Closing the Gap Between Concrete Maturity Monitoring and Nonlinear Time-dependent FEM Analysis through a Digital Twin. Case Study: Post-tensioned Concrete Slab of an Office Building, Barcelona, Spain

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Abstract –

This paper proposes a pipeline for the automation of data between two realms: i) simulation, in a fully nonlinear, and time-dependent structural analysis model and, ii)concrete maturity monitoring data from the construction site. The connection enables an information construct understood for its use within the Digital Twin of the building during construction phases. The pipeline requires a comprehensive coordination between stakeholders at both the site (Construction) and the structural control office, which is challenging. The pipeline consists of a) temperature sensors, b) a mobile app connected to the sensor via Bluetooth with basic instructions for data-gatherers, c) integration and interoperability of BIM, and, d) an advanced Finite Element (FE) model. By measuring the concrete temperature during many days, realistic concrete mechanical properties are inferred and infused into the FE models using adequate calibration. Two applications for the improvement of construction activities are identified. Formwork striking and tendons stressing. The paper describes the testbed of all the connections, for the construction of an in-situ casted concrete building in Barcelona, Spain.

Keywords –

Digital Twin; Concrete Maturity; BIM; Sensor-based Data; Mobile App; Nonlinear Finite Element Analysis

1 Introduction

A Digital Twin is an information construct that may include manifold pipelines from data-gathering to decision-making. In the specific realm of the built environment, it would be a data representation of the physical infrastructure that takes real-time and other data into the management processes of that real-infrastructural component, as defined by the National Infrastructure Commission in the UK, NIC (2017) [1]. It becomes the living version of a Building Information Model (BIM). Active connections between the virtual and the physical realms enable a data-driven decision-making process [2].

The level of maturity of BIM in the construction sector is significant. Nevertheless, the road to automation to deliver smarter construction services by ensuring information interoperability, a consistent use of information constructs forming the Digital Twin is required [3].

Many technological solutions for automatically monitoring construction works are available and applied commercially, anyway, this data is generally used in disaggregate manners [4]. Providing information pipelines for erecting a richer Digital Twins of an asset is a way of centralizing many potential layers of information. The ability to process and merge data from multiple sources enables a more efficient construction control [4].

This paper aims to present a case study on the digital twinning of buildings during the construction phase. Through the monitoring of concrete maturity, compressive strength evolution is predicted with sensor-based data collected from the construction site. Subsequently, a nonlinear and time-dependent finite element analysis is fed with the adequately calibrated, predicted strength evolution. Data and results are infused and visualized within a Digital Twin platform. This information is thus available for many stakeholders, i.e., construction managers. Decisions on construction tasks such as formwork striking or tendons stressing in post-tensioned and long-spanned concrete slabs can then be taken based upon a more realistic analysis. More accurate models that account for the rheology of the materials are developed to describe the time-dependent structural behavior of the concrete structure during construction.

The study is developed within the frame of the H2020 European project ASHVIN (Assistants for Healthy, Safe, and Productive Virtual Construction Design, Operation & Maintenance using Digital Twins). The purpose is to pull the digital threads and methodologies into coherent solutions to be implemented over the construction process, as well as wrapped up data systematically for further use during the life-cycle of the asset. Ten democases are under development (design, construction and maintenance phases). The particular demo case regarding this research is the construction of an office building in Barcelona.

This paper proposes a pipeline for the automation of nonlinear and time-dependent structural models with concrete maturity monitoring data from the construction site. A coherent integration of data from the site, sensors, a mobile app, FE-models, and BIM within a Digital Twin platform is presented. An assessment of how this pipeline is enabling efficient decision-making and quality control for formwork striking and tendons stressing activities is the ultimate goal of this case study.

2 The Office Building

The case study is a concrete building under construction located in the Barcelona district of Poble Nou. Currently, there are considerable construction projects under development inside this district under the umbrella of the 22@ innovation district. BIS structures, a Barcelona-based structural engineering office, together with many other stakeholders, agreed upon collaborating with ASHVIN, by facilitating access to MILE – Business Campus project construction site. MILE is an office building project of 38,093m^2, divided into three complexes: MILE-Badajoz, MILE-Llul, and MILE-Ávila. The access was provided for the specific module of MILE-Ávila, a cast-in-place reinforced concrete building of long-spanned post-tensioned slabs, consisting of eight levels, and a total area of 16,524m^2.

Figure 1. MILE Ávila office building render (Provided by BIS structures)

This case study represents an ideal scenario to define a framework for building construction digital twinning on several levels:

- The concrete casting of this building is continuous and sequential, monitoring the formwork installation process is vital for project productivity.
- The structure is heavily controlled and dependent on the slab deformation and serviceability limit states, prestressed activities play an important role in securing maximum allowable deflection.
- The construction site is located within an urban area, where space is limited and heavy traffic is constant.

Figure 2 shows the plan view of the post-tensioned slabs under study. These elements span 15.60 m plus a cantilever of 4.40 m. The transverse direction span is 5.40 m. Their cross-section height is 50.0 cm, with hollow core, and top and bottom slabs of thickness 7.5 cm. Ribs of width 38.0 cm are distributed every 1.08 m in the longer span direction. Beams are post-tensioned through single-strand tendons with a diameter of 15.2 mm, an area of 140 mm^2 and a prestress load of 195kN. The concrete class for the slabs is HP-40/B/20/IIa, defined in the EHE-08 structural concrete Spanish code [5], which is equivalent to C40/50 in the Eurocode classification.

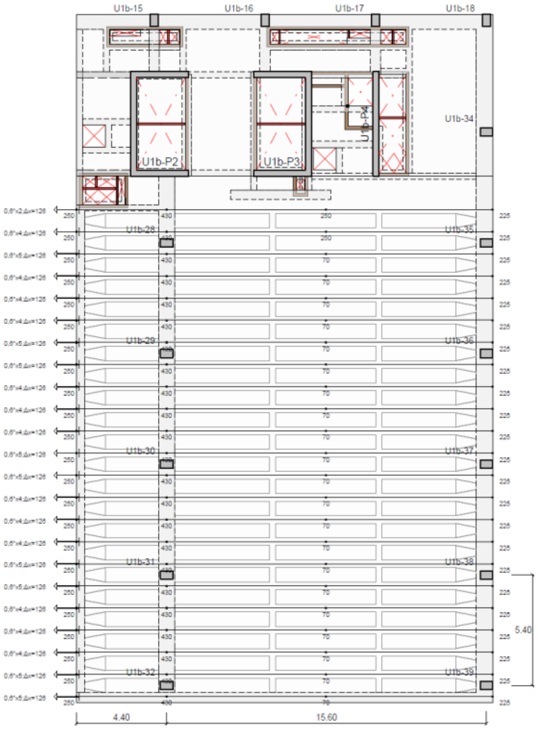


Figure 2. Mile Ávila post-tensioned long-spanned slab plan view (Provided by BIS structure)

3 Concrete Maturity Monitoring

Monitoring the concrete maturity by measuring physical variables such as temperature may provide a good estimate of the compressive strength evolution. Prediction of such properties requires a maturity method. In this section, the theory and attributes of the ASTM C1074 method are first described in 3.1. Subsequently, potential benefits of its use are pointed out in 3.2.

3.1 The Maturity Method

Maturity is the development of the physical properties of the concrete as the hydration process progresses, including the gain of strength [6].

Since the 1950s, a maturity method has been developed to estimate the early-age concrete strengths as a function of temperature and time [6]. The widely-implemented method adopted by ASTM C10741 [7], which assumes a nonlinear relationship between concrete temperature and the rate of development of concrete properties [8], defines an equation to calculate the maturity index:

$$t_e = \sum_0^t e^{\frac{-E}{R}\left(\frac{1}{T}-\frac{1}{T_r}\right)} \Delta t \tag{1}$$

Where t_e is the equivalent age at the reference temperature, E is the apparent activation energy, R is the universal gas constant, T is the average absolute temperature of the concrete during interval Δt, and T_r is the absolute reference temperature.

According to ASTM C1074, the relationship between concrete strength (S) development vs time (t) can be determined for a particular concrete mix, using Carino's hyperbolic equation, as modified by Knudsen [9]:

$$S = S_u \frac{\sqrt{k(t-t_0)}}{1+\sqrt{k(t-t_0)}} \tag{2}$$

Where S_u is the ultimate compressive strength, t_0 is the initial time due to the compressive strength development, which corresponds to the time of hydration heat increase, and k is the reaction constant.

Implementing the maturity method provides data nearly immediately and does not involve transporting samples or the management of crushing deadlines [10]. It requires calibration and it is mix-dependent. The model cannot be extrapolated to considerable changes within the mix that may occur in subsequent concrete batches.

Currently, sensor-based techniques are accessible for measuring and monitoring temperature in the interior of the concrete during the curing process. For instance, *SmartRock2, TM TEMPCON or CONCRETE SENSORS* are some of the brands available in the market [11].

Yikici et al. developed a wireless real-time monitoring system for concrete maturity calculation, which predicts the compressive strength of steam cured precast concrete, in addition, an IoT technique continuously compares measurements to expected values and sends emails notifications to production engineers [12].

For the prediction of long-term strengths, the existing maturity equations do not provide a good estimation. This model only considers the chemical reaction as the only affecting process [13], however, it is relevant for construction operations.

3.2 Advantages in construction activities

3.2.1 Formworks Striking

The cost of formworks for casted on-site constructions of concrete buildings is significant. For most structures, the time and cost required to erect, and strike the formwork is greater than the time and cost to place the concrete or reinforcing steel [14]. Formworks are often rented, representing the largest single cost component of a structural frame building construction. It varies between 35 and 45% of a reinforced concrete structure's unit cost [15].

Monitoring the temperature of the concrete at early ages allows predicting the compressive strength evolution. This information can be used to reduce the striking time of the formwork [16-17]. Idle time can be minimized and decisions can be taken using real data. For this purpose, an adequate framework that intertwins production, cyber-physical systems, and digital and computing technologies is required.

3.2.2 Tendons Stressing

During the construction of the post-tensioned concrete slabs, the post-tensioning of the tendons must not be initiated before the concrete reaches the transfer strength specified by the structural project engineer [18]. According to ACI 318-19[19], compressive strength must be at least 17,5 MPa for single-strand or bar tendons, and 28,0 MPa for multistrand tendons. To verify the early age strength of the concrete, samples shall be tested, securing storage and curing conditions similar to those of the in-situ concrete [19].

Adequately calibrated concrete maturity functions prove to give reliable strength development data. This has the potential to simplify the procedure of prediction of the strength and monitor the development on post-tensioned concrete slabs [20].

Luke et al. [21] investigated the ability of the maturity method to predict the prestressing release strength for steam cured precast/prestressed concrete box beams, comparing the compressive strength of several companion cylinders with the one obtained using the maturity method, which led to accurate results. A set of recommendations was proposed to reduce the number of test cylinders.

4 Methodology

An automated pipeline framework (Fig. 3) is proposed in this study. An information construct that adds a decision-prone layer to the Digital Twin of the building is proposed. The pipeline connects nonlinear time-dependent FE models with concrete monitoring data for cast-in-place reinforced buildings during the construction phase. The rheology of the material is thus considered within the time-dependent structural analysis.

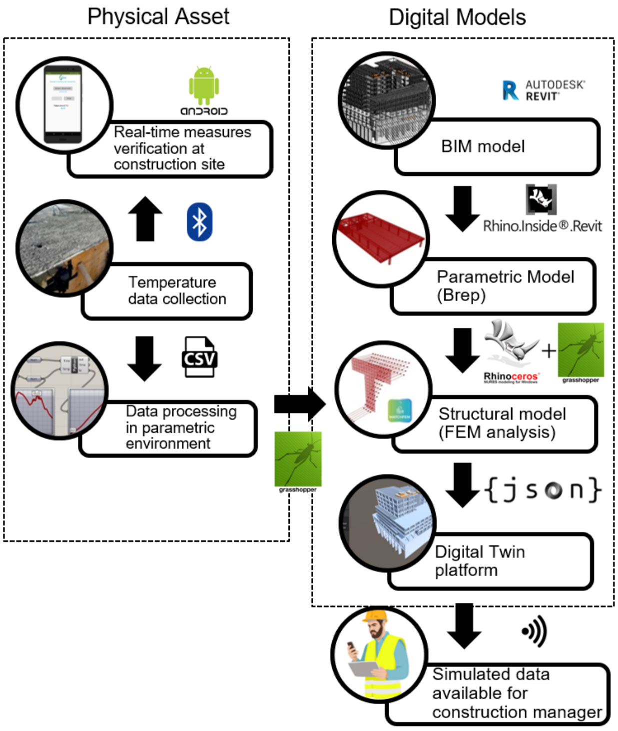


Figure 3. Proposed automated pipeline

4.1 Temperature data collection

For this study, prototypes for data acquisition were developed. Electronic prototyping platforms allowed tailor-making of the data flow. Two different types of temperature measuring sensors were used to collect data from long-spanned slabs. The first sensor type was a thermocouple K-type sensor with a range from 0ºC to 400ºC and an error of ±2.2ºC, connected to a MAX6675 module that transforms the analog signals to digital, two units of this sensor were used. The second sensor type was a DS18B20, a waterproof digital sensor that uses a Wire-1 protocol to communicate and measure temperature in a range between -55ºC to 125ºC with an error of ±0.5ºC. The energy was supplied by power banks of 5000mAh. The sensor data was saved on an SD card for further processing. A Bluetooth HC-05 ZS-040 shield sent data to mobile phones for real-time values verification. All these components were plugged and synced to an ESP32 SoC (System on Chip) module through the Arduino IDE (Integrated Development Environment) platform. These hardware modules represent a cost-effective tool with open prototyping capabilities.

Figure 4. DS18B20 hardware module installed during concrete slab pouring

The locations of the sensors are shown in Figure 5. Access during the concrete pouring of the slab was restricted. Sensors were mounted in the allowable areas and fully embedded in the concrete mix to avoid interference with ambient temperature. There is a margin of improvement when it comes to the number of sensors as well as their location for capturing more adequate data. In this particular case, due to the site restrictions, a limited amount of points were set.

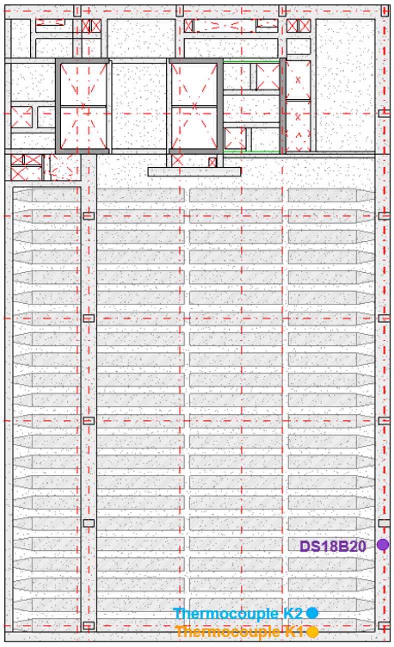


Figure 5. Sensors' locations at building top slab (Image extracted from the BIM provided by BIS structures)

Figure 6 shows data collected from sensors. Temperature evolution was recorded for 34 hours by Thermocouples K and 30 hours by DS18B20 sensor.

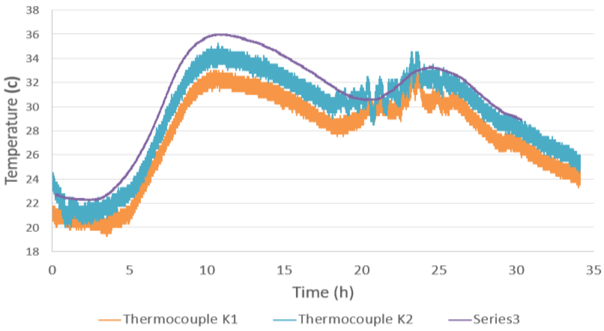


Figure 6. Data collected from temperature sensors

4.2 Real-time temperature verification

A Mobile App was developed to retrieve real-time data from the sensors via Bluetooth (BT) at the construction site. The app was conceived for its use by non-technical staff, with a user-friendly and simple interface. The open prototyping environment also allowed embedding BT protocols. The app was developed using the MIT block-based coding online platform App Inventor, which consists of an intuitive visual programming environment (IDE) for developing Android-based applications [22].

Temperature(°C)
20.75

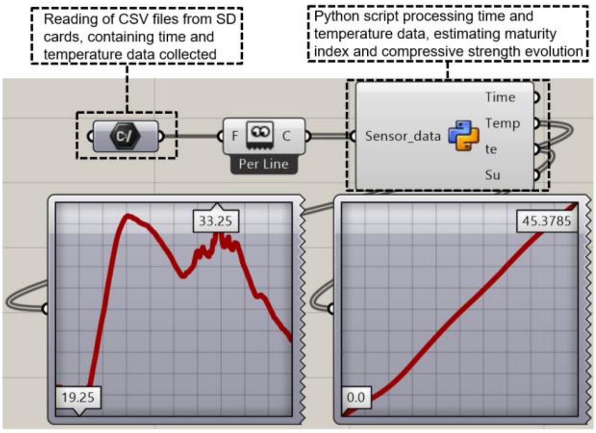
Figure 7. Android-based mobile application developed

The Bluetooth communication between sensors and the mobile app is performed through the HC-05 shield connected to the ESP32 SoC. The data received at the time interval defined by the user can be stored in a CSV file together with a time stamp.

4.3 Data processing

Concrete temperature history is the input data to calculate the maturity index (Eq.1). This leads to predicting the compressive strength evolution by computing values in the calibrated graph of strength vs. maturity index. This graph is obtained through laboratory testing following the instructions of the ASTM C1074 [7], the results are valid for a particular concrete mix.

The temperature sensors data, stored as CSV files in the SD cards of the hardware modules, is transferred to Grasshopper, in which a developed Python snippet allows estimating the maturity index. Using the temperature data, and predicting the concrete strength evolution within the parametric environment (Fig. 8).


Reading of CSV files from SD cards, containing time and temperature data collected

Python script processing time and temperature data, estimating maturity index and compressive strength evolution

Figure 8. Data processing in a parametric environment (Grasshopper 3D).

4.4 From BIM geometry to FEM structural model

BIM is called to implement a digital track of the building and infrastructure. In this way, BIM significantly improves information flow between stakeholders involved during design and construction phases [23].

The Digital Twin is called to implement a digital track of the building and infrastructure during the entire lifecycle of the asset. This living BIM model becomes useful at all stages (design, construction and operation).

BIS structures provided the BIM structural model for MILE Ávila on Revit 2019. No architectural information was supplied, rebar detailing was retrieved from sheets for retaining walls, slab foundations, floor slabs, and beam active reinforcement. The building was primarily conceived for cast-in-place concrete. The BIM model is classified as LoD (Level of Development) 350.

Using Rhino.Inside.Revit, a Grasshopper plug-in, parametrics models were built. It was thus possible to access the topological components of a three-dimensional Brep (body, face, edge, and vertex). This option enables the model for the further discretization of cross-sections to perform elastic or inelastic analysis (Fig. 9).

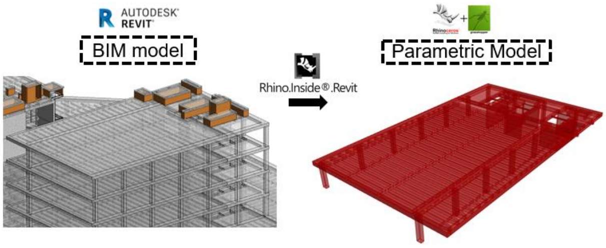


Figure 9. From BIM model to top floor slab parametric model

Having access to the components of Brep (Boundary Representation), the discretization is enabled and calculations are performed using one of the methods developed within MatchFEM. MatchFEM is a tool under development within ASHVIN. Data collected from the sensors, processed in the same parametric environment will feed the FE-models.

4.5 Finite Element Numerical Model

The maturity method estimates with accurate precision the development of the concrete compressive strength as a function of time (see section 3). This information is embedded within the time-dependent analysis. Since one of the purposes of the study is to monitor structural behavior during a construction process, the application of loads and boundary conditions change over time as part of an evolutive construction sequence.

To process accurately the conditions of the construction sequence, structural elements are calculated based on the numerical model of nonlinear and time-dependent analysis for three-dimensional reinforced, prestressed, and composite concrete, developed by Marí [24].

The mathematical model is based on frame finite elements with six degrees of freedom per node. Each element has a length and a prismatic cross-section discretized in filaments, which have a material (concrete or steel) associated and are geometrically defined by their area and position with respect to the sectional local axes.

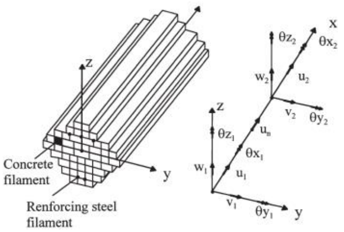


Figure 10. Filament frame element. (Source [24])

For two different materials, strain compatibility exists, therefore, perfect bond is assumed. The plane strain principle is implemented, consequently, is satisfied for mechanical and nonmechanical strains:

$$\Delta\varepsilon(z) = \Delta\varepsilon_m - z * \Delta c \qquad (3)$$

Uniaxial stress-strain constitutive models are applied for concrete, active and passive reinforcement, including the rheology of the materials. Loads are imposed to the nodes on specific instants, being able to introduce load increments, allowing a step-by-step analysis over time. Prestressing loads are introduced as an equivalent load vector obtained by balancing the forces of the prestressing tendons [25].

This numerical model was the base for the development of a computer program called CONS, which presents great computational efficiency.

MatchFEM, one of the tools under development for the ASHVIN project digital toolkit, will implement several methods to stochastically adjust input parameters for multi-physics simulations using sensor-based measurements. The aim is to accurately represent many layers of behavior within the Digital Twin of the asset. In this particular case, to perform the structural analysis, MatchFEM benefits from the efficiency and accuracy of CONS and levels up to a powerful graphical environment through parametric design tools such as Rhino and Grasshopper. Notwithstanding, the information construct is conceived for proper interoperable models based on IFC (Industrial Foundation Classes). Sensors, FEM analysis and geometries can be then matched seamlessly.

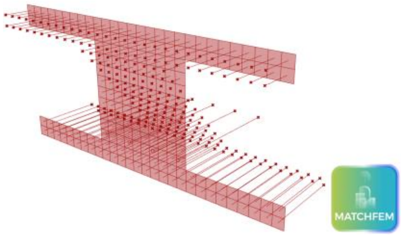


Figure 11. MILE-Ávila top slab cross-section filaments model in MatchFEM tool.

4.6 Digital Twin platform

Within the ASHVIN project, a game engine based Digital Twin platform is under development. It is conceived for enabling connectivity, device management, data acquisition and embeddedness of the different tools. The ASHVIN platform will allow for plug-and-play connectivity with a wide range of devices and real-time data processing functionality. First, the incorporation of as-designed data from BIM models is necessary. An IFC standard format or open file format can be converted to the platform together with all BIM metadata.

Simulated data from the Grasshopper software via MatchFEM ASHVIN tool is converted to JSON string. As a result, visualization of the proper physical behavior of the Digital Twin is possible, including the temperature history, maturity index, concrete strength evolution, and the nonlinear time-dependent FEM analysis.

Figure 12. Simulated data to Digital twin platform to Construction Manager

Construction managers can track the evolution of realistically fed models of sequential constructions. With such information, it may be possible to take decisions on construction activities, such as formwork striking or stressing of tendons.

5 Discussion

This section summarizes the advantages and challenges of the proposed methodology.

5.1 Automation advantages

The result of the automated pipeline is a digital asset that holds the physics behavior data history of a real building structure at the construction phase. This information is assembled in a Digital Twin environment, where is available in a user-friendly graphical interface. Construction managers can benefit from the Digital Twin for a more data-driven decision-making process.

Applying isolated concrete monitoring systems without an active connection between the real asset and the digital models could lead to deficient data management and increase data loss risk, reducing their impact on construction activities.

In addition, Digital Twins store data for long-term use, therefore, owners or stakeholders have access to the physics history of the structure and could use this information for future interventions or maintenance plans.

Particularly for the case study, prestress activities were planned to start after 5 days of concrete curing time. Maturity index results showed that stressing of tendons could initiate at least one day earlier. Hitherto, data collection time was not enough to evaluate formwork striking.

5.2 Methodology implementation roadmap

Following, limitations, lessons learned, and future work are gathered to establish a roadmap for the implementation of the proposed methodology:

- The hardware modules used for data acquisition had a limited energy supply and a restricted mounting process. Future works based on integrated existing commercial sensor-based maturity monitoring systems are needed (see section 3.1), capable of sending data wireless being completely embedded in the concrete mix, enabling installation before the slab pouring to avoid interference with the activity.
- As defined by Carino [9], sensors must be mounted at locations with critical exposure or structural requirements. Project engineers must define the numbers and locations of sensors for each slab. For this research, locations were limited to accessible areas. The accuracy of the predictive model requires profuse data collection. However, this may not be possible due to site conditions. In this case, cylinder samples shall be taken.
- The development of procedures for sending data directly from the sensor to an IoT platform and then into Grasshopper, will improve the data flow and avoid human intervention.
- Traditionally, for the quality control of the concrete compressive strength, many cylinder samples are tested. The ASTM C10741 procedure has the potential to reduce cylinder testing, as it only requires crushing samples for a particular concrete mix [7]. Nevertheless, owners and stakeholders have to agree upon accepting concrete maturity as the method for quality control to have a real impact in striking formwork or prestressing activities.

6 Conclusion

A comprehensive pipeline for automation of nonlinear and time-dependent structural models with concrete maturity monitoring data from the construction site was proposed, describing the integration of the BIM model provided by the owner, the hardware modules for sensor-based temperature data, a mobile app for real-time values verification on the construction site, the finite element model analysis fed by the evolution of the concrete compressive strength at early ages, and the incorporation of the results into a Digital Twin platform. The implementation of this framework has the potential to improve the decision-making and quality control for formwork striking and tendons stressing activities.

The developed methodology paves the way for the application of Digital Twins of buildings during the construction phase, with an explicit active connection between digital models and the physics of the real asset.

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