Digital Twin Visualization of Distributed Fibre Optic Strain Data for a High-performance Early Warning System

R.G. Laver
Varadise Limited, Hong Kong

Y.F. Leung
Hong Kong Polytechnic University, Hong Kong

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ABSTRACT

Unexpected collapse of civil assets can be mitigated by implementing structural health monitoring. Distributed Fibre Optic Strain Sensing (DFOSS) is a favoured monitoring solution comprising a fibre optic cable installed on the structure, connected to a special analyser to return accurate real-time strains along the entire cable. DFOSS is particularly suited for uninterrupted asset monitoring because it can detect events that discrete sensors would fail to register. The cable is also inexpensive and durable. Despite this, DFOSS has yet to be employed commercially in Hong Kong. A key barrier to commercial adoption is the lack of an accessible platform to assist in making informed timely decisions based upon streamed DFOSS data. This paper presents a design to integrate DFOSS data into a digital twin platform to satisfy this need. Specific features of the integration deliver value to the user, including 4D visualization, BIM model superposition, dashboard charts, alert management, and functions to aggregate data and filter noise. Application of the DFOSS integration is showcased by visualizing data from a DFOSS installation at a deep excavation in Hong Kong, demonstrating that construction-induced strains can be visualized to facilitate responsive decision-making. The integration represents a critical step towards industry procurement of DFOSS.

1 INTRODUCTION

This paper describes the integration of two technologies: Distributed Fibre-Optic Strain Sensing (DFOSS) and digital twins.

1.1 DFOSS Systems

A DFOSS system is a sensor used to measure strain. The sensor comprises a fibre optic cable attached to the structure of interest. A continuous profile of strain is obtained by shining a laser down the cable and interpreting the backscatter. DFOSS is particularly suited for long-term safety-critical strain measurements, such as structural health monitoring of aging infrastructure and slope failure. Continuity of measurement opens the possibility of detecting localized strain development anywhere along the cable, which can extend for tens of kilometres. Measurements can also be made in real time, and the cable is long-lasting.

1.2 Digital Twins

A digital twin is a virtual representation of a real-life counterpart. A twin typically connects to real-time sensors and other data sources to maintain synchrony with reality, making Internet-of-Things (IoT) connectivity a key component.

In simulating the physical world, a digital twin enables prediction and optimization. They also assist decision-making by combining data from multiple sources. Digital twins are used widely in many industries, including manufacturing, healthcare, aerospace and energy. In civil engineering, digital twins are made of both the built and natural environments. Inputs typically include data from Building Information Modelling (BIM), ground investigations, photogrammetry, 3-D scans, site records and sensors.

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1.3 Digital Twin Integration of DFOSS

DFOSS has yet to be adopted by the Hong Kong construction industry, despite demonstrating clear benefits for structural health monitoring. Adoption can be accelerated by showing the value of DFOSS data in informing key decisions. Integrating DFOSS into a digital twin contextualizes the data so that it can deliver value; construction progress might highlight cause-and-effect, whilst data from other sensors may validate observations.

This paper describes a design for integrating DFOSS data into a digital twin and showcases the integration on an on-site DFOSS installation in Hong Kong.

Table 1: Key elements of DFOSS procurement

1	Installation design and interpretation methodology	Typically requires an experienced civil engineer with DFOSS expertise
2	Cable installation	Can be performed by a trained in-house team or a subcontractor
3	Interrogator procurement	May be rented or purchased depending upon the application
4	Data visualization	Integrated into a digital twin platform

Table 1 summarizes the four key elements of DFOSS procurement. The application constitutes one of the elements and therefore represents a significant contribution to making DFOSS systems readily available to the engineering industry.

2 WHAT IS DFOSS?

2.1 Overview

A DFOSS system essentially comprises a single-mode fibre optic cable attached to the structure, connected to an optoelectronic instrument called an interrogator. The set-up is pictured in Figure 1. The interrogator pulses laser light which interacts with molecules within the fibre, causing backscattering from each point along the fibre. The frequency shift and magnitude of the backscattered spectrum depend upon the strain and temperature at each point. The interrogator analyses the spectrum to determine strain and temperature profiles along the cable. Most interrogators can attain a repeatability better than 2 με for strain and 0.1°C for temperature.

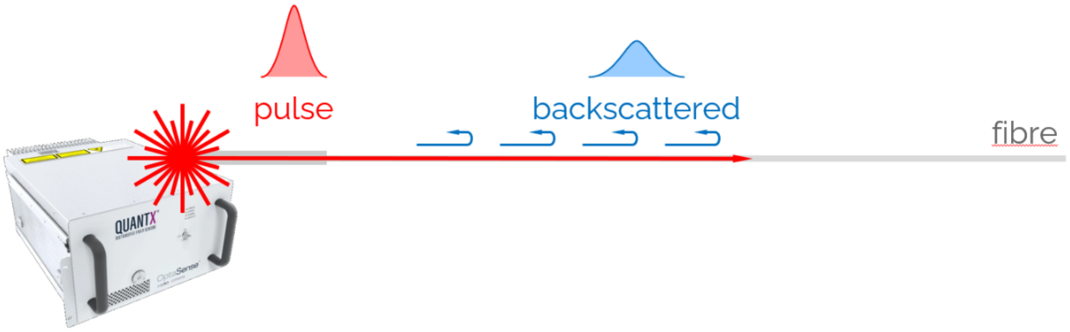


Figure 1: An interrogator interprets fibre conditions from backscattered laser light

The backscattered spectrum comprises the three components shown in Figure 2: Rayleigh, Brillouin and Raman. Raman scattering is not influenced by strain, so interrogators used for structural health monitoring examine either the Rayleigh or the Brillouin components.

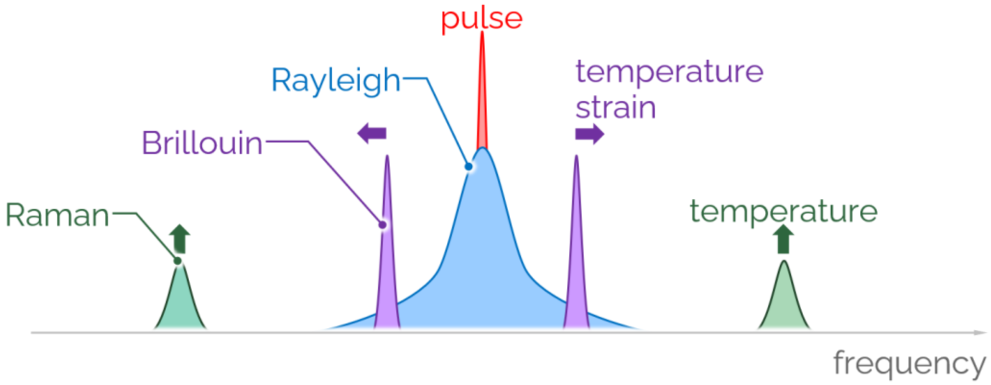


Figure 2: Temperature and strain are interpreted from different backscattered components

2.2 Temperature Compensation

Both Rayleigh and Brillouin components depend upon both strain and temperature, so measurements must be temperature-compensated to derive accurate strains. Temperature compensation is typically achieved by attaching an additional cable to the structure whose optical fibre is de-bonded from its cladding to render it strain-free. This temperature-compensation cable enables temperature effects to be eliminated from strain measurements.

2.3 Spatial Resolution

The transmitted laser pulse has a finite width, and backscattering from the leading and trailing edges of the pulse will superpose. This results in an averaging effect whereby each measurement is a moving average taken over a length of cable called the spatial resolution.

In theory, spatial resolution could be improved by shortening the pulse, but since a laser pulse disperses as it travels down a fibre, this would also limit the sensing range. Selecting an interrogator therefore involves striking the right compromise between spatial resolution and sensing range.

2.4 BODTR and BOTDA

The spatial resolution can be improved by looping the cable back to the interrogator and sending laser pulses down the other end as well. This stimulates Brillouin scattering and improves the spatial resolution. This technique is called Brillouin Optical Time Domain Analysis (BOTDA). Without stimulation, measurement is called Brillouin Optical Time Domain Reflectometry (BOTDR).

2.5 Rayleigh OFDR

The phrase “Time Domain” means that the location of measurements is calculated from the time delay between the transmitted and backscattered light. The accuracy is sufficient for Brillouin analysis, but when the Rayleigh component is used for measurement, Optical Frequency Domain Reflectometry (OFDR) is typically adopted to maximize the spatial resolution. OFDR relies upon the interference between transmitted and returned pulses; the frequency components of the resulting interference correspond to different locations along the fibre.

Interrogators utilizing Rayleigh scattering are capable of high spatial resolution. The scattering profile is unique to a particular fibre since Rayleigh scattering is generated by local defects. The interrogator detects changes in strain or temperature by the corresponding stretch or contraction of this profile. The superior performance of Rayleigh-based interrogators makes them a prime choice for Distributed Acoustic Sensing (DAS), where vibrations are recorded as high-frequency strain fluctuations.

Table 2 compares typical parameters for common interrogator types.

Table 2: A comparison of common interrogators (Barrias, Casas, & Villalba, 2016)

Interrogator Type	Sensing Range	Spatial Resolution	Measurands
Raman OTDR	1–37 km	0.01–17 m	Temperature
Brillouin BOTDR	20–50 km	≈1 m	Temperature, Strain
Brillouin BOTDA	150–200 km	2 cm (at 2 km range) to 2 m (at 150 km range)	Temperature, Strain
Rayleigh OFDR / DAS	50–70 km	≈1 mm	Temperature, Strain, Vibration

3 DFOSS IN STRUCTURAL HEALTH MONITORING

Infrastructure deteriorates with time, with the risk of failure increasing with age. In Hong Kong, slopes susceptible to landslides present a hazard to nearby habitations and transport routes. Failure can be sudden and catastrophic, but it need not occur without warning. If executed effectively, structural health monitoring can trigger pre-emptive action, saving lives and costly reinstatement.

DFOSS is a favoured solution for structural health monitoring worldwide. Table 3 highlights how DFOSS can outperform current monitoring solutions in Hong Kong in ensuring that crucial observations are identified in time to allow mitigation.

Table 3: How DFOSS compares with the performance of conventional structural health monitoring solutions

Monitoring Solution	Can Failure Occur Between Observation Times?	Can Failure Occur Between Observation Locations?
Manual Surveying*	Yes	Yes†
Visual Inspection	Yes	No
Crack Gauges	No, if the right cracks are monitored in real-time	Yes
Slope Inclinometer	No	Yes‡
DFOSS	No, if the cable intersects regions of strain localization. Measurements are real-time.	No. Measurements are distributed along the cable.

* Automatic surveying is unlikely for operational infrastructure due to service disruption and expense.

† Surveying points would need to be impractically close to register cross-crack displacement reliably.

‡ There is a significant chance that inclinometer placement is incompatible with detecting a tilt trend commensurate with landslide development.

DFOSS also boasts other notable advantages:

- The cable allows uninterrupted operation: it is small, requires connection only at its ends and does not interact with electromagnetic fields.
- Although interrogator cost is typically a deciding factor on whether to adopt DFOSS, the cable is relatively inexpensive, and once installed, the system can take advantage of future advances in interrogator technology.
- Since the measuring fibre typically comprises silica, the cable is inert even under aggressive chemical conditions and extreme temperatures. Indeed, it is likely that the cable will outlive the very structure it is monitoring.

DFOSS has delivered value in a diverse range of structural health monitoring applications worldwide for over two decades. Common applications are listed in Table 4.

Table 4: Common structural health monitoring applications for DFOSS

Application	Notes
Bridges	On rebar or retrofitted. Detects spalling, cracking, yielding and joint movement.
Tunnels	Can be aligned longitudinally and circumferentially. Detects spalling, cracking, yielding and joint movement.
Buildings	On rebar of slabs, columns and beams or retrofitted.
Piles	On rebar of bored piles and inside tubular steel piles. Also installed offshore. Outperforms inclinometers for measuring lateral deflection.
Dams	Gives early warning of dam breach.
Slopes	Embedded in a trench for overburden. Reinforced cladding protects fibre.

In Hong Kong, DFOSS has yet to be used commercially to monitor structures and slopes. Notwithstanding, in 2021 a DFOSS system was successfully installed on a construction site as the first full-scale demonstration of DFOSS in Hong Kong (Lin, et al., 2023). This installation is used in this paper to showcase the design of the integration of the DFOSS data into a digital twin of the construction site and is described later in Section 5. The anticipated outcome of the integration is to make DFOSS technology readily usable for Hong Kong practitioners.

4 INTEGRATION DESIGN

4.1 Overview

This paper presents the design of an integration of DFOSS data into a digital twin platform. Currently, software for visualizing DFOSS data is typically developed and sold by the interrogator manufacturer. The software typically lacks the ability to integrate with a digital twin of the monitored structure. In the context of a digital twin—with its associated data such as BIM geometry, site events and sensor data—decisions can be made in a more informed, timely and convenient manner. The digital twin serves as a single portal and hence is readily accessible to stakeholders. Integration of the DFOSS data into a digital twin platform will enable informed, timely and convenient decision-making, namely in respect to:

1. Pre-empting failure by detecting pre-failure movements such as cracking or excessive strain development and taking preventive remedial measures.
2. Measuring performance during construction and operation to understand more about the structural or geotechnical behaviour of the asset under loading, so that designs, construction methods and operational modalities can be optimized.

The DFOSS integration is manifested in a dedicated application in the platform. The application was designed by a probable end user—a qualified civil engineer with experience designing DFOSS systems and familiar with the peculiarities of DFOSS data and its interpretation. The digital twin is rendered using Unreal Engine. Unreal Engine is one of the leading graphics simulators on the market and is widely used for producing ultra-realistic games, movies and simulations. When DFOSS data is being viewed in the platform, the digital twin is ghosted to enable the data to be unobscured, particularly in the case of underground installations or those cast in concrete.

The application requires the inputs and produces the outputs illustrated in Figure 3.

4.2 Geo-Referencing

The interrogator locates each DFOSS measurement by cable chainage. For presentation in the platform however, each measurement must have associated Cartesian coordinates. Attributing coordinates to each DFOSS measurement is referred to as geo-referencing. During set-up for a particular project, the cable alignment is used to geo-reference a set of baseline readings. The resulting coordinates are then applied to all subsequent DFOSS readings, enabling subsequent DFOSS measurements to be displayed at the correct 3-D location.

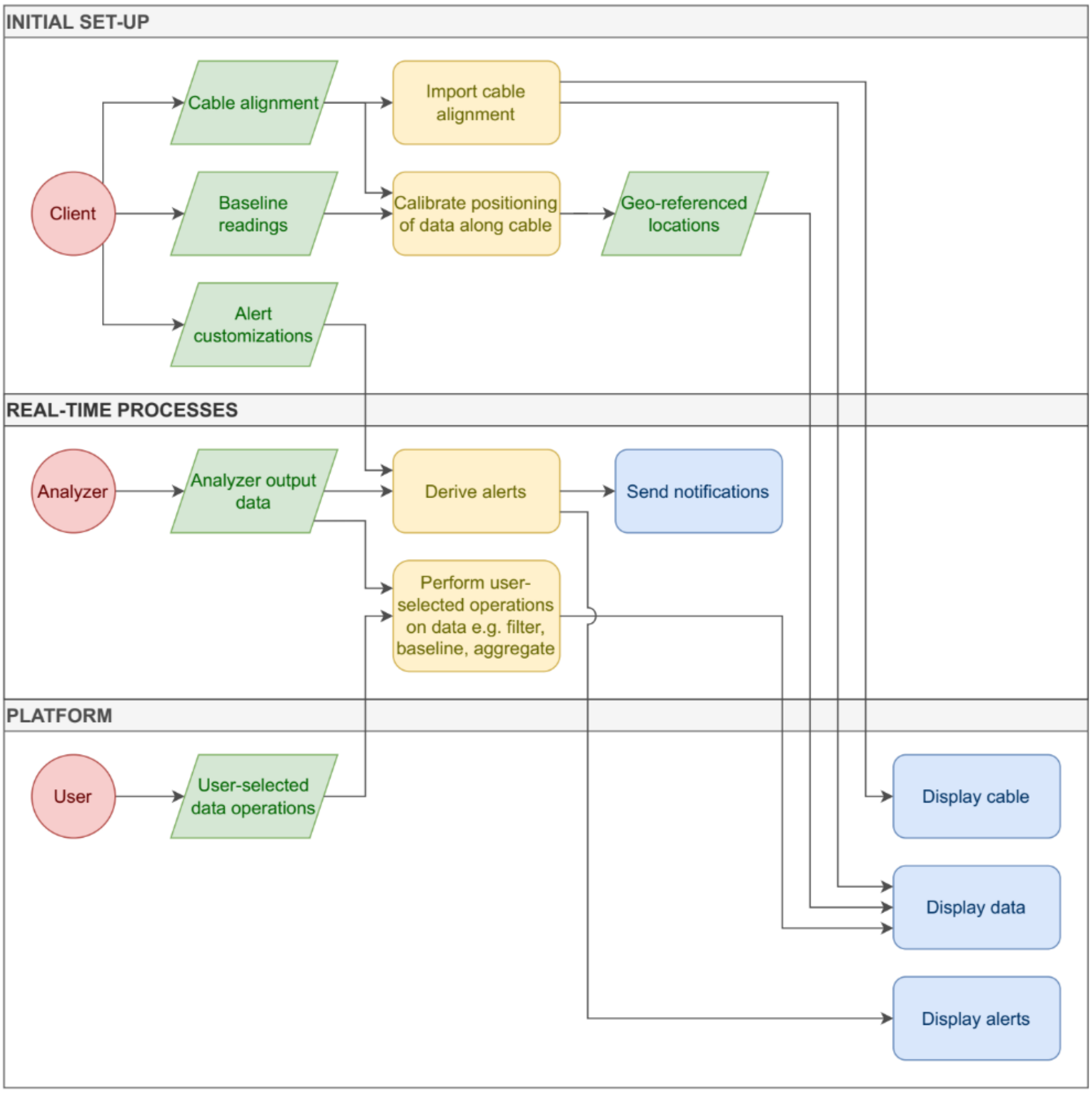


Figure 3: Inputs and outputs for the DFOSS application

4.3 Alerts

Alerts inform the user when DFOSS measurements fall outside predefined limits and enable the user to respond quickly to sudden and hazardous events. An alert can trigger sending of a notification to the user’s email, mobile device messaging app or to an in-app notification centre.

Alerts are pre-configured during initial set-up. The configuration comprises defining an envelope outside of which measurements will trigger an alert. The envelope is defined by dividing the cable into sections. For each section, a high and a low threshold can be defined for each measurand as a linear function of chainage. The thresholds can be configured to trigger for readings with or without a baseline dataset subtracted from them.

4.4 Chart Views

Chart views supplement the visualization of DFOSS data in the digital twin, as illustrated in Figure 4. Two charts may be displayed; one chart plots variation against chainage at a selected time, whilst the other plots against time at a selected chainage. The chainage and time for display are selectable interactively on the chart, and synchronize across the digital twin and time bar to maintain a consistent context. The charts enable the user to more readily quantify differences between data and to compare values against design profiles and thresholds. Each chart offers an export option allowing the user to capture data for use in other applications.

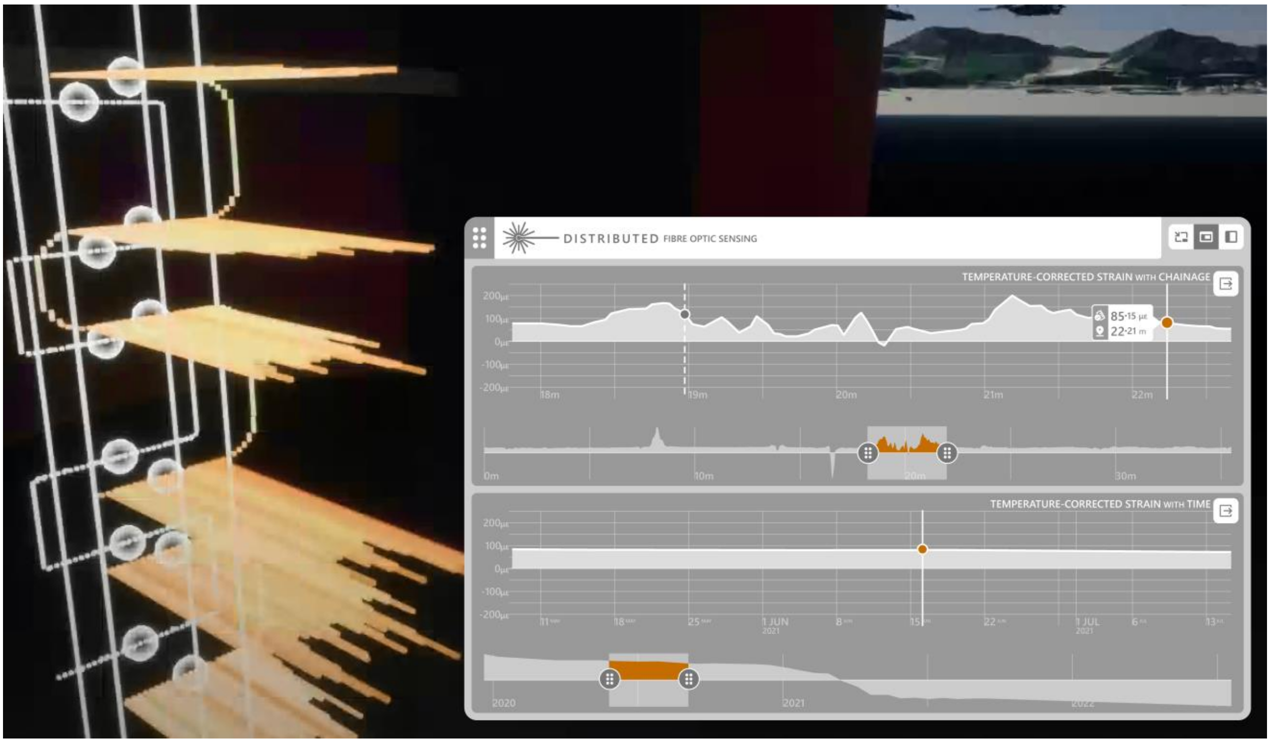


Figure 4: Chart display complements the digital twin view by facilitating more quantitative comparison of values

4.5 *Display Measurand*

Most interrogators can output temperature, directly-measured strain and temperature-compensated strain. For assessment of structural health, temperature-compensated strain would be most frequently viewed.

The platform displays one measurand at a time. As pictured in Figure 5, the user can either select which measurand they would like to view, or choose to view alerts. The alert view allows users to quickly investigate and follow-up on alert notifications.

The user can select the measurement time to view using a time slider. The entire digital twin is synchronized with the time slider, including the Building Information Modelling (BIM) model and the data from other sensors. In this way, the user can readily identify what caused particular DFOSS observations.

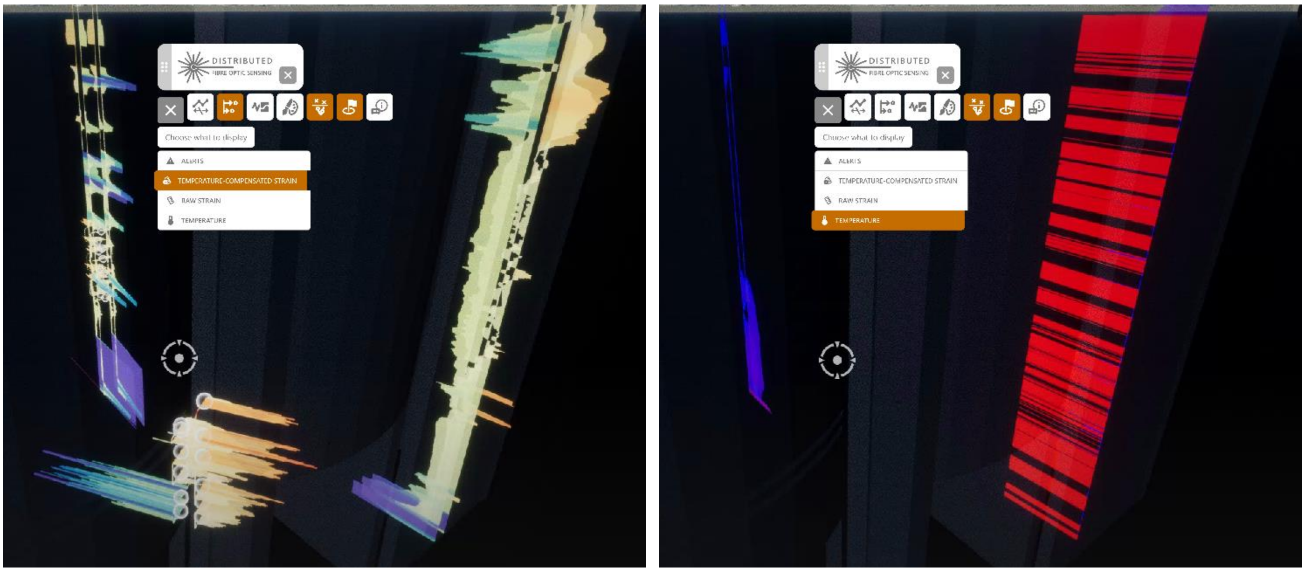


Figure 5: The DFOSS application supports display of both strains (left) and temperatures (right)

4.6 Aggregation with Time

The user can quickly draw insights by aggregating the data over time period at each measurement point, as shown in Figure 6. The period of aggregation is selected via the time slider.

The maximum, minimum and maximum absolute value aggregation functions help identify extreme-value measurements. The maximum absolute value is applicable to strain rather than temperature since strain can be both tensile and compressive. The averaging functions—arithmetic mean and median—are useful for removing noise and determining a representative profile relevant to steady-state conditions.

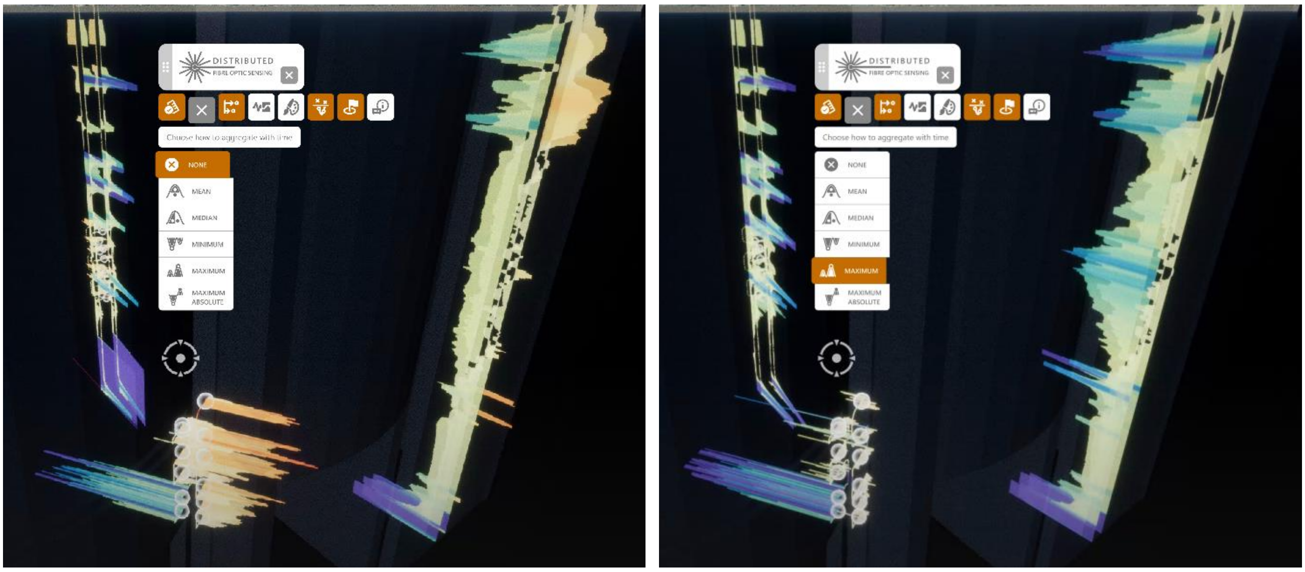


Figure 6: Viewing an envelope of the maximum values over a period (right) helps identify highest recorded values. Non-aggregated data is portrayed on the left for comparison

4.7 Baseline Dataset

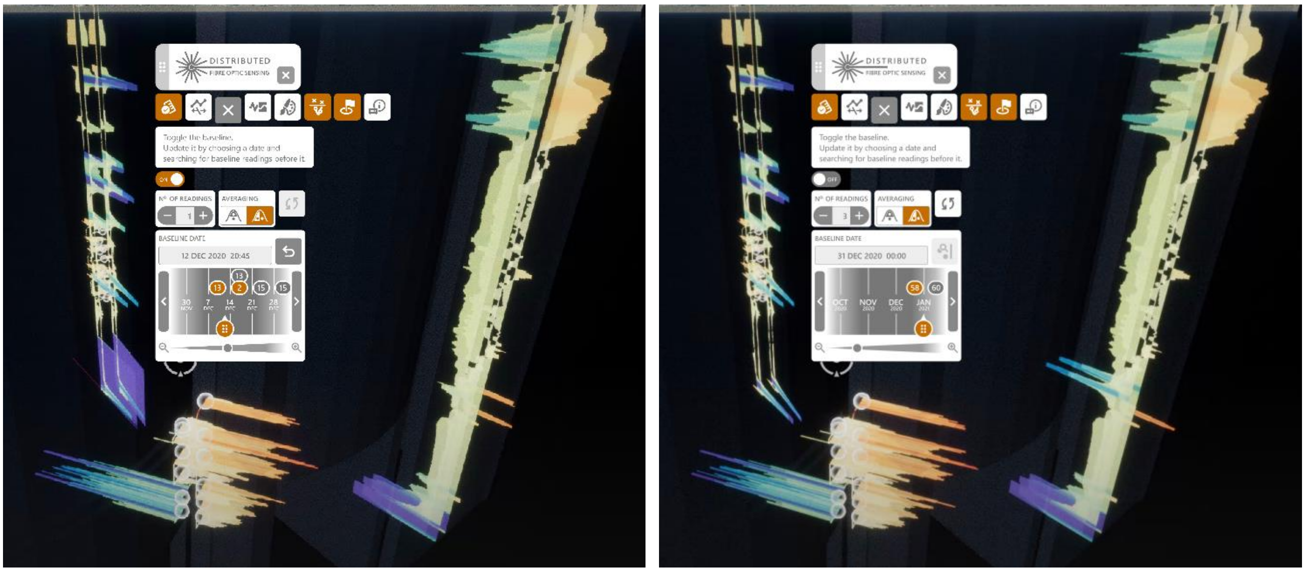
The user will typically wish to calibrate strain readings with respect to a baseline dataset:

- The strain at installation of the cable is typically non-zero, particularly if the cable is pre-tensioned to extend the registerable range of compressive strain. It is the strain incurred since installation that is relevant to structural damage, particularly if the cable is cast into concrete.
- Understanding of structural behaviour is crucial for the observational method or design optimization. In this case, observed strains will be compared with design predictions over a distinct construction phase.

The baseline dataset is defined as an average of consecutive readings, offering the opportunity to eliminate noise and spurious data. This process is simplified by automatically identifying the readings to average. As pictured in Figure 7, the user specifies the latest date for these readings via a time bar. A zoom function on the time bar helps the user determine a date by making all available readings readily discoverable. The user can also select the number of baseline readings for averaging, and whether to average by arithmetic mean or by median.

4.8 Data Rendering Options

Both colour and height bars can be used to display variations in DFOSS measurements. Where an installation comprises multiple cables, each individual cable may be rendered differently. This enables the user to focus on data from a cable of interest—particularly useful when cables are closely spaced.


Toggle the baseline.
Update it by choosing a date and searching for baseline readings before it.

ON
N° OF READINGS: 1
BASELINE DATE: 12 DEC 2020 20:45

Toggle the baseline.
Update it by choosing a date and searching for baseline readings before it.

OFF
N° OF READINGS: 3
BASELINE DATE: 31 DEC 2020 00:00

Figure 7: Changes in strain can be visualized by applying a baseline (left). Without a baseline, initial strains will frustrate interpretation of changes (right)

Height bars are plotted normal to the cable alignment to account for situations where the cable is sub-vertical. The user can choose the scale of the height bars relative to the screen. The user can choose from a selection of divergent colour scales to render strain measurements, and a variety of sequential scales are offered for temperature.

4.9 Spurious Values

It not uncommon for DFOSS data to contain spurious values which exceed genuine measurements by orders of magnitude. The maximum and minimum of the colour and height display scales are defined with respect to the extreme available values. Consequently, the spurious values would lead to genuine measurements being displayed across a limited range of colour and height, and variations being indiscernible. It is therefore essential that users are given the ability to identify and remove spurious values. As shown in Figure 8, the application allows the user to effectively ignore data exceeding a desired magnitude for the purposes of both data manipulation and display.

4.10 Reference Markers

The application allows the user to pinpoint precise locations along the cable. This facility can be used to segment the cable or to highlight a sensitive location such as a known crack or stress concentration. During initial set-up, the user can specify these locations as reference markers. These markers can be superposed on the cable alignment, as illustrated in Figure 10.

4.11 Interrogator Settings

Certain interrogator settings such as spatial resolution or measurement rate are helpful to assist in interpreting DFOSS data. The application makes this information available to the user, as shown in Figure 9.

Specify limits for data display

	TEMPERATURE COMPENSATED STRAIN	RAW STRAIN	TEMPERATURE
	ON	ON	ON
HIGH	500 με	500 με	35 °C
LOW	-500 με	-500 με	5 °C

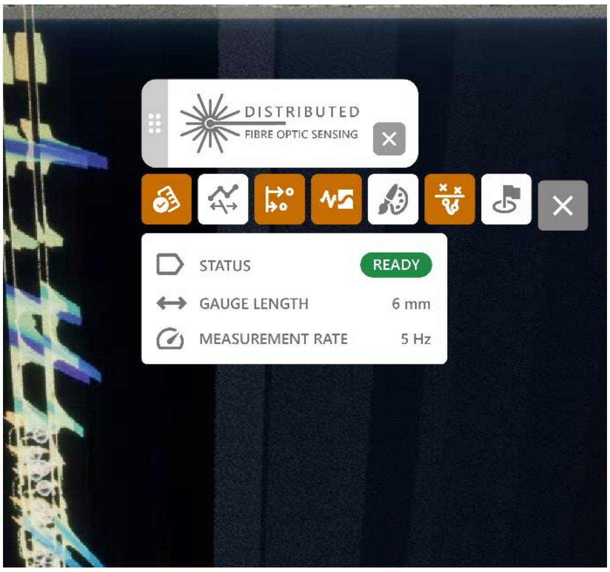
Specify limits for data display

	TEMPERATURE-COMPENSATED STRAIN	RAW STRAIN	TEMPERATURE
	OFF	OFF	OFF
HIGH	31854 με	5849 με	790 °C
LOW	-15050 με	-15225 με	-715 °C

Figure 8: Spuriously large values distort data display (right). The application allows omission of such values so that the profile of genuine data may be viewed (left)

ON Hide reference markers

Figure 10: White reference markers help focus on locations of interest



STATUS READY
GAUGE LENGTH 6 mm
MEASUREMENT RATE 5 Hz

Figure 9: Information on interrogator settings can assist with data interpretation

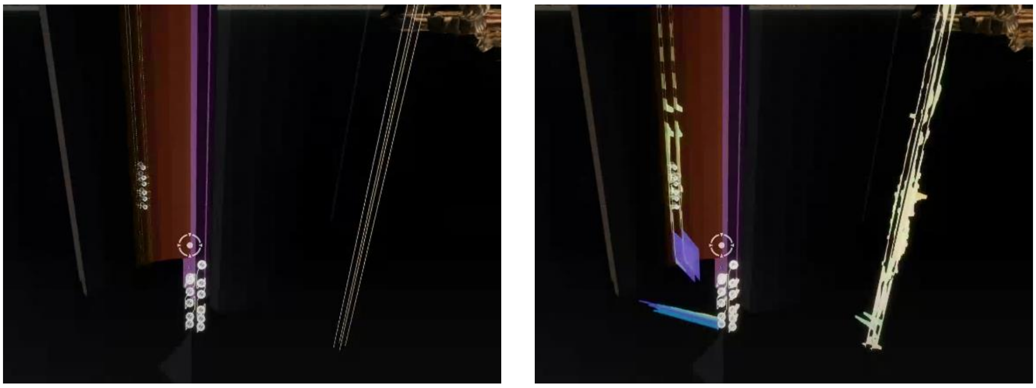
5 PROJECT APPLICATION

The DFOSS integration was evaluated by applying it to a real on-site DFOSS installation. The government of the Hong Kong Special Administrative Region (HKSAR) is keen to promulgate DFOSS in the industry, and enlisted the DFOSS expertise and equipment of Hong Kong Polytechnic University (HKPU) to execute the installation in 2021. Details of the trial are documented in a paper (Lin, et al., 2023). The fibre optic cables are installed within three of the diaphragm wall panels of a launch shaft for a tunnel boring machine (TBM) used to advance the tunnels for the Trunk Road T2 project. The launch shaft is situated in Kai Tak, Hong Kong. The cables were attached directly to the steel bars of the reinforcement cages before concreting.

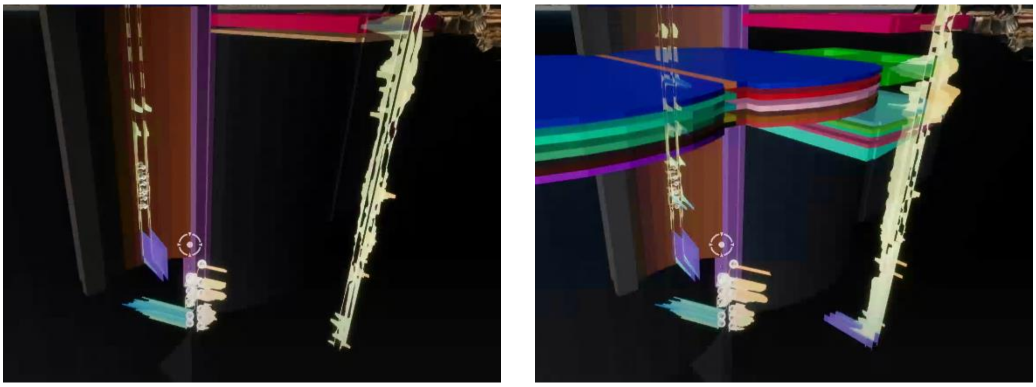
A key purpose of the installation was to evaluate hoop stresses developing during excavation within the unique circular peanut-shaped cofferdam of the launch shaft. The results verified the effectiveness of DFOSS in monitoring hoop strains compared with more conventional instruments such as inclinometers, movement markers or vibrating wire strain gauges.

A digital twin was constructed in Unreal Engine by referencing the geometry and construction staging described in the paper. The DFOSS data from fifteen cables was georeferenced from the installation details given in the paper. The zigzag configurations of the two cables measuring hoop strain were deduced by noting development in their strain profiles. Height bars to display the DFOSS data were orientated intuitively—perpendicular to both the diaphragm wall alignment and the cable.

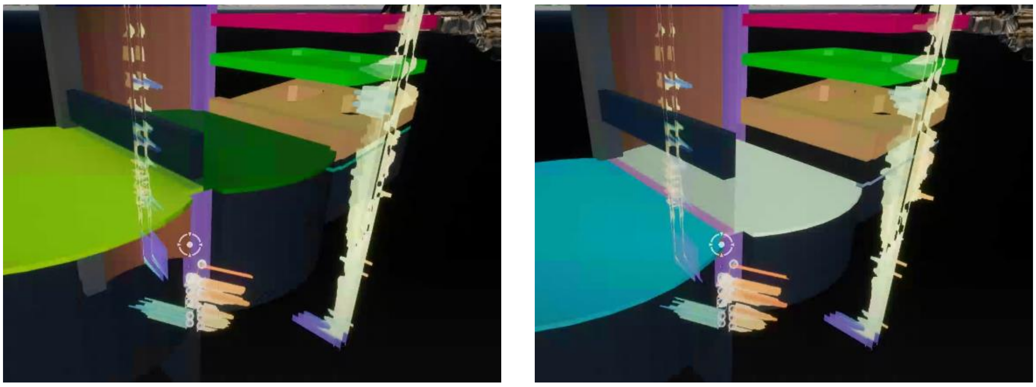
Figure 11 illustrates that DFOSS measurements can be readily explored in the context of construction progress.



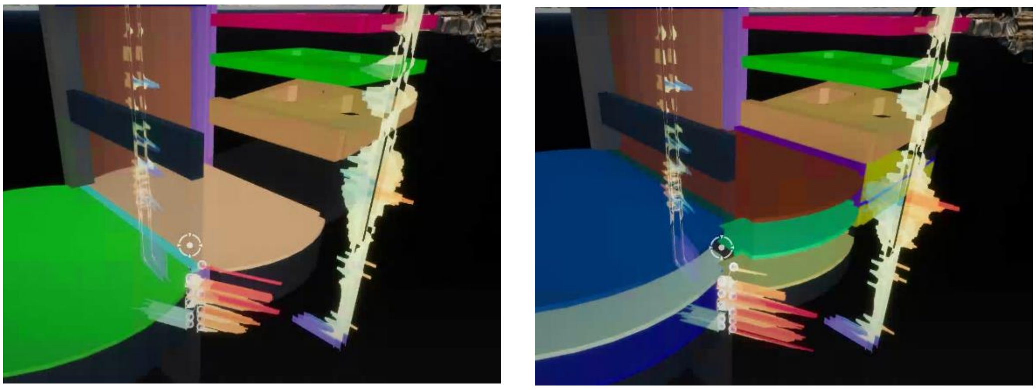
(a) 15 Dec 2020 (b) 6 Jan 2021



(c) 11 Feb 2021 (d) 24 Mar 2021



(e) 3 May 2020 (f) 26 May 2021



(g) 17 Jun 2021 (h) 29 Jul 2021

6 CONCLUSION

An application has been designed to integrate DFOSS data into a digital twin. The integration is the first of its kind in Hong Kong. In the context of structural health monitoring, the integration helps identify impending failure so that pre-emptive mitigation can be made. DFOSS data can be viewed and manipulated alongside a 4-D BIM model and data from other sensors to correlate observations with site events, and so establish causation. The readiness of the application for industry use has been demonstrated through a real on-site DFOSS installation in Hong Kong during the construction phase. The demonstration showed that the application can clearly visualize strain evolution as construction progressed. The proven strain visualization capability of the application suggests that anomalous strains during the operational phase can also readily be recognized.

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