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Continuous monitoring of concrete *E*-modulus since casting based on modal identification: A case study for in situ application

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ABSTRACT

An in situ application of a recently developed technique for continuous measurement of concrete *E*-modulus since casting is addressed in this paper. Such technique is based on the continuous modal identification of a composite beam that contains the material under test. As concrete hardens, the flexural resonant frequency of the beam increases and the computation of *E*-modulus can be made with recourse to the beam's equation of motion. Even though recent publications have shown the feasibility of this technique in laboratory environment, no actual in situ application has been tested so far. That is one of the topics of this paper, which also proposes improvements to the originally devised method and compares results with ultra-sound wave velocity measurements. The scope of the work is extended with the modal analysis of a prefabricated beam made of the same concrete under test, allowing insights to be made regarding the *E*-modulus of concrete.

1. Introduction

The quality control of in situ applied concrete is of extreme importance, and it is usually carried out with recourse to compressive strength testing of cubic or cylindrical concrete samples (according to EN12390-3:2009 [1]), at a range selected ages to assess that the desired performance criteria are met (e.g. a concrete grade according to EN1992-1:2010 [2] has been achieved). This methodology cannot provide the engineer with continuous information about the mechanical properties of concrete, as the destruction of the specimen is required to obtain data, and a limited number of specimens is usually available. However, the availability of continuous information about concrete mechanical properties through non-destructive methodologies would be desirable, because of two main reasons: (i) on one hand, it would avoid the necessity of conducting a "new test" to get an updated result, as the results would be fed continuously to the user; (ii) on the other hand, the continuous information obtained could provide accurate estimations of the instant in time at which a certain performance criterion would be met, and therefore allow construction decisions to be made in advance, and material/workmanship be relocated as a function of the expectable behaviour of the material (e.g. know at the age of 36 h that the target compressive strength of concrete will be met at the age of 64 h, and therefore adapt the construction schedule accordingly). This second point is of paramount importance in view of the increasing pressure of owners for tight construction schedules, as well as the indirect cost savings associated to a faster construction (e.g. less rental time of heavy equipment; smaller times for interruption of traffic, etc.).

One of the most widespread techniques for overcoming the mentioned shortcomings of traditional compressive testing is the maturity method [3,4], which demands a full characterisation of the mechanical property evolution and activation energy of the concrete mix in laboratory beforehand, but allows continuous estimations of the mechanical properties of the actually placed concrete with basis on the "in situ" measured internal temperature. This temperature information is used together with the reference mechanical properties previously obtained in laboratory, whose evolution is corrected for chemical activation effects, thus allowing an estimate of the actual mechanical property at the location of the temperature sensor. The fundamental drawbacks of applying the maturity method rely on the fact that a preliminary laboratory characterisation is required, and also on the fact that temperature is a physical measure that is not directly related to the mechanical properties. Actually, if the concrete composition applied in the construction deviates from that which was previously characterised in

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laboratory, thus jeopardising the applicability of the maturity method, the temperature monitoring results do not warn the engineer to such problem, thus possibly conducting to the use of misleading information through the maturity procedure.

The in situ continuous assessment of mechanical properties of concrete since its early ages has also been accomplished in the past with recourse to indirect estimation through Ultra-Sound Pulse Velocity (UPV) measurements (either through transmission or reflection probes) [4–7]. A specific remark is also given to the UPV measurement method based on wave reflection, which solely demands access to one side of the concrete hardening structure [8]. This approach (UPV measurement) allows overcoming part of the problems associated to the maturity method, as it is feasible to consider that the speed of wave transmission/reflection is more intimately related to the mechanical properties of concrete than temperature development. Even though several works have been devoted to in situ application of the UPV measurements for assessment of mechanical properties, with successful measurements, several limitations should be kept in mind: (a) the relationship between measured speeds and the mechanical properties of concrete (namely static *E*-modulus), are often of a qualitative rather than quantitative nature (e.g.: the wave speed can be theoretically related to the dynamic *E*-modulus, whose relationship to the static *E*-modulus does not have an undisputable definition [9]); (b) the application of the theoretical background that relates wave speed to the dynamic *E*-modulus of concrete can be considered arguable, as the equations used for such purpose were derived for isotropic homogeneous materials at the scale of the wavelength [8,10,11].

It is also worth to mention the relatively recent attempts to perform continuous estimates of mechanical properties of concrete with recourse to the measurement of dielectric properties [12,13]. Even though the basic principle of this methodology is quite interesting, it still carries the shortcoming associated to the maturity method of requiring a previous study of the relationship between the dielectric properties and mechanical properties in order to obtain quantitative information.

In view of the acknowledged difficulties of existing solutions, recently, a method for continuous measurement of concrete *E*-modulus based on modal identification of a simply supported composite beam (tube of acrylic internally filled with the concrete to be tested) has been proposed by Azenha et al. [14] and it is termed EMM-ARM (Elasticity Modulus Measurement based on Ambient Response Method). The method basically consists in casting the fresh concrete into a 2 m long acrylic tube, with inner/outer diameter of 92 mm/100 mm, which is in turn placed in simply supported conditions. The resonant frequency of the resulting composite beam is continuously monitored throughout time with recourse to output-only identification techniques (meaning that no direct excitation is applied or measured to the beam, and ambient vibrations are enough to allow proper modal identification). As a consequence of cement hydration, concrete hardens along time, and the resonant frequency of the beam starts increasing accordingly. At each instant, the monitored resonant frequency of the composite beam is used to provide the value of the concrete *E*-modulus, through application of the beam's equation of motion. This allows obtaining a continuous curve for the evolution of *E*-modulus of concrete along time, in a fully automatic fashion, without the necessity of any human intervention or control. These are quite interesting features in view of the desirability of having a continuous measurement method that allows gathering results since casting, as mentioned in the previous paragraphs. The good prospects in application of EMM-ARM to concrete also led to the successful downscaling of the methodology, making it suitable for the study of cement pastes [15,16].

The pilot application of EMM-ARM in laboratory environment for concrete [14] has allowed checking its repeatability, as well as the coherence of its results in regard to those obtained from compressive cyclic testing of concrete cylinders. It was however acknowledged that the type of modal identification technique involved made the methodology prone to disturbances caused by surrounding vibrations, which could possibly represent a limitation in view of in situ application. The main purpose of the present research was to show that EMM-ARM can be used in actual construction environment. For that reason, a pilot experimental program was conducted in a pre-fabrication plant. This experimental program also involved additional contributions to the understanding and test setup of EMM-ARM, such as: (a) implementation of a new test mould, suitable for larger aggregate sizes, and re-usable (as opposed to the case of the original EMM-ARM version); (b) comparison of results with the results obtained through US transmission probes; and (c) comparison of results with those obtained from a precast concrete beam cast with the same tested concrete.

As far as the organisation of this paper is concerned, Section 2 deals with issues regarding the EMM-ARM, with a general description of the original implementation and the proposed modifications in the scope of the present research. The experimental program that was carried out is described in Section 3, whereas the corresponding results and discussions are addressed in Section 4. Section 5 closes the paper with the main conclusions and future developments of the research work.

2. EMM-ARM

2.1. General description of the original implementation

The present section aims to provide brief and basic information about the original implementation of EMM-ARM, namely in regard to its geometry and experimental procedure, in view of its application in the scope of this paper. For deeper information on EMM-ARM, the reader is directed to Refs. [14,17]. The basic unit of the test specimen is the mould, which is a transparent acrylic tube, as shown in Fig. 1. Before actually casting concrete inside the tube, some preparations are necessary. Firstly, two horizontal rods are placed through holes near the extremities of the beam, in order to materialise simple supports for a 1.80 m span beam. Five vertical rods are also inserted into the beam, evenly spaced in its longitudinal direction, performing as connectors and improving composite behaviour. The mould also comprises two extremity lids, one of which is kept fixed, and the other one is removable for casting operations. Casting of the specimen is made with the mould in an inclined position, until complete filling is achieved (with the mould placed vertically) and the top lid is fixed in place. It should be stressed that the shape and length of the acrylic tube poses difficulties in casting specimens of ordinary concrete. The pilot experiments have actually been conducted with self-compacting concrete in order to avoid problems in the casting procedure, or the occurrence of air voids in concrete. After casting is finished, the composite beam is placed horizontally and simply supported on its extremity rods. An accelerometer is attached to the mid-span of the beam, and acceleration measurements start within a period of less than 20 min from the beginning of casting operations. Based on the measured accelerations, and assuming that environmental vibrations behave on average as a white noise (i.e. with similar energy content within all the frequencies of interest), modal identification is performed with recourse to the Welch-procedure [18] and the peak-picking method [18]. Detailed information on the application of these procedures in the scope of EMM-ARM can be found elsewhere [16,17]. Even though this is a quite simple modal identification technique, it has shown a good performance in the pilot EMM-ARM experiments, allowing a continuous plot of the evolution of the resonant frequency of the composite beam (which naturally evolved in correspondence to the hardening of concrete).

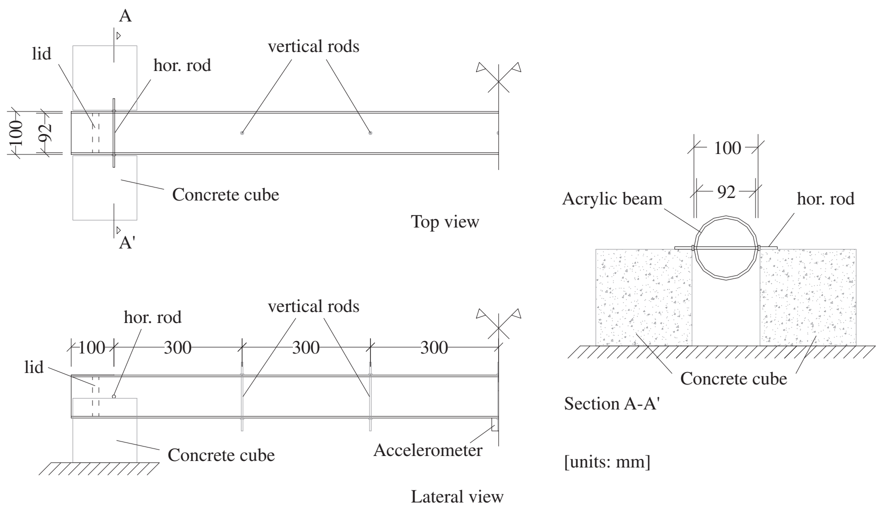

Fig. 1. Overall scheme of the original implementation of EMM-ARM.

The next stage in the application of EMM-ARM consists of transforming the identified evolving resonant frequency along time, into the estimated evolution of the *E*-modulus of the tested concrete. Assuming homogeneous isotropic materials, for a simply supported beam with the first flexural resonant frequency *f*, free span *L*, and subject to an uniformly distributed mass $\bar{m}$, the flexural stiffness of the composite beam *EI* (*E* standing for the *E*-modulus and *I* for the second moment of area of the composite cross-section) can be assessed by [19]:

$$EI = \left(f \cdot \frac{2L^2}{\pi}\right)^2 \cdot \bar{m} \quad (1)$$

The existence of the accelerometer (concentrated mass) at mid-span of the beam jeopardises the applicability of Eq. (1). For such purpose, the full analytical derivation of the relationship between *EI* and *f* for the case of a beam containing a uniformly distributed mass is shown in Ref. [14]. However, in the cases where light-weight accelerometers are used, the errors associated to the application of Eq. (1) become negligible (e.g. for accelerometers weighting less than 100 g, the error in the estimated concrete *E*-modulus remains under 1% of its value).

After obtaining the flexural stiffness of the composite beam *EI* for a given instant, it is possible to assess the actual concrete *E*-modulus E_c through the following equation:

$$E_c = \frac{EI - E_a \cdot I_a}{I_c} \quad (2)$$

where E_a is the *E*-modulus of the mould and I_a, I_c stand respectively for the second moments of area of the mould and the internal concrete.

In line with previous works on modal identification of concrete structures [20], as well as the work conducted so far with EMM-ARM [14,16], the *E*-modulus that is obtained through EMM-ARM seems to be close to that which is usually termed as 'static *E*-modulus' rather than the 'dynamic *E*-modulus'. In fact, the resonant frequencies involved in EMM-ARM testing (less than 100 Hz) are quite low when compared to those of UPV measurement (usually above 50,000 Hz).

2.2. Modifications to the test setup

The original implementation of EMM-ARM described above carries two fundamental drawbacks: the mould is not re-usable, and casting procedures may reveal problems if conventional concrete (i.e. not self-compacting) is used. Therefore, it was decided to explore the possibilities and pitfalls of using an alternative mould which could be re-used, while allowing easy access of a vibrating needle to the entire specimen. The basic conception of the mould for the new test setup followed the same principles as those already adopted for the acrylic tube. One of the principles regarded the resonant frequency of the composite beam, which should preferably range from ~10 Hz (with concrete in fresh state) to less than ~50 Hz at the hardened state (to avoid the introduction of electricity noise in the acquired signals in this final state). This demand causes the beam to be relatively slender, which carries the interesting feature of being easily excitable by ambient vibrations, thus facilitating the use of output-only modal identification techniques. The other principle was to maintain the centre of gravity of the mould coincident with the centre of gravity of the tested concrete, as to simplify the analysis procedures. It was also decided to increase the minimum cross-sectional dimension of the specimen to 15 cm in order to be able to test the same types of concretes that are used in the traditional cylinders (15 cm diameter) and cubes (15 cm edges) [21], in terms of maximum admissible aggregate size. A mould was therefore devised, based on bent 1 mm thick steel alloy plates, with the geometry shown in Fig. 2.

The mould has a total length of 2.6 m and a "U" shaped cross section that assures inner cross-sectional dimensions for the specimen of 15 cm × 15 cm. Extremity lids are placed at 10 cm distance from the extremities of the mould, causing the length of the concrete specimen to be of 2.4 m, which is coincident with the free span of the simply supported beam assured by the bottom supports. These bottom supports solely sustain the bottom part of the mould along its 15 cm width. Aluminium stiffeners are placed on top of the beam in order to assure that the geometry of the mould remains unchanged after casting (i.e. the mould does not suffer cross-sectional deformations associated to the lateral pressure caused by fresh concrete). Casting procedures are relatively straightforward, with possible recourse to vibrating needles, and can be conducted with the mould placed in its final structural arrangement (simply supported). Upon the end of casting operations (total concrete height of 15 cm), a plastic cover should be placed in order to assure proper curing conditions and prevent water loss from the specimen (which would affect its overall mass). During the experiment, accelerometers are placed at 3 spots throughout the beam's bottom surface, allowing a more accurate modal identification to be conducted (as shown in Section 2.3).

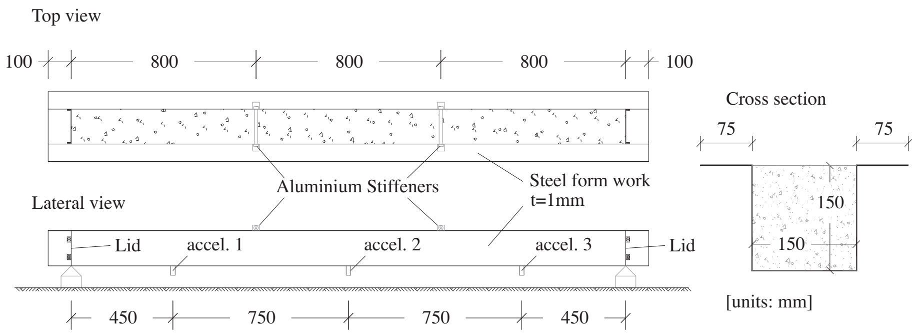

Fig. 2. Overall scheme of the alternative implementation of EMM-ARM.

After the end of the experiment, the accelerometers are removed from the mould, the extremity lids and aluminium stiffeners are removed, and the mould is turned upside down, allowing the easy removal of the concrete specimen through slight bending of the lateral walls of the mould. It should be remarked that this experimental setup causes the experiment to have no expendable parts: everything is re-usable.

Even though the test setup was initially implemented according to the above description, debonding problems between concrete and mould were detected, and removable connectors had to be added to the mould. The detailed description of the observed problems, and the proposed introduction of connectors is relegated to Section 4.1.

2.3. Modifications to the modal identification technique

In previous research with EMM-ARM [14] only frequency domain modal identification methods (non-parametric methods) were used, namely the Welch method [18], also called the periodogram method. The accuracy of this method has high sensitivity to the noise level of the measuring environment, as observed in [14]. The time domain methods (also known as parametric methods) [22–24] are usually more robust and less sensitive to noise levels [25].

In the approach devised for this paper, the Stochastic Subspace Identification (SSI) parametric method [23] was chosen to estimate the modal parameters in EMM-ARM. Time discrete models require that the continuous response (e.g. structural accelerations recorded along a time interval) can be represented with a certain fixed sampling period Δt. Then, the response can be discretized and solved at every instant t_k, where $t_k = k\Delta t$ and k is an integer. If it is assumed that excitation forces are unknown but exhibit white noise properties, the following discrete-time model can be assumed [26]:

$$\begin{aligned} \boldsymbol{x}_{k+1} &= \boldsymbol{A}\,\boldsymbol{x}_k + \boldsymbol{w}_k \\ \boldsymbol{y}_k &= \boldsymbol{C}\,\boldsymbol{x}_k + \boldsymbol{v}_k \end{aligned} \quad (3)$$

where $\boldsymbol{x}_k$ is the discrete-time state vector with the sampled displacements and velocities in instant $k\Delta t$; $\boldsymbol{y}_k$ is the response vector and contains the sampled accelerations in instant $k\Delta t$; $\boldsymbol{A}$ is the state matrix; $\boldsymbol{C}$ is the output matrix; $\boldsymbol{w}_k$ is defined as process noise resulting from input perturbations and modeling inaccuracies; and $\boldsymbol{v}_k$ is measurement noise due to transducers and data acquisition disturbances. Both stochastic vectors ($\boldsymbol{w}_k$ and $\boldsymbol{v}_k$) are impossible to measure but their statistic properties can be assumed as: zero mean and white noise [22,25].

The main objective of the SSI method is the identification of the state matrix $\boldsymbol{A}$ and the output matrix $\boldsymbol{C}$ – see Eq. (3) – which contain the information about the resonant frequencies, mode shape vectors and damping coefficients [22,23,25,27].

The results from the SSI method can be observed in a stabilization diagram (Fig. 3), which results from the information of matrices $\boldsymbol{A}$ and $\boldsymbol{C}$ [23]. In this diagram the parameters of a range of model orders, the so-called stochastic state-space realizations, are presented. The horizontal axis regards to the frequencies, whereas the vertical axis is related to all model orders (also known as the state space dimension, which is the dimension of the matrix $\boldsymbol{A}$). The physical modes reveal themselves as straight vertical lines, according to several criteria (isolated or combined), such as: frequency, mode shape, and damping. In opposition, noise modes will appear scattered all over the diagram. At this stage, and based in the stabilization diagram, the user should select a model order, according to the stable vertically aligned poles. Normally this procedure is not straightforward, as the selection of the model order depends on the experience of the user and on the quality of data.

In a previous work of the authors [28,29], a method has been developed to allow the automatic identification of stabilized poles without the need for human intervention using a combination of a rule-based approach and cluster analysis. Such automatic system identification method has been applied to the data of EMM-ARM in the scope of this paper.

The previous implementation of EMM-ARM relied on the use of a single accelerometer for the modal identification using the Welch procedure. The proposed implementation not only shifts modal identification to a parametric method, but also involves the addition of two further accelerometers to the beam. The use of three accelerometers allows modal identification to be easier, as more information can be perceived in regard to relative ordinates in

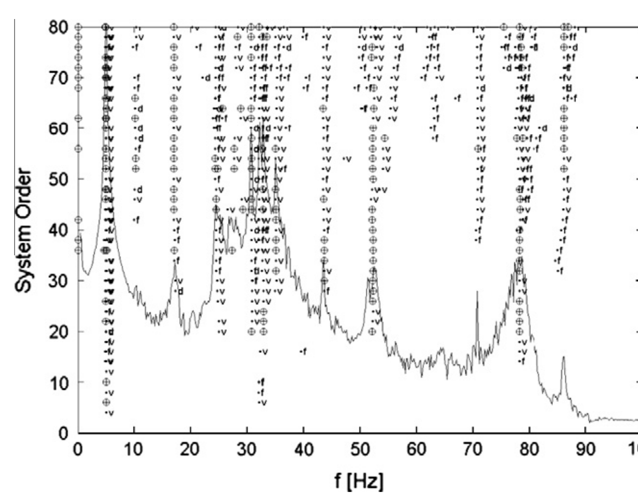

Fig. 3. Typical stabilization diagram of the stochastic subspace identification method (Symbols: '' stable pole; '·v' pole with stable frequency and mode shape vector; '·d' pole with stable frequency and damping; '·f' pole with stable frequency) [39].

the modal shape. Thus, the first flexural resonant frequency can be much easier to recognise due to the well-known expectable mode shape.

To illustrate the advantages of the alternative modal identification approach here proposed (both regarding the use of parametric methods, and the recourse to three accelerometers), in regard to the previous approach that solely relied in one accelerometer and used the Welch procedure, Fig. 4 presents a comparison between the results obtained with the two approaches in the same beam. The reader can observe that in the previous approach (see Fig. 4a) the spectrogram is contaminated with undesired noises which lead the results to exhibit some scatter. If the proposed approach is used (see Fig. 4b), the frequency variation is clearer and more accurate.

3. Description of the experimental program

3.1. General outline

The two versions of EMM-ARM described in the previous section were tested inside a prefabrication industry plant, in parallel with the production/testing of a 27.4 m long prestressed concrete beam for a bridge in Portugal. Concomitantly, a laboratory campaign for characterisation of the evolution of concrete mechanical properties was carried out.

3.2. Materials

A single batch of concrete (not self-compacting) has been studied in the scope of this test in the prefabrication plant, with the mix composition per cubic meter being shown in Table 1.

The steel rebars for concrete are S500 according to EN 1992-1:2010 [2], and the pre-stressing strands are Y1860S7-15.2 according to EN 10138-3 [30]. The *E*-modulus for rebars and prestress cables was considered equal to 210 GPa.

The acrylic used for the EMM-ARM tube has an *E*-modulus of 3.50 GPa and density of 1443.1 kg/m^3, whereas the zinc-coated steel alloy (non-structural) used for the EMM-ARM open mould has an *E*-modulus of 170 GPa and an approximate density of 7800 kg/m^3. These *E*-modulus and density values (for both acrylic and steel alloy) assessed in laboratory by weighing, performing modal identification of empty moulds, and cyclic testing of material samples. The obtained values reasonably match the data provided by the suppliers of both materials.

The density of the concrete was assessed by averaging the density of six 15 cm edge cubes, and a value of 2396.54 kg/m^3 was obtained. This was a quite consistent value when compared with the 2369 kg/m^3 that are obtained by summation of the constituents weight according to Table 1.

Table 1
Mix proportions of the concrete used in the prefabrication plant.

Constituent	kg/m^3
CEM I 42.5R	430
Water	143
Coarse sand (river)	377
Fine sand	418
Gravel 5/15	1006
Polycarboxylic ether polymers superplasticiser	3.9

3.3. The prestressed beam

The experiments shared the same concrete batch of a prestressed beam, with total span of 27.4 m, whose cross-section and reinforcement are shown in Fig. 5. It should be noted that the cross-section of this beam is constant throughout its whole length. The beam was poured in a casting bed, where the prestressed reinforcement had been previously placed and stressed. The formwork for the beam was composed of 5 mm thick steel panels placed laterally. No heat curing was applied but the water used in the mixture was heated as to ensure an initial concrete temperature of 20 °C (hotter than the environmental temperature, as shown below).

Taking into account the rebar distribution, as well as the prestress reinforcement, the average density for the reinforced concrete beam was calculated to be 2533.63 kg/m^3.

3.4. Experiments and procedure

The overall experiment consisted in casting two EMM-ARM specimens (one with the acrylic tube version, and the other in the steel mould), placed next to the actual precast beam, and simultaneously to its casting operations (see Fig. 6). The acrylic tube version of the method had the geometrical characteristics and material properties mentioned in Section 2.1, whereas the steel mould corresponds to the description of Section 2.2. As concrete could not be classified as “self-compacting”, the casting operations inside the acrylic tube had to be done with external vibration (handheld vibrator coated with a cloth and slightly pressed against the mould). In the case of concrete inside the steel mould, casting operations were easier because of the easy access of the vibrator. The accelerometers used for in the scope of this research work had a sensitivity of 10 V/g, within the range ±0.5 g, and having a total mass of 220 g each. Fans were placed in the

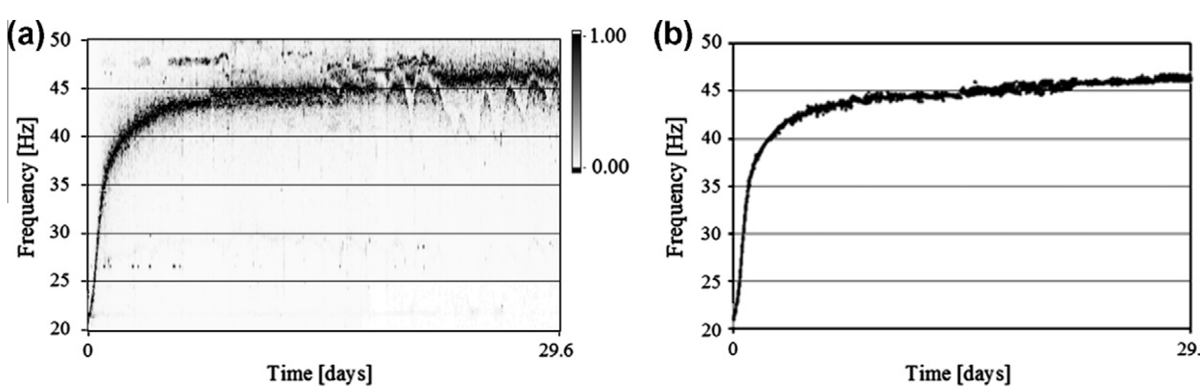

Fig. 4. Example of EMM-ARM results with two distinct approaches: (a) previous approach with only one accelerometer and using the Welch method; and (b) the proposed approach with parametric system identification method and three accelerometers.

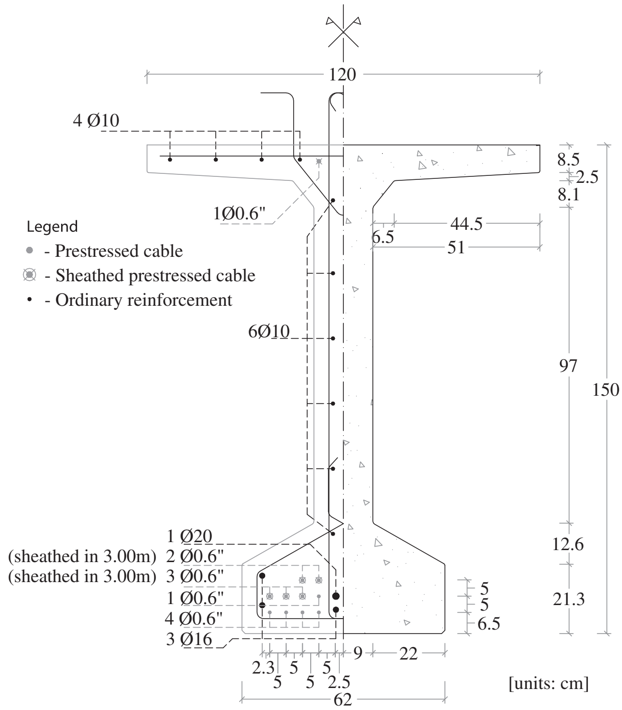

Fig. 5. Geometry and rebar/prestress disposition of the prestressed beam at mid-span (sheathed stretches of strands correspond to the extremities of the beam).

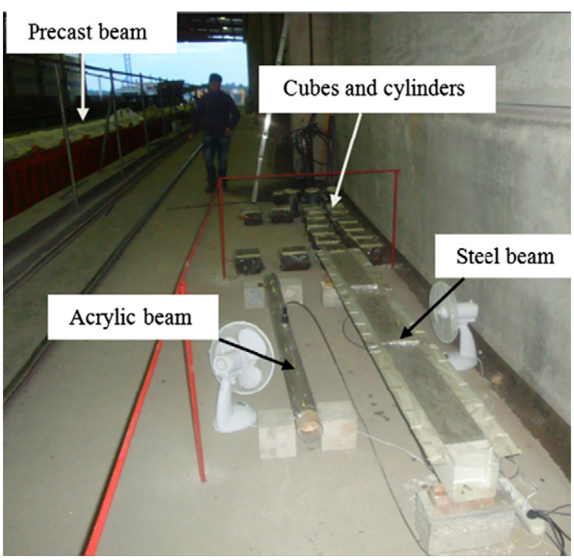

Fig. 6. Overall view of the experiment.

vicinity of EMM-ARM specimens to increase the ambient vibration associated to air movement (random turbulent motion).

In addition to the EMM-ARM specimens, two concrete cubes (15 cm edge), named as cube 1 and cube 2, were cast with the purpose of assessing the evolution of US wave velocity (P-waves measured using a 54 kHz probe with 5 cm diameter – TICO equipment). These US wave velocity measurements were not carried out in the EMM-ARM specimens due to limitations associated to the moulds, and due to the added mass that the probes would represent in the beams under test. Alongside with these experiments, the compressive strength of concrete has been determined in 15 cm edge cubes at the ages of 1, 4, 7, 14 and 28 days (three cubes tested at each age) according to EN12390-3 [1]. *E*-modulus was determined at the same ages of testing in 15 cm diameter and 30 cm long cylinders (total of 3 cylinders) according to ISO 1920-10 [31], with stresses being applied at a rate of 0.28 MPa/s and a maximum stress level of 1/3 of the cylinder compressive strength at the instant of testing.

In regard to the placement of test specimens, the following relevant information may be forwarded

- All test specimens (EMM-ARM, cubes and cylinders), as well as the prestressed beam have been cast in the same pavilion, which had several openings both laterally and at the extremities. It may be considered that this corresponds to outdoor conditions, except for the shielding from solar radiation and night cooling provided by the roof. The average temperature during the 33 days of testing in the prefabrication plant was of 9.2 °C, whereas its evolution is shown in Fig. 7;
- The EMM-ARM specimens were kept in the prefabrication pavilion throughout the entire test;
- The prefabricated beam was kept in the prefabrication pavilion until the age of 0.784 days (18.8 h), and it was then transported to outdoor conditions next to the pavilion;
- All the other test specimens (cubes and cylinders) had to be transported to the laboratory for testing. They were cast and sealed in the prefabrication pavilion, where they rested for 18 h, and then transported to a controlled climatic chamber at 15 °C and RH = 50%.

As a result of the differences in environmental temperatures to which the EMM-ARM specimens were subjected in comparison to those endured by the cubes and cylinders, the comparative results to be presented in the next section for these specimens are shown in reference to their equivalent age (t_{eq}), computed according to [32]:

$$t_{eq} = \int_o^t e^{\frac{-E_{act}}{R}\left[\frac{1}{T(\tau)}-\frac{1}{T_r}\right]} d\tau \quad (4)$$

where t is the instant at which the equivalent age is being computed, E_{act} is the apparent activation energy, R is the universal gas constant (8.314 J/mol K), $T(\tau)$ is the temperature at instant τ and T_r is the reference temperature (here adopted as 20 °C). As no measurements were made in order to assess the apparent activation energy, the value recommended by Chengju [33] for concrete containing Portland cements was adopted:

$$\frac{E_{act}}{R} = \begin{cases} 4000\ (K) & T \geq 20\ ^\circ\text{C} \\ 4000 + 175 \cdot (20 - T) & T < 20\ ^\circ\text{C} \end{cases} \quad (K) \quad (5)$$

Also, as no temperature measurements were made inside the specimens (EMM-ARM or cubes/cylinders), the equivalent age

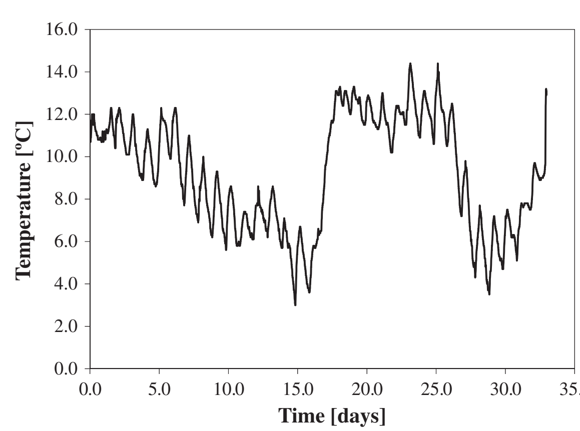

Fig. 7. In-situ temperatures recorded at the prefabrication plant.

computation is made with basis on the environmental temperature to which they were subjected during the experiments. This simplification carries a slight error associated to the temperature rise of the specimens due to hydration heat. Nonetheless, due to the relatively small cross-sectional size (always equal or lower than 15 cm), the inaccuracies caused by the simplification are considered negligible. Further experiments (and/or computations) can provide a clear answer in regard to the limits of this simplification. Due to logistic issues, it was not possible to monitor temperature evolution in the prefabricated beam.

As mentioned above, the prefabricated beam was demoulded and transported to a storage area (outdoors) at the age of 0.784 days, and placed in simply supported conditions on solid wood pieces, according to the scheme of Fig. 8. The dynamic response of the beam was tested with recourse to the same modal identification technique of the EMM-ARM described in Section 2.3. The response has been assessed at 7 points in the top of the beam (measurement period of 10 min with a sampling rate of 200 Hz), as shown in Fig. 8. In regard to the measurement of US wave speed, a measurement spot was selected at the beam's web (as signaled in Fig. 8), carefully located as to avoid the interference of reinforcement in the speed measurement. Such location was established with the help of a marker previously left in the beam, as well as with a rebar locator immediately before the measurements through the web's thickness.

4. Results and discussion

The results are cumulatively presented, beginning with the comparison between the EMM-ARM specimens themselves and the cyclic compression tests. Then, the ultra-sound wave propagation speed in concrete cubes is added to the comparison and afterwards comments are made in regard to the results obtained with the precast beam.

4.1. EMM-ARM

The raw data in, terms of identified resonant frequencies along time, that was collected from both EMM-ARM specimens is shown in Fig. 9a. It can be observed that a wide range of frequencies is covered during concrete hardening in both cases, ranging from 9 Hz to 40 Hz in the acrylic beam and from 20 Hz to 45 Hz in the steel alloy beam. Both evolution curves seem plausible, exhibiting an initial dormant period (where frequency remains almost unchanged) in the first two hours, and then having steep evolutions until approximately 2 days age. After that, both beams exhibit a significantly smaller rate of resonant frequency growth in time. It should however be remarked that some interruptions exist in EMM-ARM data, for example, around the age of 5 days (Fig. 9a). These interruptions were caused by power supply failures to the system which was operating autonomously during the whole experiments. These lacks of data are considered unimportant as they occur at stages where the evolution of stiffness is clearly low, and the probable path of the evolution curve can be easily inferred.

The analysis of interest in the scope of this work is centred in the *E*-modulus of concrete, which was estimated with recourse to Eqs. (1) and (2) applied to the data of Fig. 9a, together with the information forwarded in Table 2. The estimated evolution of *E*-modulus based on the resonant frequencies for both beams is shown in Fig. 9b, plotted in regard to the equivalent age (t_{eq}) of concrete. The results obtained from compressive cyclic testing are also shown in the same figure. Regarding the *E*-modulus estimation by the acrylic mould EMM-ARM, it can be stated that an excellent coherence in regard to compressive cyclic testing was obtained, within an error margin that relies below $\sim$2 GPa, which is consistent with the kind of accuracy already reported for laboratory application of EMM-ARM [14]. It is also noticeable that the initial *E*-modulus amounts to $\sim$0 GPa, which denotes the feasibility of the assumption of zero initial stiffness (this observation is also valid in the case of the steel alloy mould). Further remarks on the determination of the setting time (and time 0) with EMM-ARM are relegated to Ref. [34]. The application of the initially devised version of EMM-ARM for acrylic is thus considered valid for use in construction environment, in view of its ability of having the same kind of performance that it had in laboratory environment. However, the same conclusion of adequate performance cannot be withdrawn by observation of the results for the steel alloy EMM-ARM in Fig. 9b: in fact, after an initial period where the estimated *E*-modulus evolution was remarkably similar to that obtained from the acrylic EMM-ARM, at the equivalent age of 0.7 days, the behaviour started to deviate, conducting to significant underestimations of concrete *E*-modulus at the final age of $t_{eq} \approx 15.5$ days. The reason for this deviation was successfully determined at the end of the experiment, as it was possible to remove the plastic sealing from the top of the beam and observe it. It was seen that some parts of the edge between concrete and the steel mould were slightly separated, thus pointing to the debonding of the two materials. This debonding is bound to have been caused by the effect of autogeneous shrinkage of concrete (as drying was prevented), and it has probably occurred at the equivalent age of 0.7 days mentioned above. In order to make sure that the concrete in the specimen was actually well cast and that its stiffness was adequate (thus ruling out the possibility of internal voids or defects), it was removed from the steel mould and tested individually as simply supported, with a span of 2.3 m. The measured resonant frequency was of 49.8 Hz, which by application of Eqs. (1) and (2), together with the analysis parameters shown in Table 2, leads to an estimation of 35.1 GPa for the *E*-modulus at the instant of testing (t = 32.8 days; t_{eq} = 15.5 days). As the *E*-modulus of concrete obtained through compressive testing at a similar age (t_{eq} = 14.7 days) had the comparable value of E = 36.9 GPa, this satisfactory coherence rules out the possibility of the error in steel alloy EMM-ARM being caused by the concrete itself, and confirms the plausibility of appointing the loss of bond between the materials as a cause. In fact, the occurrence of debonding may induce overall stiffness loss of the system and/or motivate the occurrence of local modes of vibration (that may lie within the frequency range of the experiment) in the bottom steel plate that supports the accelerometer.

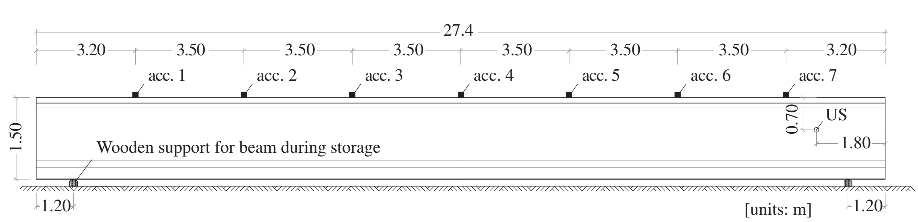

Fig. 8. Scheme of the prefabricated beam during the modal identification test.

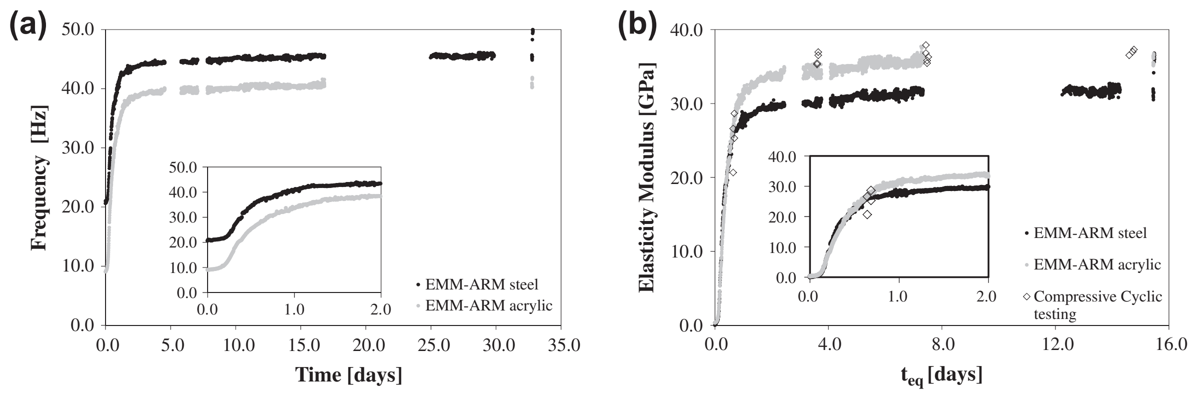

Fig. 9. (a) Identified resonant frequencies in the EMM-ARM specimens and (b) *E*-modulus obtained through EMM-ARM and through compressive cyclic testing.

Table 2
Parameters used for the transformation of the frequencies in *E*-modulus.

	$\bar{m}$ (kg/m)	L (m)	E_{mold} (GPa)	I_{mold} (m^4)	I_{conc} (m^4)
Acrylic beam	17.604	1.800	3.5	1.45E-06	3.44E-06
Steel beam	59.830	2.405	170.0	2.30E-06	4.22E-05
Concrete beam	52.740	2.300	–	–	4.22E-05

Bearing in mind the reported problem with the steel mould EMM-ARM, it was decided to perform a second experiment with measures being taken to mitigate the possibility of debonding.

A new experiment was devised in order to overcome the debonding problem. Drive screws with 3.6 mm diameter and 38 mm length were attached to the mould at several parts of the lateral panels, as shown in Fig. 10a and b. This second test with the steel alloy mould containing connectors took place at a distinct construction site, and with recourse to a distinct type of concrete. Such details have been omitted in this paper for the sake of brevity, and for specific information the reader is forwarded to Ref. [35]. Compressive cyclic testing has been conducted in cylinders for several ages, and the corresponding comparison with EMM-ARM results for this case is shown in Fig. 10c. The results show similar coherence to that which had been previously obtained in the acrylic EMM-ARM application. This leads to the conclusion that the addition of drive screws in the steel mould avoids the debonding problems, and thus allows proving the steel alloy EMM-ARM as a feasible alternative to the initially devised acrylic mould. It is further remarked that the inclusion of these screws does not endanger the re-usability of the mould, as they can be easily unscrewed before concrete removal.

4.2. Ultra-sound wave propagation

The UPV measurements taken at several ages (starting on $t = 0.33$ days = 8 h) on cubes 1 and 2 are shown in Fig. 11a, where a good coherence between the values measured with both specimens can be observed. Furthermore, the shape of evolution of velocity increase fits the expectable tendency already noticed in previous works [36].

In order to convert the velocity measurements into estimated dynamic *E*-modulus (E_{din}), the application of Eq. (6) is necessary [37]:

$$V_p = \sqrt{\frac{1 - \vartheta_{din} \cdot E_{din}}{((1 + \vartheta_{din})(1 - 2\vartheta_{din})) \cdot \rho}} \tag{6}$$

where V_p is the P wave velocity, ρ is the density of concrete and ϑ_{din} is the dynamic Poission's coefficient. As the Poission's coefficient was not measured in the scope of this research work, and bearing in mind that the *E*-modulus obtained through Eq. (6) is proportional to V_p^2, the comparison with the results obtained by EMM-ARM and cyclic compression are made in relative terms to the recorded value at the equivalent age of 5 days (instant at which, data from all tests was simultaneously available), as shown in Fig. 11b. From the observation of this figure, it becomes clear that the relative evolution of stiffness captured by EMM-ARM is quite coherent with that obtained through UPV measurement, with the advantage of providing quantitative information that can be directly used by the user.

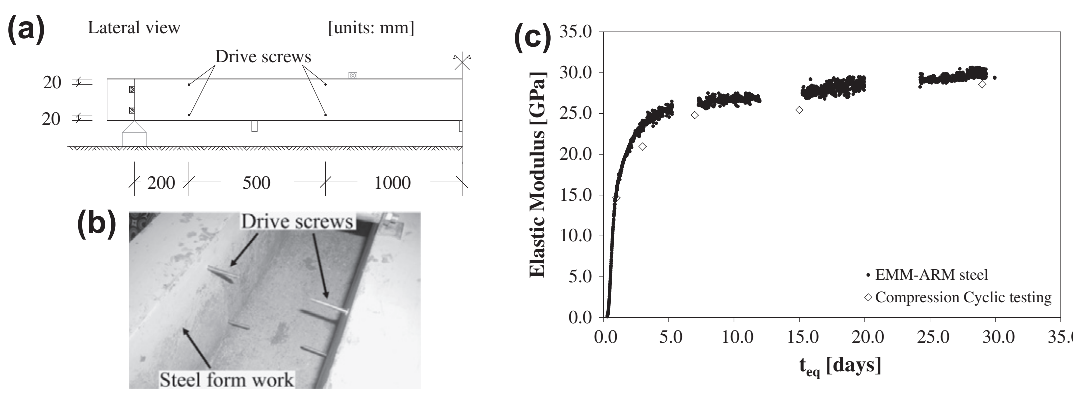

Fig. 10. Placement of connecting devices along the steel mould: (a) scheme; (b) photo and (c) *E*-modulus obtained through steel alloy EMM-ARM with connectors and through compressive cyclic testing (2nd experiment in a distinct construction site).

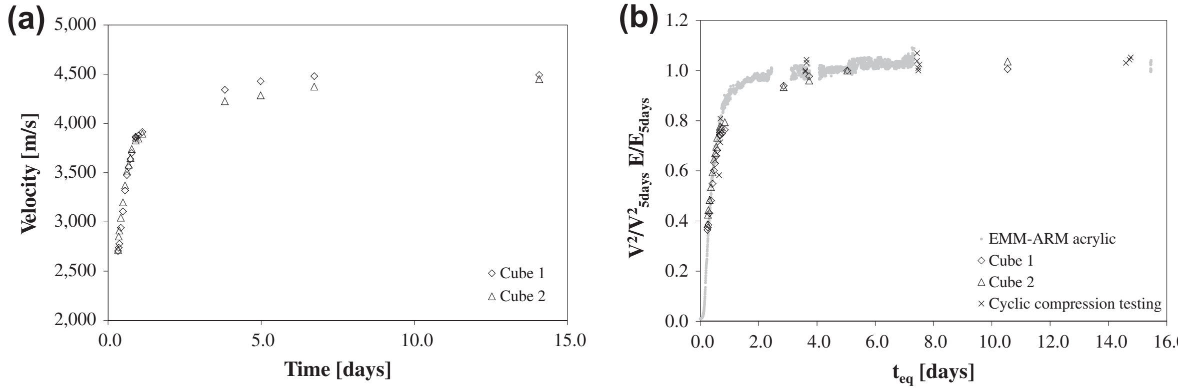

Fig. 11. (a) Measured UPV along time in the concrete cubes and (b) Comparison between relative evolution of results of EMM-ARM, cyclic compression and UPV.

4.3. Experiments on the precast beam

After placement in the storage area, detailed system identification tests were carried out aiming at identifying, at least the first three vertical mode shapes of the precast beam (more complex problem than the EMM-ARM specimens). For this purpose, 7 measurement points were considered, with accelerometers placed at the positions shown in Fig. 8.

The stabilization diagram of the recorded data is presented in Fig. 3c, already addressed in Section 2.3. The existence of several stable poles ranging from 5 to 85 Hz is clear, corresponding to all mode shapes within this range.

The first three columns of Table 3 show the obtained results in terms of natural frequencies f_{exp} and damping coefficients ξ for the three lowest flexural vibration modes. The identified natural frequencies are well spaced and equal to 5.23 Hz, 17.18 Hz and 27.42 Hz, whereas the observed average damping was equal to 2.17%, which is in the range of the typical values for reinforced concrete structures [25].

With the aim of estimating the concrete *E*-modulus that corresponds to the observed dynamic response of the beam, a 3D Finite Element (FE) model was built in DIANA [38], as to dully account for the effect of rebars and prestress. Finite element bricks with 20 nodes were used to simulate concrete and bar elements were used to simulate all the longitudinal rebars and prestressed cables (initially stressed at 1395 MPa). In terms of boundary conditions, the beam was assumed as simply supported.

The numerical analysis was carried out by varying the concrete *E*-modulus to minimise the relative frequency error between the experimental and the numerical results. For the best case, an *E*-modulus of 29.7 GPa was obtained. The calculated frequencies, and the relative errors in regard to the experimental frequencies are presented in columns 4 and 5 of Table 3. It should be stressed that this is a simplified approach, as the *E*-modulus of concrete has been assumed as constant throughout the beam's cross-section and length, which does not hold completely true due to differential maturity development caused by non-uniform temperature fields in the beam (induced by heat of hydration).

Simultaneously with the modal identification of the beam, the US wave propagation velocity has been measured at position US according to Fig. 8. The average speed was of 4014 m/s. A direct comparison with the wave velocity obtained in the cubes at the same absolute age cannot be made, as the temperature history is distinct (heat of hydration causes significant temperature increases in the prestressed beam, which thus hardens faster). However, it is possible to assess the age at which the cube exhibited the same US speed of 4014 m/s. This occurred at the age of 1.75 days (interpolated from Fig. 11a), confirming the time lag of stiffness development in regard to the precast beam that already has this US speed at the age of 0.784 days. The EMM-ARM, with similar maturity to the cubes, has revealed an *E*-modulus of 32.2 GPa at 2.32 days (time at which $V = 4014$ m/s), which is reasonably coincident with the *E*-modulus of 29.7 GPa assessed at 0.784 days in the precast beam through modal identification (error margin within ~2.5 GPa). This similarity points to the feasibility of assessing concrete *E*-modulus through EMM-ARM. However, in order to assure that EMM-ARM provides updated values (i.e. without time lags) of the *E*-modulus of the actual precast beam, temperature matched curing strategies are necessary. This should be a further step of this line of research.

Table 3
Summary of the modal identification results and those resulting from finite element simulation with the fitted *E*-modulus value.

Mode	f_{exp} (Hz)	ξ (%)	f_{FE} (Hz)	f_{error} (%)
1	5.23	1.86	4.79	−8.4
2	17.18	2.88	17.65	+2.7
3	27.42	3.31	28.75	+4.9

5. Conclusions

Based on the methods, experiments and results presented throughout this paper, the following main conclusions can be forwarded:

– The original implementation of EMM-ARM devised with an acrylic tube mould has been tested in in situ conditions, with the results being as promising as those previously reported in laboratory application: good coherence between *E*-modulus estimated by EMM-ARM and by compressive cyclic tests;
– An alternative mould for EMM-ARM based on a "U" shaped cross-section made of steel alloy has been proposed, with the advantages of being re-usable, and allowing easier casting conditions. The results of the initial attempt have revealed problems associated to debonding of the mould, which were probably caused by contractions associated to autogenous shrinkage of concrete;
– Based on the problems of the initial implementation of the "U" shaped mould, a second attempt was made, in which removable connecting screws were added to the mould (without endangering the mould's re-usability). This attempt has shown no signs of debonding, and the coherence with *E*-modulus obtained from static cyclic testing of concrete was good;
– A comparison between stiffness evolution obtained from EMM-ARM and from ultra-sound wave propagation speed was conducted for the first time, and quite similar results were

obtained, pointing to the mutual validation of these two techniques for concrete. Emphasis should however be given to the fact that EMM-ARM allows obtaining continuous quantitative data which is directly comparable to the results of compressive cyclic testing;

– The modal identification test conducted on the actual precast beam allowed estimating the *E*-modulus of concrete, and relating it successfully to the *E*-modulus estimated by EMM-ARM at an age in which the measured US wave speed was coincident. This occurred in distinct instants because of the acceleration of hydration reactions caused by heat of hydration in the precast beam. The application of EMM-ARM for assessment of the actual stiffness development in concrete structures would either demand for maturity corrections, or for temperature-matched curing. These were known limitations when the experimental program was devised, which was rather centred in the evaluation of possible in situ application and shift to a re-usable mould. Further research is now focused on devising and testing a temperature-matched curing version of EMM-ARM aimed for in situ estimation of stiffness/strength.

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