

Design and data modelling of fibre optic systems to monitor reinforced concrete structural elements

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ABSTRACT

Structural monitoring of built assets, performed to ensure safety, usability, and to better understand the assets' structural behaviour, is becoming common practice. One method to monitor structural behaviour is to use fibre optic systems to measure temperature and strain in structural elements. Fibre optic systems are relatively inexpensive, easy to install, versatile, and widely applicable. However, all the data acquired by monitoring systems are meaningless if they lack context within the built asset, and they are of little use if they cannot be appropriately exchanged and visualised. This paper presents an extension to the IFC data model standard for structural monitoring systems. The extension allows (i) to model structural monitoring systems, (ii) to store and retrieve acquired data, and (iii) to visualise the data directly on the BIM model. The James Dyson Building at the University of Cambridge is used as a case study, in which selected reinforced concrete columns, beams, and slabs have been instrumented with two types of fibre optic sensors. The case study demonstrates that the extension is able to fully describe the fibre optic monitoring system and that it can aid in its design, deployment, and further operation.

INTRODUCTION

The operation and maintenance of built assets requires constant monitoring of the actual conditions of the assets. This monitoring, known as Structural Health Monitoring (SHM), primarily deals with damage and anomaly detection, improving safety and maintainability, remote management, and measuring structural performance (Farrar & Worden 2007). To measure the performance of structural elements, three physical components are required: sensors, to measure variable attributes of the structural elements; a communication network, to transmit measured data; and a data processing unit, to generate useful information from the acquired raw data. However, these data are of little use if they lack context within the built asset or if they cannot be easily shared and visualised for decision making.

The Building Information Modelling (BIM) approach is being adopted to formally organise all the generation, exchange, and visualisation of information related to built assets, during their entire life cycle. Adopting the BIM approach for the operational phase of a built asset would represent the largest opportunity to reduce the asset's total life cycle cost. Ensuring that the exchange of information is efficient and robust (without errors or any data loss) is vital to the successful adoption of the BIM approach for the operational phase of built assets. This requires standard data models, which prescribe guidelines and rules to organise and link data.

Standard data models for the Architecture Engineering and Construction (AEC) area have been developed; however, they are not yet sufficient to fully describe structural monitoring systems or to ensure a robust exchange of data acquired by sensors. Currently, informal approaches are used for modelling and data exchange of structural monitoring systems, such as using proxy and user-defined elements or by combining different standards. These are not definitive and robust solutions, which could lead to errors, ambiguities, and hinder the benefits of using the BIM approach during the operational phase of built assets.

This paper presents an extension to the Industry Foundation Classes (IFC) specification –based on SensorML– that intends to facilitate the (i) modelling of structural performance monitoring systems, (ii) storing and retrieving acquired data, and (iii) visualising the data directly on the BIM model. The proposed extension is the result of an investigation of the capabilities of current standard data models and common practices and minimum requirements to model monitoring systems. The ultimate goal of this research is to showcase the possibilities for improving structural performance monitoring, and asset management in general, by using a standard data model to describe structural monitoring systems. The proposed extension has been used to model a fibre optic system that monitors reinforced concrete structural elements in the James Dyson Building at the Engineering Department of the University of Cambridge.

A brief description of fibre optic systems used to measure structural performance is presented in the next section. Current and missing capabilities of existing standard data models for built assets and sensors are presented in the subsequent section. The developed extension to the IFC specification and the case study are then presented, followed by conclusions.

FIBRE OPTIC SYSTEMS FOR STRUCTURAL MONITORING

Fibre optic monitoring systems can be broadly classified as distributed sensing systems or point sensing systems. A distributed fibre optic sensor (DFOS) system consists of an optical fibre connected to a fibre optic interrogator which measures changes in the optical properties along the whole fibre. These changes can be due to a change in temperature, or a change in strain, or both.

Brillouin optical time domain reflectometry (BOTDR) is one of the DFOS techniques that can be used to interrogate an optical fibre (see Figure 1). A BOTDR interrogator sends short pulses of light into the fibre. Most of this incident light is transmitted through the fibre uninterrupted. However, due to small crystal impurities in the glass core of the optical fibre, as the light travels along the fibre, some of it is scattered back towards the interrogator. The frequency spectrum of this backscattered light is made up of a number of different components, one of which is the Brillouin spectrum. The peak frequency of the Brillouin spectrum is shifted from the frequency of the incident light pulse by an amount that is proportional to the temperature and strain within the optical fibre at the point where the backscatter occurred. This phenomenon is exploited by the BOTDR technique to measure temperature and strain changes along a fibre optic cable, up to tens of kilometres in length.

After sending each pulse of light, the BOTDR interrogator measures the power of the backscattered light at a particular frequency. By scanning through a

range of frequencies, the interrogator finds the peak Brillouin frequency at that particular measurement time, for each point along the optical fibre (see Figure 1). The distance along the fibre where the backscattered light is coming from is resolved by taking into account the time of arrival of the backscattered light and the speed of light in the fibre's glass core. Once the peak Brillouin frequencies are known for each point along the optical fibre, they can then be compared to those measured at a previous time in order to calculate the changes in temperature and strain in the optical fibre, and hence of the structure in which it is embedded or fixed to.

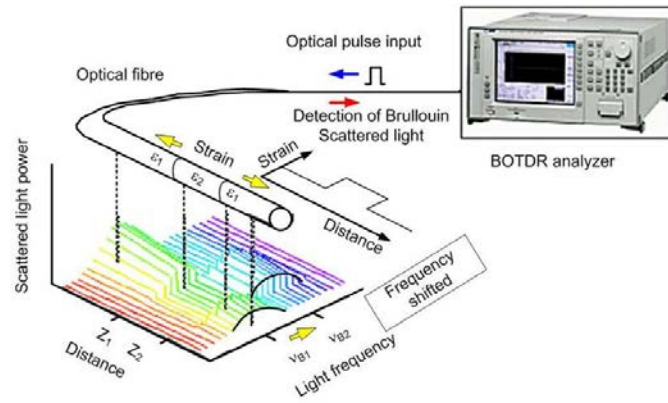


Figure 1. Schematic of the BOTDR technique for interrogating distributed fibre optic sensors

Point fibre optic sensor (PFOS) systems are used to measure changes in the optical properties at discrete locations along a fibre. Fibre Bragg grating (FBG) sensors are one of the most common types of PFOS. An FBG sensor consists of an optical fibre with a sequence of refractive index variations inscribed in its core. These inscriptions, or ‘gratings’, act as a mirror that reflects light of a certain frequency, which is determined by the spacing of the gratings.

When an incident light pulse is transmitted through the optical fibre, the FBG allows most of the light to propagate past it, but will reflect back towards the source that part of the light spectrum which corresponds to the FBG’s signature frequency. If the strain in the optical fibre at the location of the FBG changes (i.e. the fibre shortens or elongates), the resulting change in spacing between the gratings shifts the FBG’s signature frequency.

An FBG interrogator is used to send pulses of light through the fibre optic and detect the changes in the FBG’s signature frequency, which can then be related to a change in thermal or mechanical strain at the FBG’s location. By inscribing FBGs of different signature frequencies along the same optical fibre, it is possible to have tens of PFOS on a single fibre optic cable.

Being distributed measurement systems in nature, DFOS provide measurements all along the fibre optic sensors, as opposed to PFOS which can only provide data at a limited number of discrete locations. On the other hand, PFOS systems tend to be more accurate than DFOS systems. The choice of which fibre optic monitoring system to use depends largely on the application at hand. Sometimes

it could be useful to have both systems installed in parallel in the same structure, as in the case study presented in this paper.

DATA MODEL STANDARDS FOR STRUCTURAL MONITORING OF BUILT ASSETS

The most widely used standard data models for the AEC area have been developed and maintained by buildingSmart and the Open Geospatial Consortium (OGC). Standards to describe sensors and monitoring systems have been developed for particular applications, as noted in literature (Hu et al. 2007; Lee 2007). Nevertheless, none of the existing standard data models have the sufficient capabilities to describe structural monitoring systems for built assets (Davila Delgado et al. 2015).

The IFC specification (Liebich et al. 2013) includes an entity to model sensors commonly used in buildings (*IfcSensor*). It can describe predefined types of sensors that measure parameters such as temperature, humidity and light, or sensors that detect movement, fire, etc. Most of the predefined types are only related to building services monitoring activities. A sensor entity with special properties can be used to model user-defined sensors, but this is still not sufficient since entities to model sensor networks, processing units, data storage, visualisation, etc. are not considered.

The IFC specification has been used to “virtually” model sensors that measure strain in structural elements in a building (Rio et al. 2013). For this, smoke sensors with user-defined properties were used as proxies to model vibrating wire strain gauges. Manual adjustments to the IFC files had to be made so that the files could be used in different authoring tools. The paper concludes that new types of sensors considered in IFC are needed. Correct management and visualisation of data is also important. As found in literature (Chen et al. 2014), data collected by temperature sensors embedded in concrete elements have been incorporated using specific authoring tools. In this case, Autodesk Revit has been used to model user-defined temperature sensors. Sensor data, stored in text files, are incorporated in the model and visualised in charts within the authoring tool. The data are then included in IFC files using user-defined entities.

Other standards applicable to the AEC have also been developed. The OGC develops standards that focus on facility planning, asset and emergency management, and navigation. OGC developed SensorML, which is a generic data model that describes devices and processes related to complex monitoring systems (Botts & Robin 2007). SensorML can model simulations, planning processes, alert systems, and storage and archiving systems, but it cannot describe the object being monitored. For example, SensorML has been used to model monitoring systems that, in real-time, determine a vegetation index, which categorises soil, green, and water areas using satellite imagery (Chen et al. 2012). SensorML can deal with different types of sensors, different data formats and ownership, and large amounts of data (Aloisio et al. 2006).

IFC and SensorML have been coupled together and used to model a monitoring system for buildings by Liu & Akinci (Liu & Akinci 2009). IFC was used to model the building and the location of the sensors, whereas SensorML was used to model detailed properties of the sensors. In this case, the entity *IfcSensor* was linked

with the entity *component* of SensorML. The prototype presented was able to model and visualise highly detailed sensors in buildings.

EXTENSION TO THE IFC SPECIFICATION TO MODEL STRUCTURAL MONITORING SYSTEMS

The objective of the proposed extension is twofold: (i) to facilitate a better description of structural monitoring systems in BIM models of built assets and (ii) to enable the use of the modelled systems in the automation of structural performance monitoring tasks and to support decision making. Therefore, rather than just adding new enumerated types of *IfcSensor* and adapting other IFC entities for alternative uses than for which they were initially intended, a comprehensive approach has been taken to propose amendments to various schemas of the IFC specification.

The extension has been developed based on the investigation of the current IFC specification, common practices and minimum requirements for modelling monitoring systems, and on SensorML capabilities (Botts & Robin 2014). Data related to physical aspects, processes, and sensor data needs to be modelled to fully describe a monitoring system. For that reason amendments to the following IFC schemas have been proposed: *IfcProductExtension*, which defines physical elements in a building; *IfcProcessExtension*, which maps processes related to the entire life cycle of a building; *IfcControlExtension*, which defines entities to control elements and processes; *IfcSharedBldgServiceElements*, which defines general entities for flow and distribution systems; *IfcBuildingControlsDomain*, which defines specific entities for building automation, control, instrumentation, and alarm; *IfcSharedMgmtElements*, which considers general entities to model management and operation tasks.

Figure 2 shows a diagram of selected IFC4 entities. Entities required to model a structural monitoring system are shaded in light grey and the newly proposed and amended entities are shaded in dark grey. As depicted in Figure 2, the IFC specification uses a hierarchical approach, in which the entity *IfcObject* defines any process, physical element, or abstract concept. It has five subtypes. The subtype *IfcProduct* has in turn the subtype *IfcElement*, which is used to represent any physically existent thing. The subtype *IfcGroup* has in turn the subtype *IfcSystem*, which aggregates several instances of *IfcElement*. This extension proposes that *IfcDistributionSystem* would define monitoring systems, in addition to the distribution and control systems that are currently considered. “Monitoring” is proposed as new predefined enumerated type, which will be used to group elements used for monitoring tasks; its own *IfcPropertySet* is also considered. In the IFC4 specification there is a generic property set for *IfcDistributionSystem*, which defines the specific instance that it relates to, and there are only two specific property sets for the Electrical and the Ventilation predefined enumerated types. This extension proposes a new property set for the Monitoring enumerated type, which will describe generic properties of monitoring systems. Special properties will be described using user-defined property sets.

Three physical components are required to model a monitoring system: sensors, a communication network, and a processing unit. The IFC specification only considers an entity to model sensors in the schema *IfcBuildingControlsDomain*, which is part of the schema *IfcSharedBldgServiceElements*. The entity called

IfcDistributionElement –a subtype of *IfcElement*– is used to describe all elements in an *IfcDistributionSystem*. It has two subtypes: *IfcDistributionControlElement* and *IfcDistributionFlowElement*. *IfcSensor* is a subtype of *IfcDistributionControlElement*. New subtypes are proposed to consider the other required components: *IfcMntCommNetElement*, which is used to describe elements in the communication network of a monitoring system e.g. cables, wireless receivers, etc. *IfcProcessingUnit*, which defines the unit that computes the acquired raw data; and *IfcMntGenericElement*, which is a user-defined entity. The other existing subtypes of *IfcDistributionControlElement* are shown in Figure 2.

New predefined enumerated types for *IfcSensor* and their corresponding property sets are proposed as well; these are: Strain Sensor, Fatigue Sensor, Corrosion Sensor, Acoustic Sensor, Optical Sensor, Accelerometer, Inclinometer, Fibre Optic Continuous, and Fibre Optic Discrete. This new set of enumerated types has been compiled by investigating the most commonly used types of sensors used in existing structural monitoring systems. A complete list of the existing predefined enumerated types and property sets of *IfcSensor*, in IFC4, is given by Liebich et al. (2013). Note that *IfcSensor* inherits all the property sets available for objects; therefore instances of *IfcSensor* can take any physical representation and local placement available in the extensive IFC specification.

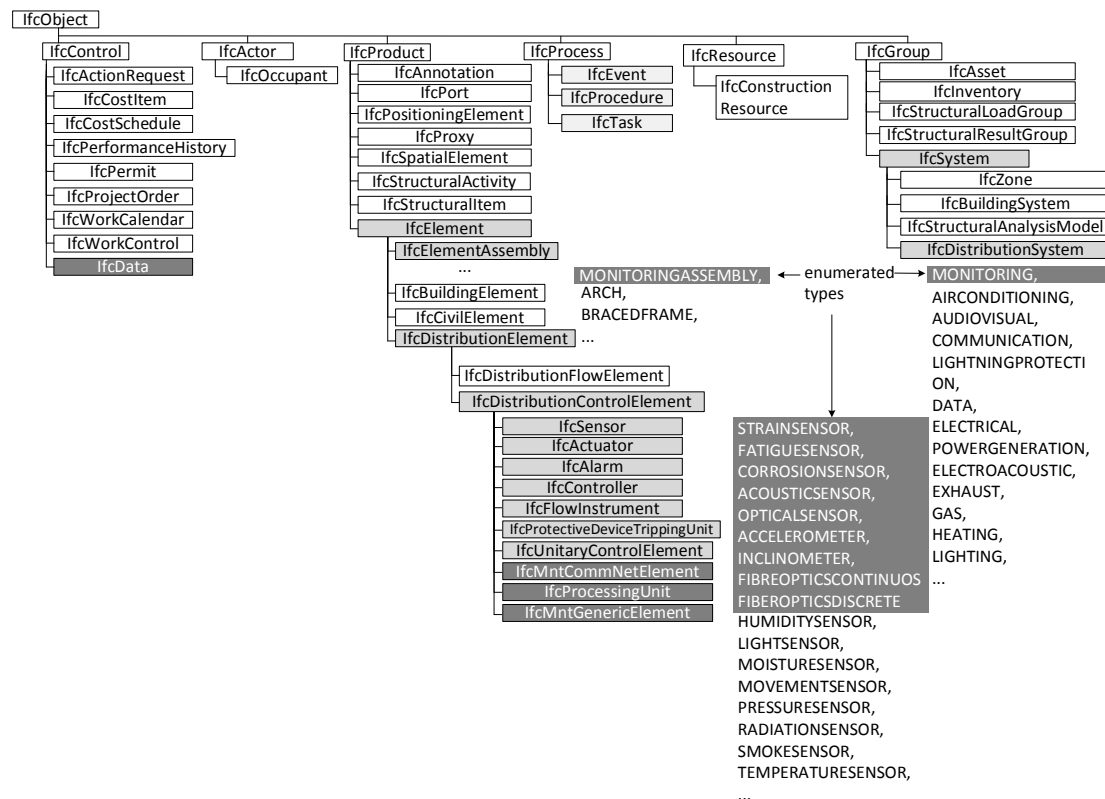


Figure 2. IFC entities required to model a structural monitoring system

The entity *IfcElement* also has the subtype *IfcElementAssembly*, which is used to describe complex aggregations of *IfcElements* of different subtypes. It is proposed

that the new enumerated type “Monitoring Assembly” is included. This will allow to aggregate together elements from different subtypes, e.g. *IfcBuildingElement*, *IfcCivilElement*, and *IfcDistributionElement*, to model parts of a complex monitoring system. In other words, the intention is that an *IfcDistributionSystem* of type Monitoring would be composed of various instances of *IfcElementAssembly* of type Monitoring Assembly, which in turn would be composed of various instances of the subtypes of *IfcElement* such as *IfcSensor*, *IfcController*, *IfcAlarm*, etc. (see Figure 4).

Regarding monitoring processes, the subtypes of the entity *IfcProcess*, shown in Figure 2, are also needed to model a structural monitoring system that can be used to aid in SHM tasks. As their names indicate, *IfcEvent* describes something that triggers an action; *IfcProcedure* is a set of logical actions; and *IfcTask* is a basic action. New entities are not required in this schema and only existing or user-defined enumerated types, of each subtype, would be required to model and to aid in automating SHM tasks.

Lastly regarding sensor data, *IfcData* is proposed as a new generic subtype of the entity *IfcControl* to store data of different types. This new entity will aid in the visualisation of sensor data to support decision making. The enumerated types of *IfcSensor* are sufficient and flexible enough to store data acquired by structural sensors; nevertheless, other types of data, or data formatted differently, are sometimes required, e.g. analytically or numerically predicted values, baseline readings, graphs and colour maps, etc.

CASE STUDY

A case study is presented, in which a monitoring system that uses continuous and discrete fibre optic cables is modelled using the proposed extension. Preliminary properties sets are defined to show the applicability of the extension. Nevertheless, to develop definitive property sets, for each enumerated type, the use-case approach (Hietanen 2006) and Information Delivery Manuals (Eastman et al. 2010) should be applied; these methods ensure that all the necessary data is considered for a successful and robust exchange of information. Note that the parts of the extension regarding *IfcProcess* and *IfcControl* and the proposed amendments that will enable the visualisation of monitoring data directly on the BIM model and the automation of SHM monitoring tasks, fall outside the scope of this case study.

A fibre optic structural monitoring system that has been installed in the James Dyson Building (JDB), at the Engineering Department of the University of Cambridge, is presented as a case study. The amended IFC specification has been used as basis to model the monitoring system. The objective of the case study was to test the proposed amendments and to showcase the possibilities of including monitoring systems and sensor data on a BIM model.

The structure of JDB consists of a four-storey cast in-situ reinforced concrete frame and slabs. DFOS cables and FBG sensors were attached to reinforcement bars in selected columns, beams, and slabs prior to the casting of the concrete (see Figure 3). The objectives of the installed monitoring system are (1) to monitor any long-term performance changes or trends that could occur in the concrete structure throughout the lifetime of the building, and (2) to serve as a hands-on “living classroom”, where

students at the Engineering Department can observe the behaviour of the structure for different loading conditions.

Figure 4 shows a non-exhaustive diagram of the hierarchy of the modelled fibre optic system. It also includes common property sets for the entire monitoring system, which defines attributes regarding the type of monitoring system (e.g. fibre optics, acoustic, corrosion, etc.) accepted thresholds and alarms; the monitoring assemblies, which defines subtypes of monitoring systems (e.g. DFOS or FBG for fibre optic systems); and a property set for sensors that would allow to activate an alarm in case a value is outside a defined threshold. Note that various property sets can be assigned to single IFC entities, allowing to further extend the attributes that can be attached to the given IFC entity.

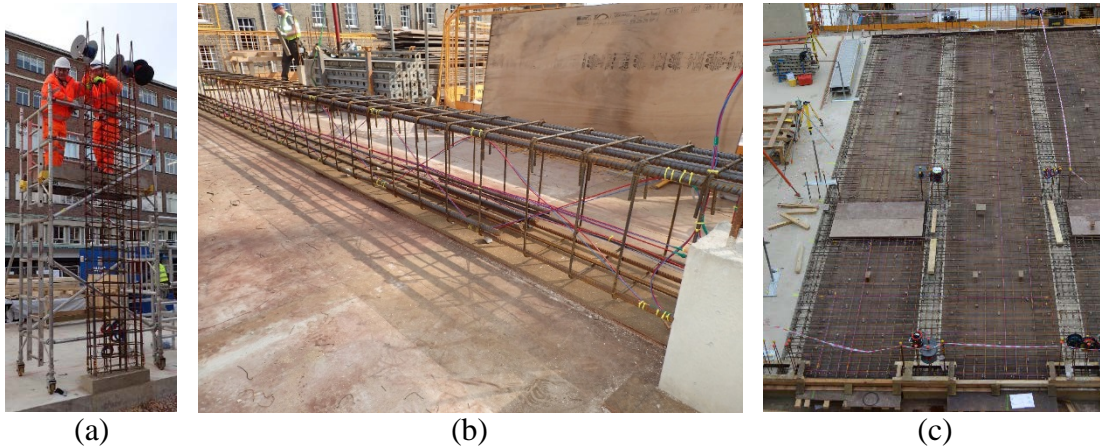


Figure 3. Fibre optic cables attached to reinforcement bars in (a) columns; (b) beams; and (c) slabs.

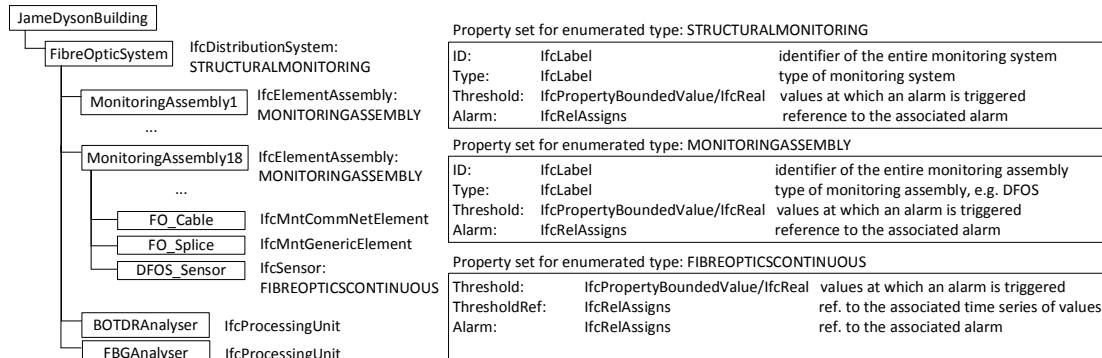


Figure 4. Diagram of the hierarchy of the modelled fibre optic system for the James Dyson Building

The left side of Figure 5 shows a diagram of the fibre optic monitoring system installed in the JDB. The monitoring system is subdivided in various monitoring assemblies. DFOS cables have been installed in three columns located on an axis transversal to the long side of the building (see Figure 3a). The cables have been installed along the entire height of the columns, on the four vertical corner reinforcement bars of one column, and on two of the vertical centre reinforcement

bars of the other columns. This assembly seeks to measure strain due to axial forces and bending moments in the three columns. A two-span beam at the second floor level, along the same axis as the instrumented columns, has also been instrumented with two different sets of DFOS cables. One set is to measure strain due to bending, for which cables have been placed along the top and bottom reinforcement bars on one side of the beam; the other set is to capture shear strain, for which the cables have been installed diagonally along the other side of the beam (see Figure 3b). A set of FBG sensor cables to measure temperature and bending strain have also been installed along the reinforcement bars at the top and bottom of the beam, with 16 FBG sensors at one meter intervals on each cable. Lastly, DFOS cables have been installed in a two-dimensional grid pattern on the top and bottom reinforcement of the slab bays on either side of this beam (see Figure 3c). These cables are intended for measuring bending strain in the slab in the direction of, and perpendicular to, the span.

In the top-right part of Figure 5, a diagram shows selected assemblies of the sensors installed in the beam and columns. For example, the monitoring assembly “Cols_DFOS_Temp_1” –that measures temperature– is composed of 4 instances per column of *IfcSensor* of enumerated type Fibre Optic Continuous.

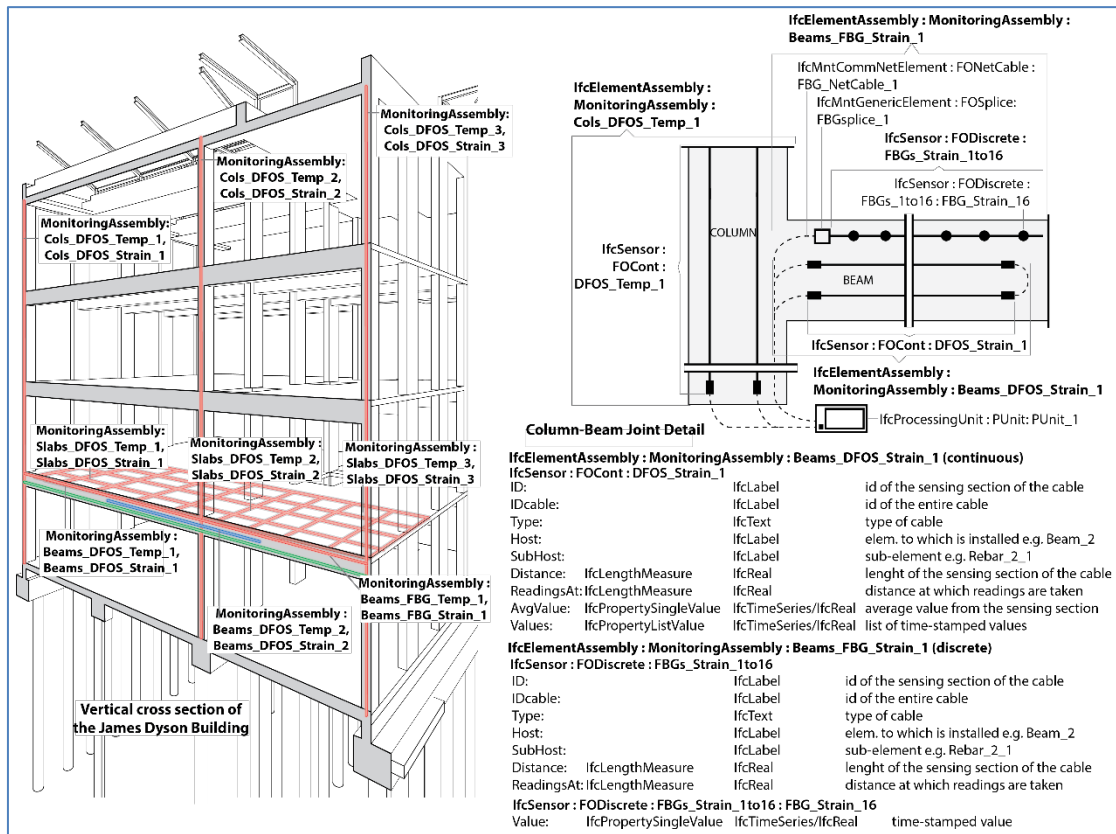


Figure 5. (Left) Diagram of the fibre optic monitoring system; (Top-right) detailed diagram of DFOS and FBG sensors in columns and beams; (Bottom-right) examples of property sets for DFOS and FBG sensors.

In the detailed diagram of the beam in Figure 5, continuous and discrete instances of fibre optic monitoring assemblies are presented. Note that only certain sections of the cable are used to take measurements; these sections are represented by bold lines, which are modelled with instances of *IfcSensor*. The dashed lines represent parts of the cable that only serve as connection between cables, these are modelled with instances of *IfcMntCommNetElement*. The monitoring assemblies are composed of both types of cable sections. The continuous monitoring assembly is composed of two sensing sections of cable. Note that for the continuous assemblies the cables require to be installed forming a closed loop. The discrete sensor is represented by a line with circles that indicate the positions where the FBG sensors are located, which is where the discrete measurements are taken. A nested instance of *IfcSensor* of type Fibre Optic is used to model all the point sensors in the FBG cable. Nested entities allow to create an aggregation of several IFC entities of the same type. In this case, an instance of *IfcSensor* that represents a section of a FBG cable is composed of 16 instances of *IfcSensor* that represent the sensors in that section of the cable. This diagram also shows the use of the other newly proposed IFC entities, *IfcProcessingUnit* and *IfcMntGenericElement*, which in this case is used to model a splice (connection) between cables.

In the bottom right part of Figure 5, the property sets of a continuous and a discrete fibre optic sensor are presented. For the continuous sensor the following is recorded: the length of the sensing section of the cable, the distance at which the readings are taken, the average of the acquired values, and a list of time-stamped values. The acquired values can be recorded using the entity *IfcTimeSeries*, which provides data structures to store time dependent values. Note that the processing unit generates a text file with the acquired data by the sensors, consisting only of a list of values with a time stamp. There is no explicit information regarding which values correspond to which sensor. This is deduced by the order of the list and the distance at which the readings are taken; in this way the sensed values can be assigned to their respective sensors. In the case of the discrete sensor, the length of the sensing part of the cable and the distance in between gratings are recorded in the general entity of *IfcSensor* and the acquired data are recorded in the nested entity. Note that the entire length of the cable is recorded in the property set of the respective monitoring assembly.

CONCLUSIONS AND FUTURE WORK

This paper showed that there is a lack of capabilities in the existing data models standards to describe structural performance monitoring systems. It presented an extension to the well-known IFC specification, a preferred solution to extend capabilities because it ensures robust interoperability (Ma et al 2011.). The extension, which is based on SensorML, has been developed using an overarching approach amending several schemas of the IFC schema, while trying to use the existing IFC entities as much as possible. This approach would allow to describe any other type of monitoring system with minimal additions to the IFC specification (e.g. new enumerated types).

A fibre optic monitoring system installed in the James Dyson Building at the Engineering Department of the University of Cambridge was used as a case study. Using the proposed extension it was possible to fully describe the fibre optic

monitoring system and to store the acquired sensor data, without the use of proxy or amended IFC entities. This reduces the probabilities of errors and avoids ambiguities. Additionally, the use of instances *IfcElementAssembly* of type Monitoring Assembly allows to aggregate different types of *IfcElement* facilitating the modelling of complex monitoring systems.

Additional benefits are also expected regarding the design, deployment, and operation of structural performance monitoring systems, as well as in supporting decision making. E.g. data as outputted by monitoring systems cannot be used directly and needs to be pre-processed into the correct physical quantity and units, and topological and relational metadata needs to be added. Standardised manners to organise it will facilitate automation efforts. This will be addressed in future work with the objective to aid in automating the modelling of monitoring systems, visualising the acquired sensor data directly on the BIM model, and automating SHM monitoring tasks.

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