Addressing the need to monitor concrete fatigue with Non Destructive Testing: results of Infrastar European project

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ABSTRACT
Fatigue is one of the most prevalent issues, which directly influences the service life expectancy of concrete structures. Fatigue has been investigated for years for steel structures. However, recent findings suggest that concrete structures may also be significantly subjected to fatigue phenomena that could lead to premature failure of certain structural elements. To date, fatigue of reinforced concrete has been given little focus. Knowledge on the influence factors and durability/capacity effects on this material should be improved. Current technological means to measure fatigue in civil structures like bridges and wind turbines (both onshore and offshore) are outdated, imprecise and inappropriate.

Meanwhile, this topic has got much more attention as time-variant loading on concrete structures plays an increasing role, e.g. in bridges with increasing traffic and heavier trucks, and for wind turbines for renewable energy production, e.g. for offshore wind turbine support structures affected by wind and waves.

The European Innovative Training Networks (ITN) Marie Skłodowska-Curie Actions project INFRASTAR (Innovation and Networking for Fatigue and Reliability Analysis of Structures - Training for Assessment of Risk) provides research training for 12 PhD students. The project aims to improve knowledge for optimizing the design of new structures as well as for more realistic verification of structural safety and more accurate prediction of the remaining fatigue lifetime of existing concrete structures.

First, the INFRASTAR research framework is detailed. Then it will be exemplified through the presentation of the major results of the four PhD students involved in the work package dealing with auscultation and monitoring. This

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includes the development and improvement of Fiber Optics (FO) and Coda Wave Interferometry (CWI) for crack sizing and imagery, new sensor technologies and integration, information management, monitoring strategy for fatigue damage investigation and lifetime prediction.

Keywords: concrete, fatigue, crack, monitoring, non-destructive testing, coda wave interferometry, embedded ultrasonics sensors, distributed fiber optic sensors, mechanical transfer function

INTRODUCTION

H2020-ITN-MSCA Infrastar project (http://infrastar.eu) started in May 2016. Twelve PhD students (ESR – Early Stage Researchers, Figure 1) have been hired by the 8 beneficiaries, which include 4 academic institutions (AAU, BAM, EPFL, IFSTTAR) and 4 industrial partners (COWI, GUD, NEOSTRAIN, PHIMECA), to work on concrete fatigue in bridges and wind turbines. Three scientific angles of attack are structuring the project: monitoring and auscultation (WP1 – Work Package 1), structural and action models (WP2- Work Package 2), reliability approaches for decision making (WP3 – Work Package 3).

Figure 1: The 12 PhD students framework (also called ESR for Early Stage Researcher) and their hiring institution

WP2 focuses on structural and action models, in particular related to fatigue loading and extreme events [Nesterova et al., 2017]. It aims to examine the structural behavior of elements and components of wind turbines and bridges more precisely than currently used methods under environmental and traffic loads. WP3 has the objective to apply the theoretical basis for reliability analysis and risk-based optimal decision making for life-cycle analysis to concrete foundations and towers for wind turbines along with bridge elements [Long et al., 2017, Mankar et al., 2017]. For formulation of the stochastic modeling, the JCSS Probabilistic Model Code is used as basis, and fatigue mitigation of the structures is considered [Rastayesh et al., 2018].

Both WP2 and WP3 are interconnected to WP1 whose aim is to develop new and advanced non-destructive testing methods for early age damage detection. In WP3 methods are developed for coupling monitoring information (throughout the life of the systems) with structural reliability models, in order to establish cost-efficient and safe maintenance planning using Bayesian statistics and optimization of maintenance scenarios [Long et al., 2018]. The deterministic and probabilistic approaches for fatigue safety verification, investigated and implemented in WP2, will retroactively guide non-destructive testing and monitoring. Finally, the interaction between wind turbine and bridge structural aspects is here to sustain the generation of novel knowledge and to explore new research areas.

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This paper highlights the results obtained so far in WP1 "Monitoring and Auscultation". More precisely, the long-term monitoring with traditional sensors (strain gauges, thermocouples) of a viaduct in Switzerland is presented in the context of a fatigue safety study. In addition, lab measurements with novel fiber optic (FO) and coda wave interferometry (CWI) sensors are summarized. Eventually, fusion of NDT data is expected to provide a robust solution for monitoring of concrete structure under fatigue loading.

'POCKET MONITORING' SYSTEM FOR FATIGUE SAFETY INVESTIGATION OF REINFORCED CONCRETE SLABS

The idea behind 'pocket monitoring' system is to adopt the last developments in data acquisition and storage to perform continuous monitoring of existing structures using standard strain gauges and thermocouples. The system is easy to use for occasional as well as for continuous monitoring, it is accessible to any engineering company, and it is practical to remove and reinstall in other structures.

The 'pocket monitoring' system is here used to investigate the fatigue safety of a road bridge, by providing the structural response to traffic and temperature with a frequency of 100 Hz for strain and 1 Hz for temperature. The time series of stresses are calculated from measured strains, and a rain-flow counting is performed to calculate the cycles of each stress range and to estimate the damage due to fatigue using the S-N approach.

Fatigue failure of reinforced-concrete elements is mainly dominated by the failure of the rebars [Schläfli, 1998]. As such, the verification of the fatigue safety of reinforced concrete slabs is limited in the current study to the fatigue of reinforcement, and the 'pocket monitoring' system is installed in the rebars directly.

This monitoring approach is implemented in a real structure, Crêt de l'Anneau, a 60-year mixed-concrete-steel viaduct located in Switzerland. The 'pocket monitoring' system is installed in the reinforced-concrete (RC) slab of the viaduct, to record strains in the rebars at mid-span, which is the most loaded part of the slab, as shown in Figure 2a. Data are transmitted thanks to a 4G internet connection.

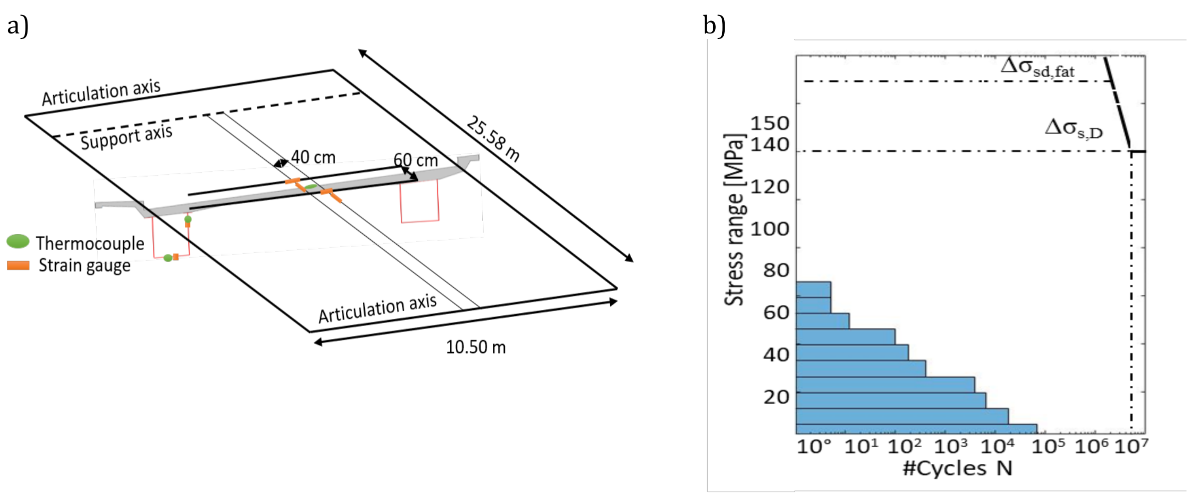

Figure 2: (a) Instrumentation of the Reinforce Concrete slab with 'pocket monitoring' system (b) Stress cycles of the transverse rebar at mid-span, with the corresponding endurance limit $\Delta\sigma_{s,D}$ and the fatigue resistance $\Delta\sigma_{sd,fat}$ of passive steel rebars.

After one year of monitoring, fatigue verification was performed by comparing the stress ranges and their cycles to the S-N curve provided by Swiss standards [SIA, 2013]. It was found that the reinforced-concrete slab does not present any fatigue problem for the actual traffic [Bayane et al., 2018]. Figure 2b presents the stress cycles of the

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transverse rebar at the mid-span, with the corresponding endurance limit $\Delta\sigma_{s,D}$ and the fatigue resistance $\Delta\sigma_{sd,fat}$ of passive steel rebars.

The data provided by the 'pocket monitoring' system present a large sample of traffic strains, which can be used to develop a probabilistic model of traffic to predict the fatigue behavior of the structure in the future [Mankar et al., 2018]. For this aim, a calibrated finite element of the structures is developed, and used to apply a range of loads in various positions. Monitoring data is used to develop a traffic model characterizing the structure under study, and it is linked to the finite element model to investigate the fatigue safety of the structure in the future.

The presented monitoring approach is using strain gauges and thermocouples to measure the strain currently experienced by the structure. Other NDT techniques can be also used, to investigate not just the strain, but also the evolution of cracks, since fatigue is related to the actual applied loads as well as to the crack activity of structural elements. Indeed, cracks are one of the main indicator of damage phenomenon in civil infrastructures, especially fatigue in concrete. Thus, their monitoring at the micro level gives the assurance of structure's strength and serviceability. Visual inspection and some traditional non-destructive techniques (strain gauges, extensometers, etc.) are commonly used to detect and monitor cracks. In the following, Fiber Optic (FO) and Coda Wave Interferometry (CWI) with embedded sensors are presented and finally combined to monitor and locate cracks in concrete lab specimen.

FIBER OPTIC

Compared to traditional techniques, distributed optical fiber sensing systems are a relatively new technology, which offers large possibilities for the development of Structural Health Monitoring (SHM) systems. The first commercial interrogators (Brillouin or Rayleigh) were available 15 years ago. The capability of these interrogators to monitor the spatial distribution of strain and temperature over long sensing ranges made them very suitable for tunnel, bridges and pipelines monitoring. However, their low spatial resolution (~1m) was not adapted to detect micro-cracks in concrete due to fatigue loading. Today, this limitation is lifted and Rayleigh interrogators can now achieve millimeter spatial resolutions. As a result, detection and localization of cracks at micro level can be achieved by laying one line of optical fiber either embedded or attached on the surface of concrete structures. However, the quantification of crack opening from spatial distribution of strain measured along an optical fiber remains a scientific problem. The optical fibers used for distributed sensing are complex assemblies (several layers of different materials) and a Mechanical Transfer Function (MTF) must be used to model the effect of deformation discontinuities due to the crack opening on the spatial distribution of strain measured along these sensors. In 2013, Feng et al. (2013) proposed an analytical MTF which is derived from that proposed by Ansari et al. (1998) and extended to optical fiber crossing a crack. By considering a crack at x=0, the relation between the strain distribution at the level of host material ε_m and in the core of the optical cable ε_f can be derived from Feng's MTF and written as:

$$\varepsilon_f(x) = \delta\,\beta\,e^{-\beta|x|} + \varepsilon_m(x) \qquad \textbf{(Eq.1)}$$

The strain distribution measured by the optical fiber $\varepsilon_f(x)$ is equal to the strain in the host material $\varepsilon_m(x)$ added to a crack induced strain part which takes an exponential form that depends on two main parameters: δ (half of Crack Opening Displacement COD) and β (the shear lag parameter describing the "optical cable / host material" system).

Validating this model for concrete applications leads to different advantages that will help monitoring crack activity in civil infrastructure due to fatigue. As a result, a crack map, for better detection and localization of cracks, to monitor the crack openings (by following δ values) and verify the integrity of the sensor/host material system under millions of load cycles (by following β values), could be provided.

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Figure 3 shows the 3-points bending experiment on a meter size concrete beam with an embedded FO cable used to validate the Equation 1. A good agreement between the computed (solid line) and applied (marked with cross) strain distribution can be observed in figure 4 in multiple neighboring crack appearance case. In addition, the opening of the central crack when compared to the one measured by a Linear Variable Differential Transducer (LVDT), can be well estimated with an error of less than 5% for CODs starting from 10 μm up to 200 μm. Additional data processing [Bassil et al., 2018] makes it possible to follow higher Crack openings of up to 400 μm with an error less than 6%.

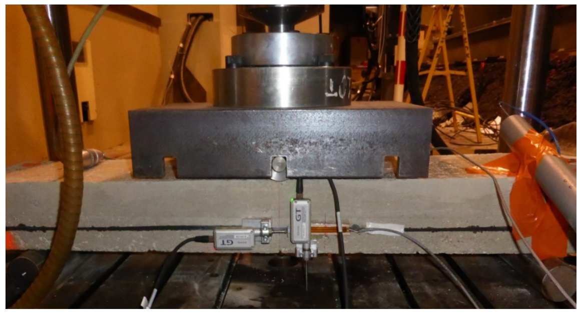

Figure 3: 3-points bending set-up with the LVDTs and strain gauge sensors visible.

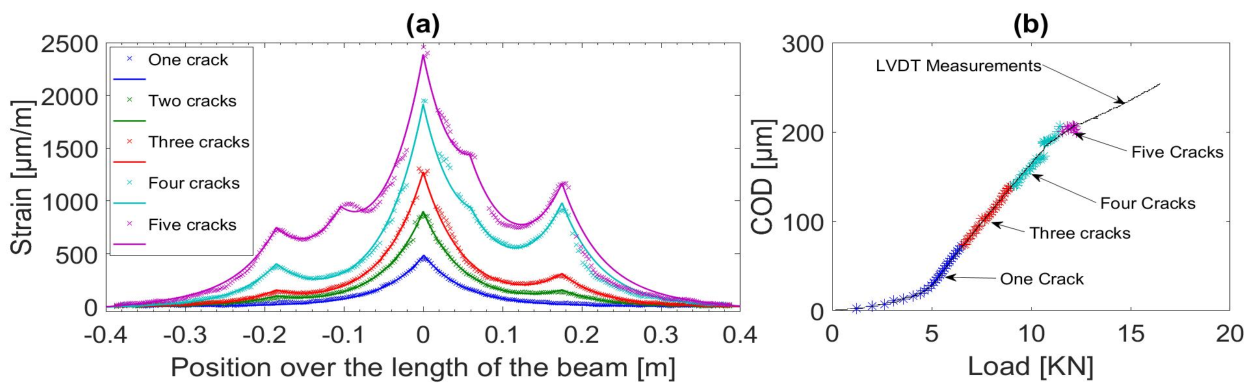

Figure 4: (a) Measured spatial strain distribution (Marked with cross) versus computed strain (Solid lines) (b) Estimated Crack opening displacement compared to LVDT measurements.

Even with the mentioned above sensing technology being able to provide localized measurement in space, a combination of FO with an ultrasonic method, sensitive to strain and cracks that investigates the volume, can bring complementary information [Zhang et al., 2013].

CODA WAVE INTERFEROMETRY (CWI)

The idea behind CWI is to take benefit of the multiple diffusion of ultrasonic waves due to the heterogeneity of concrete (when the wavelengths have a size similar to that of the aggregates) and/or of multiple reflections at the structures boundaries. The late part of the ultrasonic signal, which is called the coda, looks like noise but it is repetitive and very sensitive to small changes in the material due to the long path ultrasonic waves have traveled. In the literature, applications of CWI in small scale concrete specimen, typically meter size or smaller, are reported [Planes et al., 2013]. Classical CWI observables (Equation 2) are the maximum correlation coefficient *CC(θ)* and the associated velocity variation $\theta = \delta v/v$ (where v is the coda wave velocity) [Sens-Schoenfelder et al., 2006]:

$$CC(\theta)=\frac{\int_{t_1}^{t_2} u_i[t(1+\theta)]u_p[t]dt}{\sqrt{\int_{t_1}^{t_2} u_i^2[t]dt}\sqrt{\int_{t_1}^{t_2} u_p^2[t]dt}} \qquad \textbf{(Eq.2)}$$

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where $u_i(t)$ is a reference ultrasonic signal recorded for instance at the beginning of the experiment and $u_p(t)$ is the perturbed signal recorded at a later stage.

Figure 5 shows typical CWI results obtained at the beginning of a 3-point bending loading experiment of Figure 3 recorded with embedded ultrasonic sensors [Niederleithinger et al., 2015]. The use of embedded ultrasonic sensors is an originality of the CWI work conducted here together with that of a self-made electronic device which allows portable, low cost, off-line CWI measurements. The sensitivity of the CWI observables CC(θ) and the velocity variation δv/v with respect to the load is clearly observed.

14 sensors have also been successfully installed inside a 25 meters long pre-tensioned reinforcement concrete beam in the frame of the BAM thematic project BLEIB on bridge monitoring [Wang et al., 2018]. The transducers were distributed in 5 cross-sections (A, B, C, D, E) (Figure 6). This so-called BLEIB structure (Figure 6) is placed under field environmental conditions and the aim of these tests is to detect subtle changes like variation in stresses and initiation of cracks under different combinations of quasi-static and dynamic loads. Figure 7 shows preliminary CWI results obtained at different locations (colored lines) as a function of time which correspond to different load locations. Different load steps could be identified according to *CC* and *δv/v*. For some combinations of sensors (S01E05, S02E06, S11E13, etc. S: transmitter, E: receiver) which were installed in different cross-sections and parallel to the structure, the velocity changed suddenly from less than 1% to more than 5% (Figure 7 middle graph), this unusual behavior was related to the cracks opening. Low correlation coefficients (Figure 7 top graph) can be associated to the opening of cracks which modifies dramatically the shape of the signal $u_p(t)$ compared to its initial shape $u_i(t)$ as reported in the literature [Zhang et al., 2017].

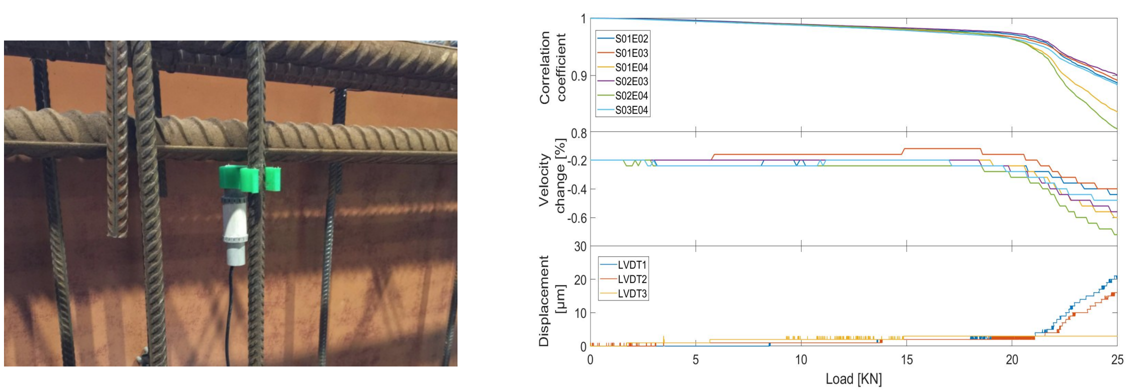

Figure 5: Ultrasonic sensor installed onto the armature (left). Results from Coda Wave Interferometry method: correlation coefficient (right top), velocity variation (right middle) and displacement measured by LVDT sensors (right bottom).

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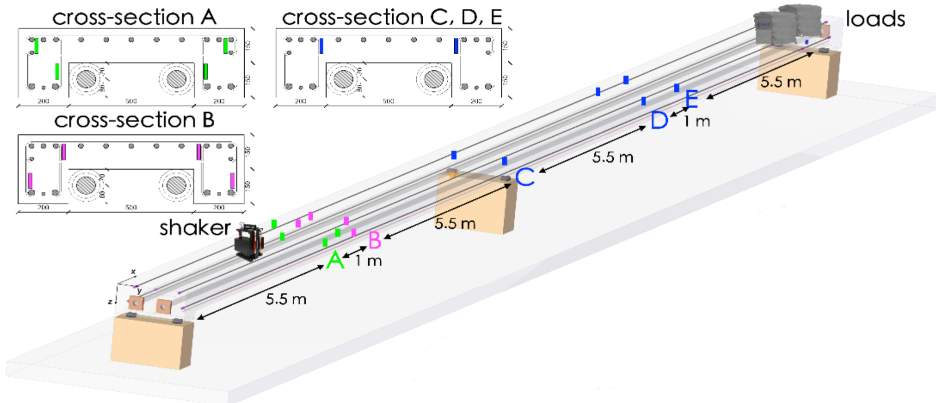

Figure 6: Positions of ultrasonic sensors in BLEIB reference structure

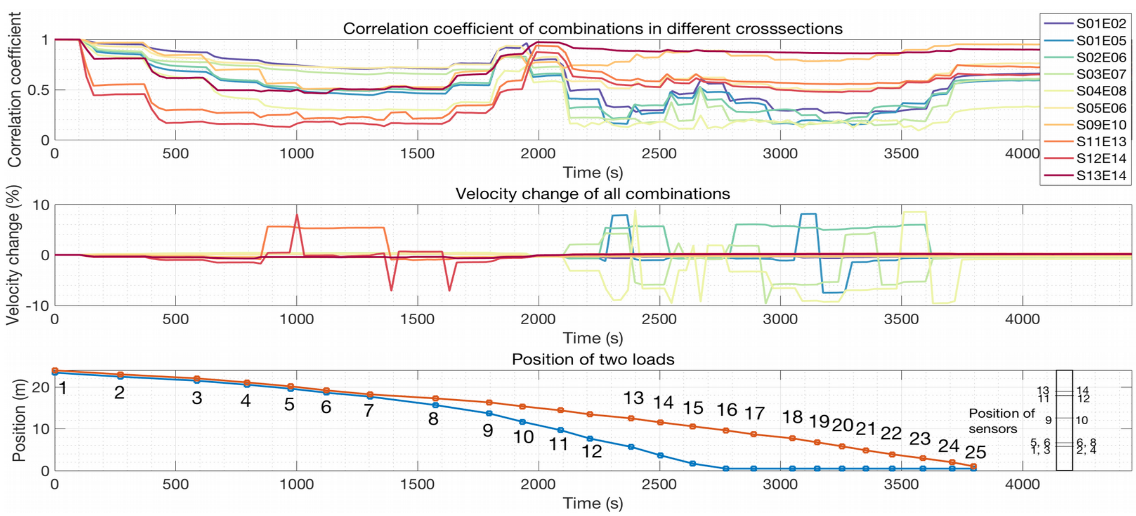

Figure 7: Results from Coda Wave Interferometry method: correlation coefficient (top), velocity variation (middle) and position of the two loads (bottom) as a function of time.

EARLY DAMAGE DETECTION BY EMBEDDED CWI AND FO SENSORS COMPARED TO TRADITIONAL SENSORS

Figure 8 shows preliminary synthesis of the results obtained by comparing by FO and CWI novel sensors with traditional standard sensors like LVDT and strain gauge sensors. CWI (see Figure 5: Zoom A) and FO sensors are more sensitive to the creation of micro-cracks than traditional sensors. FO and CWI sensors makes it possible to detect the creation of a first crack (Figure 7 dotted green line) which remains unnoticed by the strain gauge and the LVDT sensors (positioned at the very location of the crack) until a later stage (Figure 8 dotted red line). This means that with FO and CWI novel sensors there is no need to have the knowledge of the precise position of the crack prior to its creation to detect it. Once reaching the top rebar, it is detected by FO line 1,4,5 and 6 (dotted blue line) which explained the CWI observed changes in the correlation coefficient and velocity change plots for different transmitter/receiver combinations. This change in the behavior of the structure is the result of a switch in stress localization between the front and back side of the beam concluded from strain and crack openings monitored using SG1 and SG2 and LVDT1 and LVDT2 respectively. Finally, a second crack (dotted yellow line) induces high modification in the FO and CWI measurements (detected also by LVDT3) but remained undetected by the strain gauge attached to concrete.

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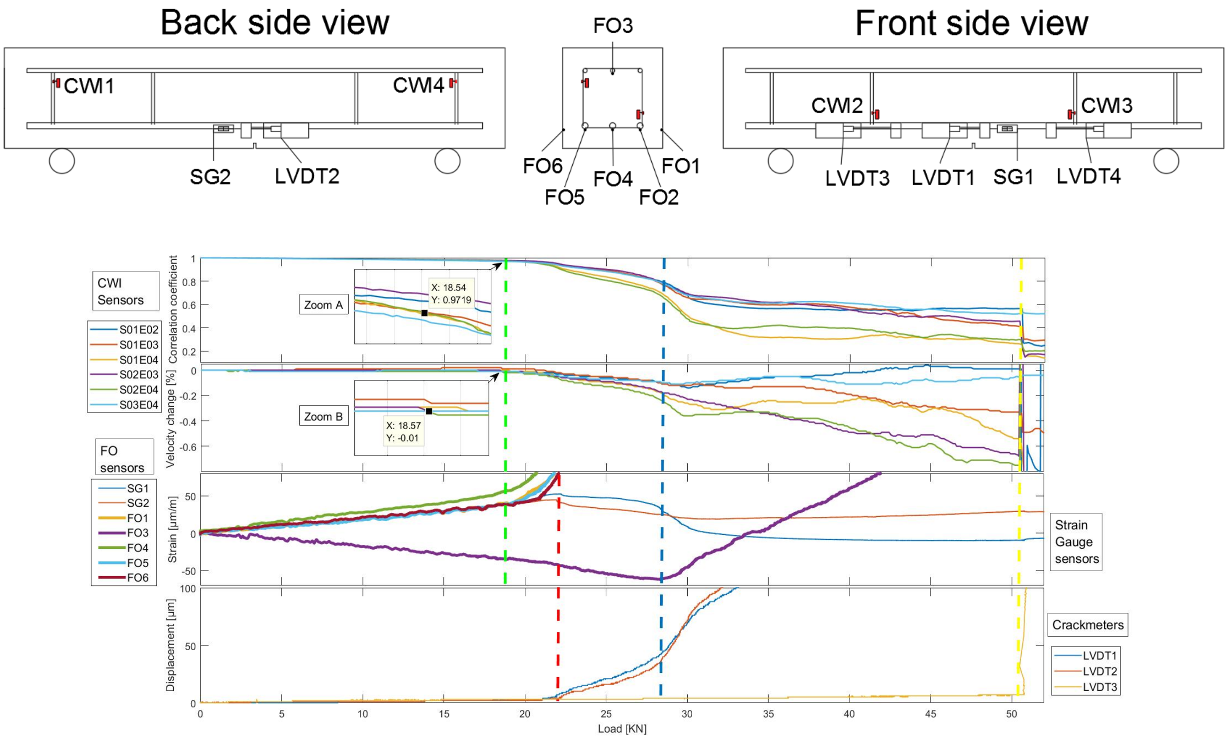

Figure 8: Schematic view of the slab with LVDT and SG (Strain Gauges) position (top), measurements obtained by CWI, FO and strain gauges and LVDTs (from top to bottom).

TOWARDS NDT DATA FUSION FOR FATIGUE DAMAGE QUANTIFICATION

The idea behind data fusion is to combine information from multiple sensors to improve overall performance of damage detection and quantification. Techniques to treat the information coming from multiple sensors located in the same area of the structure and synchronized in time, that do not show the same accuracy (different uncertainties), have received relatively little consideration in structural health monitoring (SHM). Multi-Sensor fusion techniques seek to address these challenges. For a multi-sensor system, data fusion can be classified into three levels: signal-level, feature-level, and decision-level fusion [Liu et al., 2001]. Signal-level fusion is called the lowest level fusion, which combines raw signals from multiple sensors, and produces new raw signals that are expected to be more informative. Feature-level fusion, called medium level fusion, involves calculating feature values (observables) extracted from the signal of an individual sensor or combining observables from different sensors, so that the most relevant ones are used to make decision. Then, a fusion of these features can be achieved through several techniques such as Bayesian methods. Decision-level fusion is called the ultimate-level fusion in this hierarchy. At these level, each sensor can provide an independent decision based on its own features, and the results from all of the features are then fused.

In this paper, feature level of fusion is applied to a signal coming from a pair of ultrasonic sensors (one emitter and one receiver) embedded in the BLEIB concrete specimen (Figure 7). Figure 9 illustrates the general frame of data fusion, where $X_{1,1}\ldots X_{1,n}$ is the vector of data from one transducer pair (T_{11}), $F_{1,1}$ is a feature value from one transducer pair, and D_1 is the decision from the *m* features extracted from $X_{1,1}\ldots X_{1,n}$. In step 1, "Feature level fusion" boxes represent the step of computing the features from all transducer pairs and the use of a threshold (for Receiver Operating Characteristic (ROC) curves analysis [Tom et al., 2006]) to each feature of each of the transducer pairs. In Step 2, the decisions taken from each sensor pair, are fused thanks to a binary declaration in terms of operational changes (like, "presence/absence of load", "presence/absence of crack" etc.).

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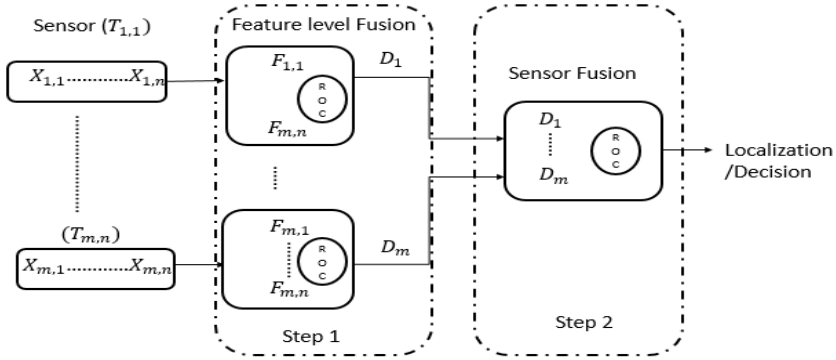

Figure 9: Two-step feature based sensor fusion model

In order to illustrate the feature level fusion, two features are computed from the time-domain signals collected on the BLEIB structure by one pair of ultrasonic sensors during the experiment depicted in Figure 7. The features are obtained from the decorrelation coefficient L_{dc} (Table 1), and the coefficients α_i of an autoregressive model (Table 1). The performance of these features is analyzed using ROC curves (Step 1 in Figure 9). For each of the two features a predetermined threshold is swept over the range of the feature values (computed at several times in the experiment), and the probability of detection (POD) is plotted versus the false alarm rate (FAR). A perfect detector, that calculates the features accuracy, measures the value area under the curve (AUC).

Table 1: Description of two features extracted from the signal of one sensor pair

Features extracted from one sensor pair	**Equation**
Drop in Correlation Coefficient (decorrelation) [Hay et al., 2006]	$\rho_{xy}=\frac{\int [u_i(t)-\mu_{u_i}][u_p(t)-\mu_{u_p}]dt}{\sigma_{u_i}\sigma_{u_p}}$ D_{cc} =1- ρ_{xy} (Eq. 4) where $u_i(t)$ is a reference ultrasonic signal and $u_p(t)$ is the perturbed signal, μ_{u_i} and μ_{u_p} are the mean values of the two signals.
Autoregressive model [Clark et al., 2008]	$\varepsilon(t)=u_i(t)-\sum_{i=1}^{n}\alpha_i-u_i(t-i)+e_m$ (Eq. 5) Where $u_i(t)$ is a reference ultrasonic signal, $-u_i$ is a predicted signal, e_m is noise and α_i are coefficients of the AR model.

The proposed two features are compared for the sensor pair 13-14 (Figure 7) in Figure 10 via their ROC curves. It can be observed that both features perform fairly well in their ability to separate the quasi-static and dynamic loads states in the presence of noises. Indeed when the dynamic load (a 30. 6 kg shaker placed 4.5 m away from the left side of the BLEIB structure (Figure 10)) is applied (before t = 15 minutes) the features have low values and when the static load is acting the features are increasing up to a maximum value when the static load is applied on top of the sensor pair (70 minutes < t < 90 minutes). High decorrelation coefficients may be an indicator of the opening of cracks. The drop in correlation coefficient (t = 90 minutes) is larger (AUC = 0.69) than the one of the feature extracted from the autoregressive model (AUC = 0.62). For the proposed features, the detection of the load position induced effects (operational changes) varies for different threshold values. Hence, even though a best feature may exist for a particular transducer pair and a specific threshold (as illustrated in Figure 10), it may be suitable to use

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the information from all features of all transducer pairs to reach an integrated better localization or detection of operation changes (such as crack opening or concrete damaging).

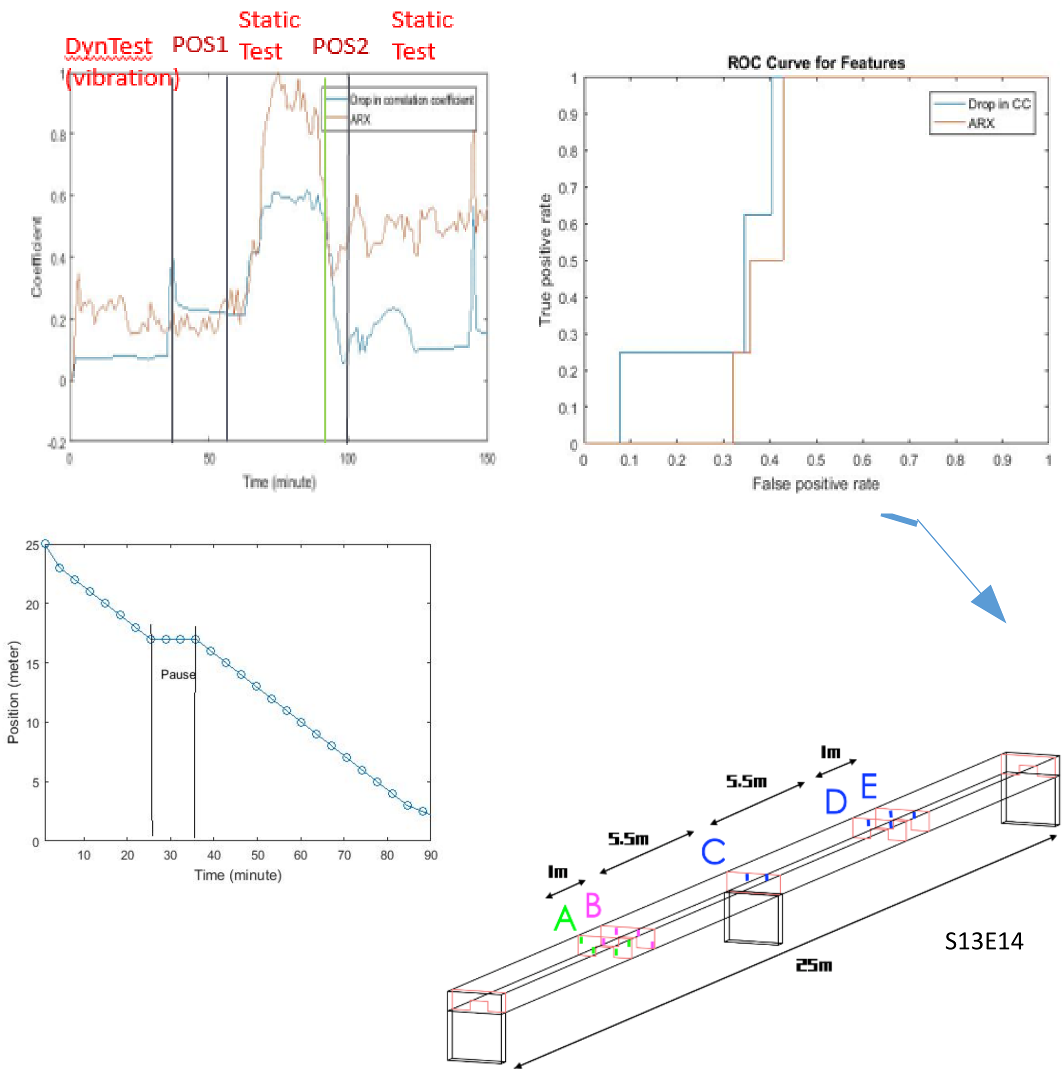

Figure 10: Results obtained the ultrasonic transducer pair 13-14 as a function of time during the loading experiment features (left top) ROC (right top), position of static loads (left bottom) as a function of time (55 minutes < t < 135 minutes) and position of sensor pair 13-14 in section E (right bottom).

The effect of additional features (like Differential Curve Length, Normalized mean square error, etc.) from all transducer pairs could be investigated for the localization of operational changes (like cracks). Furthermore, digital noise reduction (with oversampled signals) can improve the localization accuracy.

CONCLUSION

Results obtained during the first half of H2020-ITN-MSCA Infrastar project in the work package dealing with monitoring and auscultation show that information coming from sensors can efficiently be used to track and quantify:

- early damage in concrete (here cracks from 10µm to to 400µm) when using new fiber optic and coda wave interferometry embedded sensors;

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- strain experienced by the structure when using the 'pocket monitoring', to provide sufficient information for estimating the fatigue safety of an old structure subject to repeated loading (traffic and temperature).

The combination of localized and global information coming from sensors not using the same physics is highlighted for robust and advanced interpretation of measured data. Finally, it is important to remind that the spirit of European ITN project is to have the PhD students sharing their expertise to produce new advanced knowledge. The second half of Infrastar will be focused on joint work on risk based decision making, optimal maintenance planning, value of information, advance material behavior and action modeling (for RC and UHPFRC concrete) that uses at some point information coming from monitoring and auscultation methods. For example, a collaboration between the WP1 and WP3 is ongoing to use the data provided by the 'pocket monitoring' system to evaluate the reliability of the structure and to quantify the value of information of the monitoring system.

ACKNOWLEDGEMENT

This project (2016-2020) has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement no. 676139. The authors would like to extend a special thanks to Hakim FERRIA for the management of the project.

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