pipeline sections in which the self-cleansing velocity is not reached. Therefore, if the pumping does not continue long enough after the pipeline is fully primed (for example because of limited sump capacity), there is a risk that sediment accumulates at the foot of steep slopes and causes blockage in the long run. Moreover, the drained sections of an undulating pipeline might suffer from excessive corrosion. The exposure of the internal lining to air and possibly corrosive gases existing in the pipeline increases the risk of failure. A visual inspection of a failed pipe at an intermediate peak point has shown internal corrosion of the pipe wall (Figure 10). The corroded area has a reduced thickness which is more susceptible to transient pressures.

FIGURE 9

High frequency - HIFPSM PS with defunct air valve

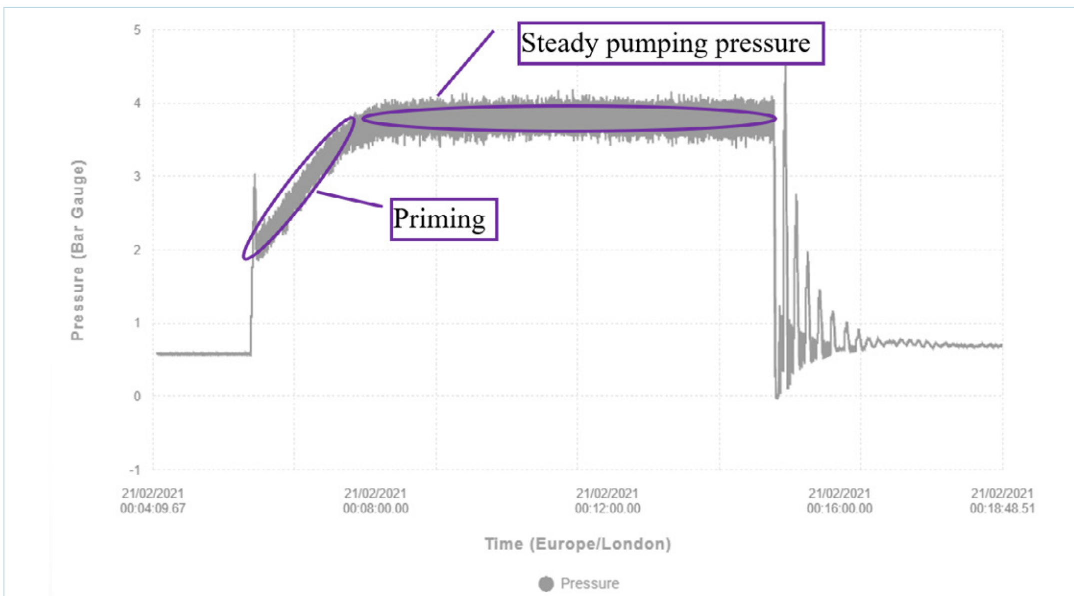


FIGURE 10

Failed pipe section at intermediate peak point BDBASM

3.2 Pump Steady State Operation Analysis

Pump performance and efficiency deteriorate over time (9) with an estimated 1% increase in energy use per year in potable water systems (10). Therefore, it is vital to monitor the pump performance and take corrective measures to ensure efficient operation.

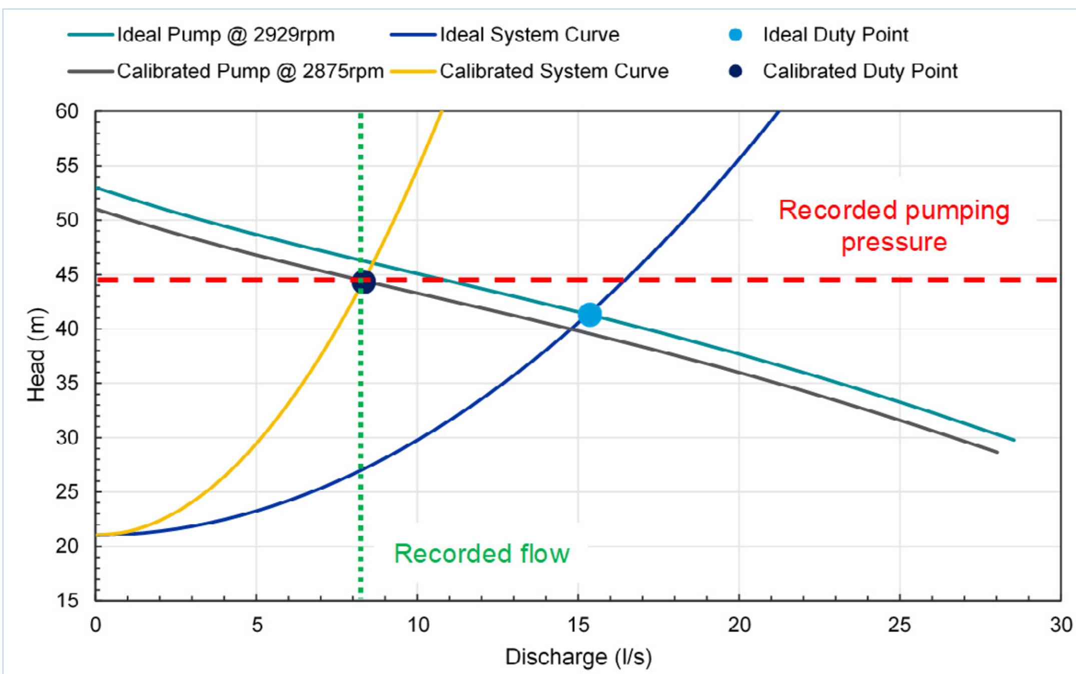
The below example shows how the pressure and flow measurement can be used to assess the hydraulic performance of the pipeline system (Figure 11). The ideal pump curve at the rated speed provided by the manufacturer crosses the ideal system curve with an assumed pipeline roughness of 1.5mm at a duty point of approximately 15.3l/s at 41.3m of head. The pump efficiency at this duty point would be 35% (typical value for Sulzer XFP Vortex Impellor). However, the recorded flowrate and pressures give a duty point of 8.3l/s at approximately 44.3m of head. The pump efficiency at this duty point is 26%.

The recorded duty point is at a significantly lower flow and higher head than would be expected from the pump at peak performance with a clear rising main. As such, the pump curve and system curve have both been calibrated to meet the recorded duty point. The pump speed has been artificially reduced to 2875rpm to reflect a small level of degradation. The pipeline roughness and local losses have been increased to reflect deterioration in pipe surface condition and sediment deposition.

The combination of pump underperformance and poor pipe condition have led to a low flow velocity of 0.45m/s which is well below the recommended self-cleansing velocity of 0.75m/s calculated based on the formula given by May (11). This means that further particle settlement (and eventually blockage) is inevitable unless corrective measures such as impellor replacement and pipeline pigging are taken.

FIGURE 11

ESSESM PS - Pump and system curve



4. Transient Modelling

Although pressure monitoring at a single location within the pumping station provides useful information regarding the system operation as described above, it does not show the impact of the pressure transients propagating through the rising main. It is therefore essential that hydraulic transient modelling is utilised to assess the pressure along the pipeline in order to identify any conditions which would be detrimental to the integrity of the pipeline system such as cavitation and exceedance of pressure ratings.

Pump start-up and pump shutdown have been found to be the most critical scenarios when analysing the sewage rising mains. Although emergency events such as power failure can generate significant pressure transients, they are considerably less likely to happen. A pump can be switched on and off more than 100 times a day whilst a power cut is not frequent in the United Kingdom. Also, it should be noted that there is no difference between shutdown and a power cut if the shutdown is implemented by tripping the pumps which was often found to be the case.

4.1 Model Calibration

An essential preliminary stage of simulations was to calibrate the model against the recorded data to achieve a close match which increases the confidence level in the simulated data thus allowing for potential system modifications to be recommended.

An initial comparison between the recorded pressure trace and simulated data for a pump shutdown is shown in Figure 12. The simulation accurately predicts the amplitude of the wave but shows a higher frequency. To improve the quantitative match between the recorded and simulated data several calibrations to the model can be applied. Firstly, the wave speed in the rising main can be manually adjusted to reduce the frequency of the oscillations. Doing this accounts for the presence of air bubbles and reduced pipe thickness due to aging which allows the model to replicate the wave speed seen in the recorded data. For the example shown here, the wave speed of PVC pipe has been reduced to 250m/s. As shown in Figure 13, the calibrated simulated pressure shows a better match regarding the frequency of the wave.

Other calibration techniques within the models were also utilised depending on the system being investigated:

- Surge vessel components added at pipeline peaks to replicate trapped air pockets which result in reflections in the pressure waves.
- Bypass pipes around NRVs to replicate NRV leaks.
- Air valve inflow/outflow characteristics adjusted to replicate seized valve behaviour which leads to a gradual pressure rise as air is compressed and released at a very low rate.

It should be noted that WANDA uses quasi-steady friction for transient simulations. This assumption may be satisfactory for slow transients where the wall shear stress has a quasi-steady behaviour. However, previous investigations of the behaviour of steady friction models for rapid transients (Covas *et al.* (12) and Bergant *et al.* (13)) showed considerable discrepancies in attenuation, shape, and timing of pressure traces when computational results were compared with measurements. In the current study, the model is calibrated such that the computed and measured results show good agreement specifically for initial peaks and troughs with the largest amplitude. Having said that, the calibrated model will not be useful if one were to compute transients caused by a change or changes in the settings of the control devices prior to the dissipation of transients completely.

FIGURE 12

HIFPSM PS – Uncalibrated shutdown pressure trace

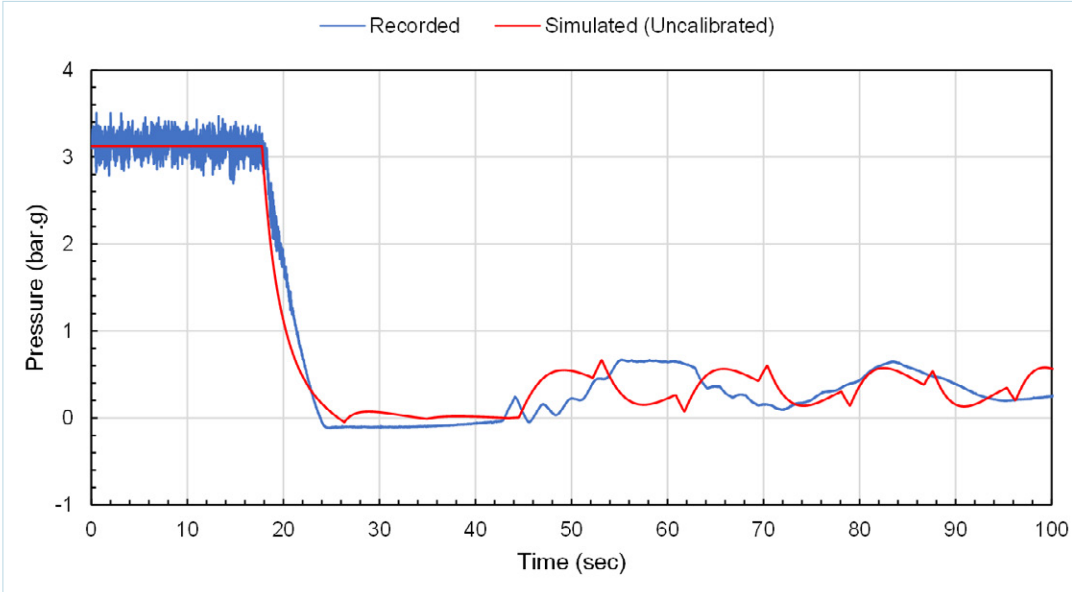
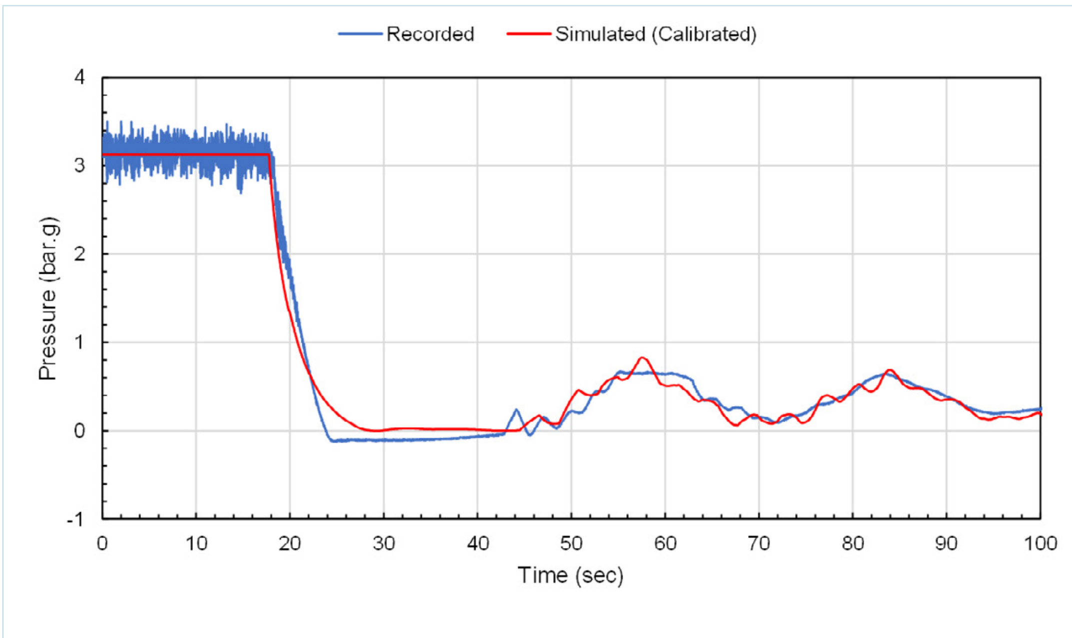


FIGURE 13

HIFPSM PS – Calibrated shutdown pressure trace



4.2 Transient Analysis

The calibration process results in an increased confidence level in the simulated data which can then be used to analyse the pressure envelopes developed throughout the rising main. As noted earlier, the systems investigated did not include controlled pump start-up or shutdown. During start-up, pumps reached their rated speed rapidly which generated a significant pressure spike (Figure 14). Shutdown was implemented by cutting power to the motor resulting in a considerable drop in pressure (Figure 15).

The pressure spike and pressure drop due to pump start-up and shutdown propagate through the rising main. The simulated head envelope is shown in Figure 16. The maximum pressure at the upstream end of the rising main reaches 7barg which exceeds the 6bar pressure rating of the Class B PVC pipe. The minimum pressure along the entire rising main is sub atmospheric down to a minimum of -0.8barg at the upstream end.

FIGURE 14

DIDDSM – Uncontrolled start-up

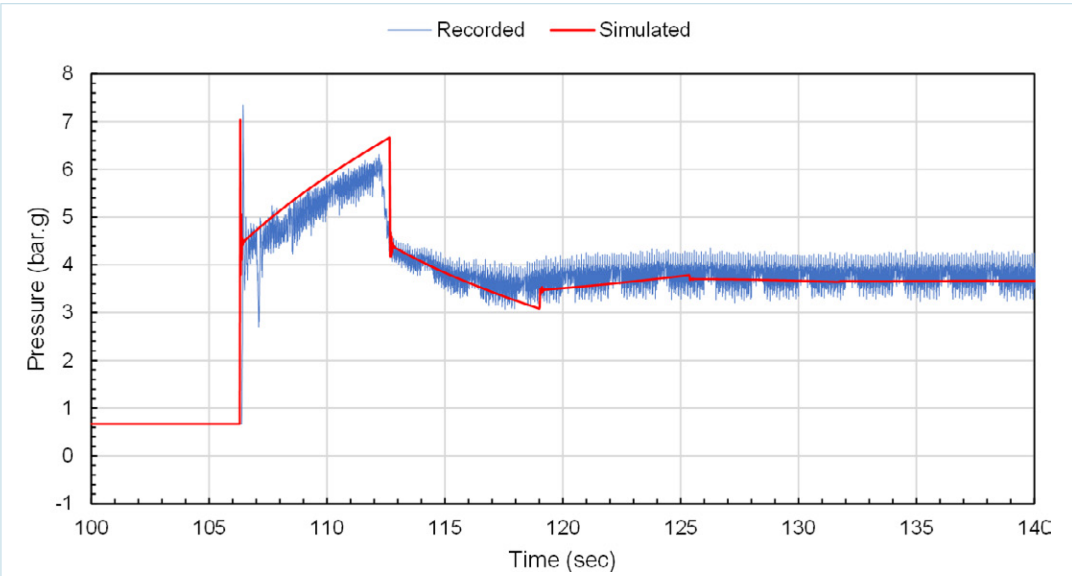


FIGURE 15

DIDDSM – Uncontrolled shutdown

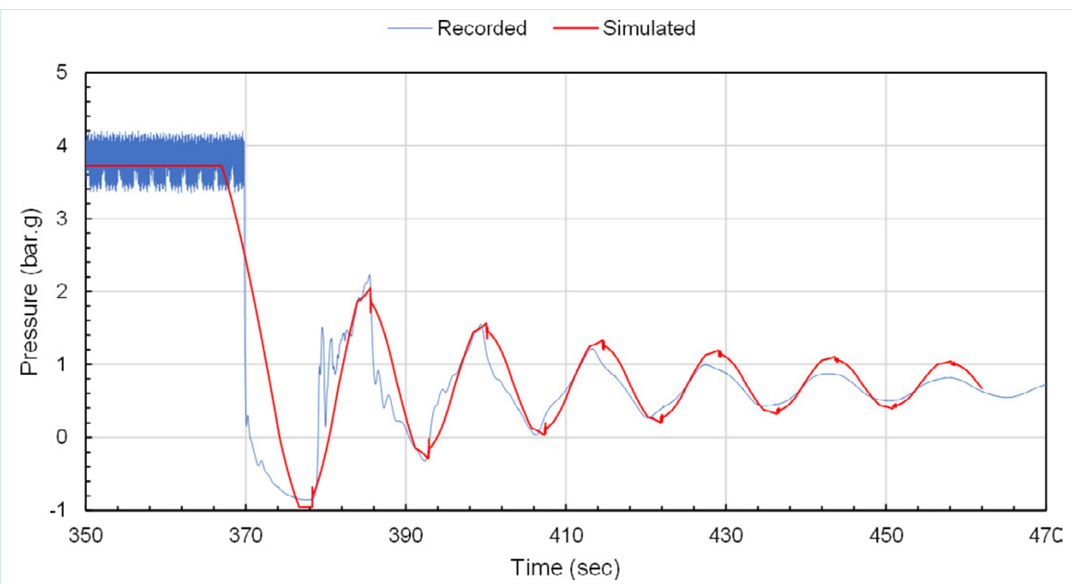
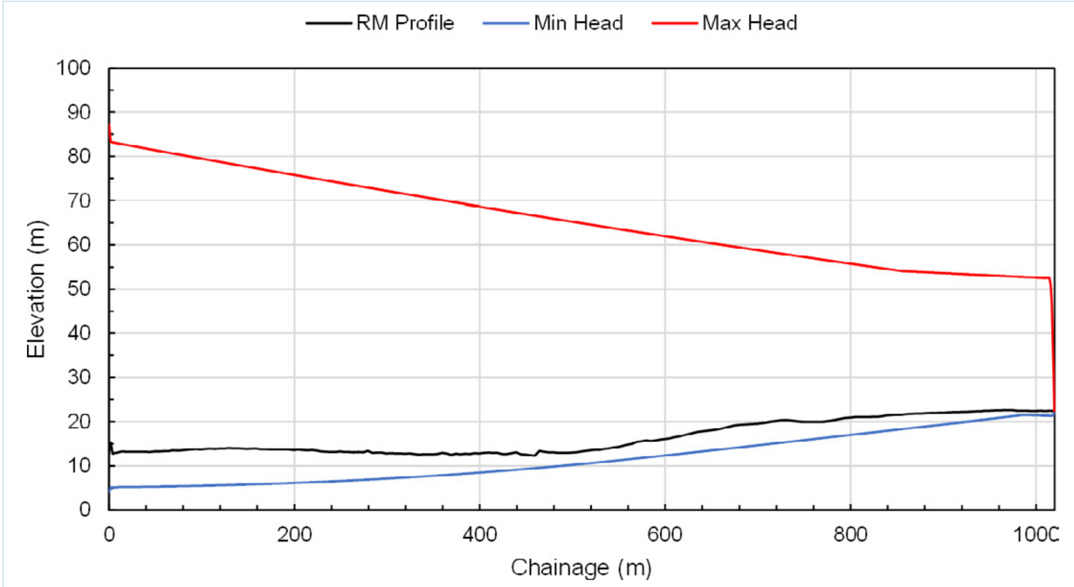


FIGURE 16

DIDDSM – Uncontrolled shutdown head envelope



To alleviate the pressure surges associated with the pump operation it was recommended to equip the motors with VFDs. In the model, the pump start-up and shutdown were modified such that it was ramped up to its rated speed over 30sec and ramped down to stop again over 30sec. This recommendation was then implemented in the system with the effects seen in the recorded pressure data. Figure 17 and Figure 18 show the simulated and recorded pressure for the start-up and shutdown.

FIGURE 17

DIDDSM – VFD start-up

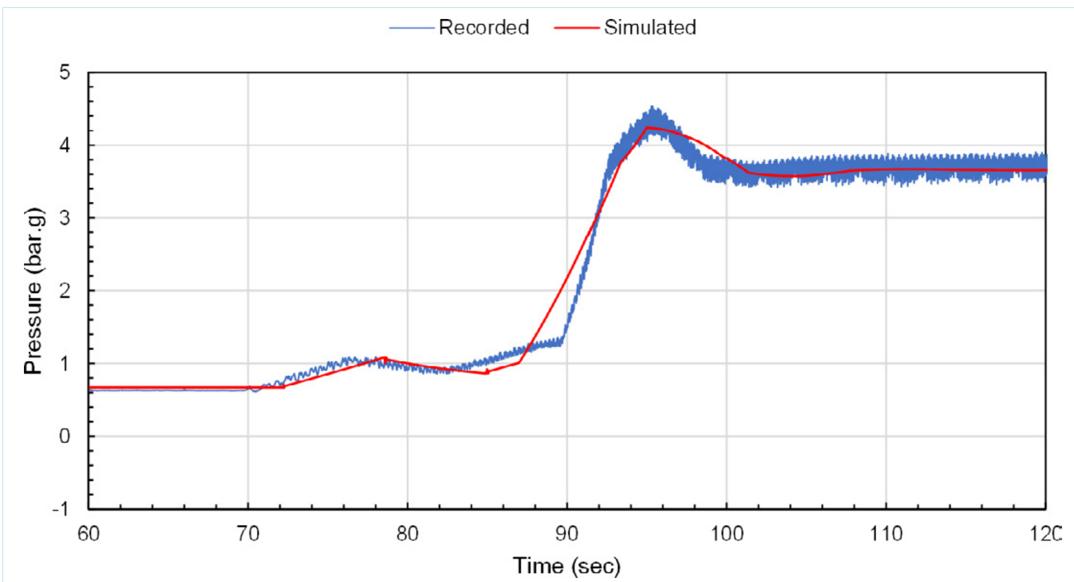
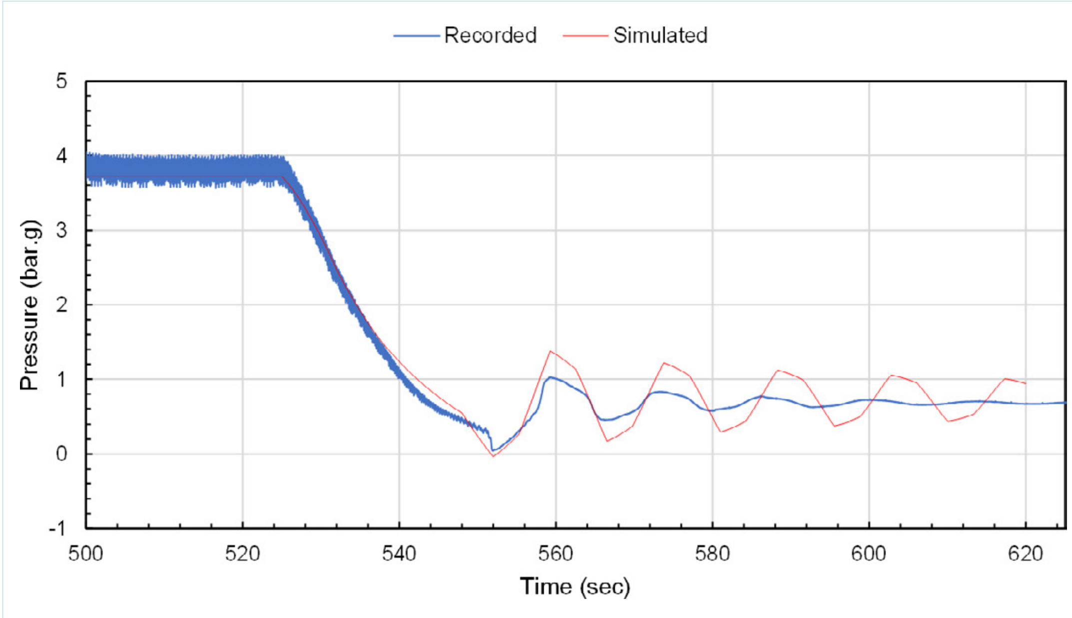


FIGURE 18

DIDDSM – VFD shutdown



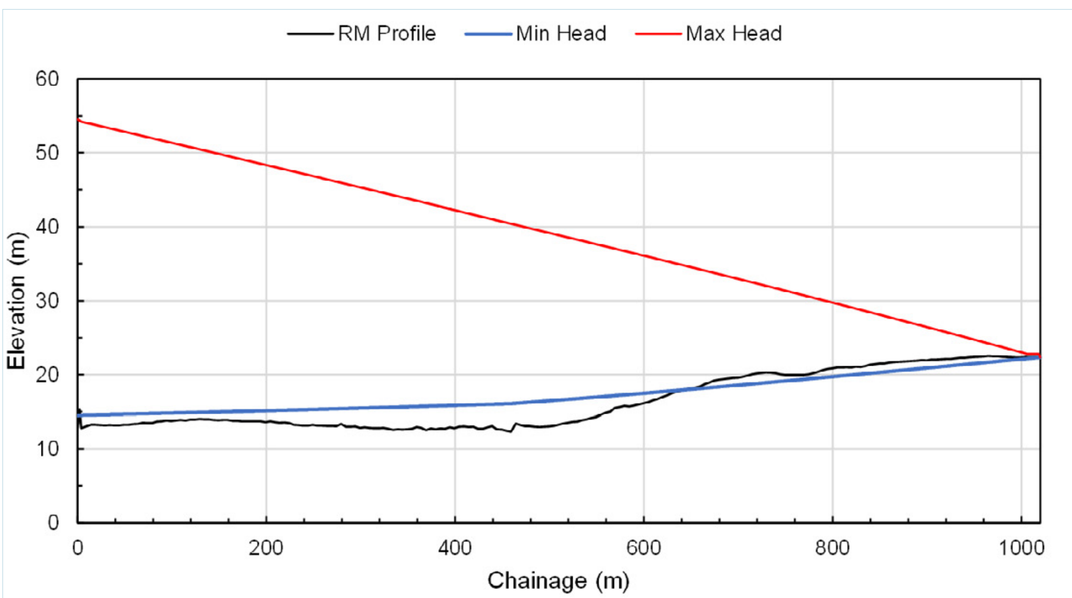
The resulting simulated head envelope for the controlled operations is shown in Figure 19. The maximum pressure at the upstream end of the rising main now only reaches 4barg which is significantly below the 6bar pressure rating of the pipe. The minimum pressure is now only sub-atmospheric along the final 175m of the main and only down to -0.15barg.

The match between the recorded pressure data and the simulated pressure data at the pumping station following the implementation of VFD control provides confidence that the system is operating with the same pressure envelope as predicted by the simulations.

Each system studied underwent the same process of model calibration and pressure envelope analysis in order to make design modifications to improve the operating pressure range. In addition to installation of VFDs, common modifications included air valve replacement and additional air valve installations.

FIGURE 19

DIDDSM – VFD head envelope



5. Summary and Conclusions

Data collected from pressure monitoring devices deployed at several pumping stations was used to analyse the operation of the complete pipeline systems. A diagnostic overview of a wide range of failure mechanisms such as air valves with reduced capacity, NRV leakage and slam was provided.

A transient model of the pipeline systems was created using site survey data. It has been shown that it is possible to accurately predict the transient behaviour of the rising mains using a calibrated model. The model was used to confirm the initial assessment of the recorded pressure and to examine the effectiveness of possible surge alleviation measures. As an example, the effect of controlled start-up and shutdown was demonstrated. It is clearly shown that the pressure transients are considerably mitigated by equipping the pumps with VFD and implementing controlled operating procedures.

Currently, to identify any failure pattern, the recorded pressure should be assessed by a surge analyst. Future developments will focus on Real Time Control applications, i.e., the automated recognition of failure patterns and automated diagnosis of causes.

Acknowledgments

Originally presented at and published by 14th International Conference on Pressure Surges, Eindhoven, NL (12th – 14th April 2023) pressuresurges14.win.tue.nl

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