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Citation for the original published paper (version of record):
Fernandez, I., Gil Berrocal, C., Rempling, R. (2024). Making the invisible visible: Augmented Reality and Distributed Optic Fiber in educational
Structural Engineering labs. International Conference on Higher Education Advances: 169-177.
http://dx.doi.org/10.4995/HEAd24.2024.17142

10th International Conference on Higher Education Advances (HEAd'24)
Universitat Politècnica de València, València, 2024
DOI: https://doi.org/10.4995/HEAd24.2024.17142

Making the invisible visible: Augmented Reality and Distributed Optic Fiber in educational Structural Engineering labs

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How to cite: Fernandez, I.; Gil Berrocal, C.; Rempling, R. 2024. Making the invisible visible: Augmented Reality and Distributed Optic Fiber in educational Structural Engineering labs. In: 10th International Conference on Higher Education Advances (HEAd'24). Valencia, 18-21 June 2024. https://doi.org/10.4995/HEAd24.2024.17142

Abstract

In the present work a framework for the implantation of Augmented Reality in educational labs within the structural engineering field is presented. In order to close the existing gap between theory and practice in engineering courses, lab activities have been always an important media. However, due to the associated costs, both in time and economic resources, particularly in structural engineering where the test elements are big, the use of such labs is declining. Therefore, new approaches that enable the maximisation of the use of such resources while enhance the student's learning are paramount. In this regard, new technologies such as Augmented Reality, combined with top-notch sensing technology, applied in such lab activities are devised as a key step in that direction.

Keywords: *Educational labs; Augmented Reality; Enhanced learning; Structural Engineering*

1. Introduction

Structural engineering is the branch of engineering that takes care of the design and analysis of a large part of society's civil infrastructure such as roads, tunnels, bridges, dams, harbour piers, etc. Consequently, one of the main objectives of structural engineering courses in higher education is to provide students with the necessary knowledge and tools to be able to design and analyse different types of structures.

However, one of the persisting problems that have been identified in the assessment activities within structural engineering courses is that most students are unable to repeat a certain task or exercise as soon as minor changes are introduced in the assignment. This is indicative that students fail to grasp the physical meaning behind the equations and tend to memorize procedures without understanding the concepts, meaning they might succeed in passing an exam but fail in reaching the intended learning outcomes. Given that the theory and fundamentals in structural engineering have remained nearly unchanged for the last 150 years, the current problem cannot be attributed to the content of the subject. In trying to identify possible ways in which the learning process of the students could be improved, two main aspects have been considered: the media and the method.

Regarding the media (PowerPoint presentations or books), in the past, it had been hypothesized that did not play any significant role in the student's achievements and media were considered mere channels to carry information, see e.g. (Clark, 1983). Conversely, subsequent investigations postulated that the media influence the learning process of some students (Kozma, 1991). Today, there seems to be a general agreement that certain media, or combinations of them, can be more effective than others depending on the type of content to be communicated (Bates, 2015).

Additionally, as recently pointed out in an opinion article published in a Swedish online news website (Nandorf, 2017), one of the causes of the high number of dropouts in engineering compared to other subjects is that the content of the courses does not match the students' expectations. This situation could be partly due to the large amount of math courses that students need to go through during the first year, but it may also be attributed to a missing link between theory and real-world applications in more subject specific basic courses.

In this regard, educational lab activities are presented as a good solution to close this gap between theory and reality (Breunig, 2017; Gadola & Chindamo, 2019; O'Brien et al., 2021; Regev et al., 2008). However, due to large costs associated to lab within structural engineering courses, both in terms of economic resources and time, where the testing specimens are typically large, e.g. structural components such as beams or walls of several meters, a common trend has been to either eliminate them from course syllabus or replacing them by other activities such as Finite Element Modelling (FEM), which are typically more cost effective. In an effort to promote and recognising the added value of such occasions in order to help the students to meet the different learning outcomes of the course syllabus, the department of Architecture and Civil Engineering, and particularly the division of Structural Engineering, has made important efforts to introduce more lab activities in their courses and develop them to strengthen the outcomes and benefits of such activities in the students' learning. However still one of the biggest problems related to testing in the lab is how to enhance the students' learning, hence, how to maximise the ratio effort (economic and time) to benefit, or in other words enhance the students' learning deepening in the learning outcomes covered by the activity.

On top of that, an obvious limitation of a lab testing activities, is that it can be difficult to connect the background theory with what is happening in the element now of the lab occurs. An obvious reason that explains that is that typically the naked eye observations are quite limited. If that is true that they provide a different perspective form the observed phenomena, to couple the observation with the background theory or even with the internal response of the element, is not straight forward, what needs some level of abstraction and understanding about the topic.

Therefore, in this manuscript it is presented an implementation of a series of new enabling technologies that reduces such limitation and hence significantly enhances the outcome of the lab activity. In this regard two set of technologies are implemented; first the use of Distributed Optic Fiber Sensors (DOFS) that allows for a thorough description of the strain distribution inside the beam and second the use of Augmented Reality (AR), which combined to the DOFS data allows for making the invisible visible, enabling a different perspective of the test.

2. Theory and method

2.1. Sensing technology

As previously mentioned, one of the main problems of the current lab activities in education is the complexity to link the internal response of the structural element with visual observations. By implementing a distributed network of sensors to collect and transfer data regarding the real-time state of the structure, it is possible to know more of the structure response. In this regard, DOFS, based on Rayleigh scattering, is devised as good alternative for the activity purpose; systems using this technology can deliver unprecedented spatial resolutions, reaching down to the sub-millimetric scale, and thereby offering new possibilities for the development of damage detection and condition assessment.

2.2. Real-time web-based condition monitoring

A promising approach to obtain a deeper insight into the behaviour and condition of our element is the use of the so-called “digital twins”. A digital twin is a virtual replica of a physical asset that combines numerical modelling and updated sensor data to simulate and visualize the behaviour of its physical counterpart in real-time. In this study, our own concept of digital twin is developed, tailored to the educational lab activity needs. The concept relies on DOFS for the collection of data, cloud computing, and a web-based application as the user interface for the retrieval and visualization of results. The developed framework delivers the information in a clear and straightforward manner in near-real time, which is valuable for the students to better meet the learning outcomes. The system’s architecture devised in the present work can be divided into three main modules: Monitoring Module, Analysis Module, and Interface Module.

The Monitoring Module comprises the elements required to acquire measurements of physical properties of the structure, namely the sensors and the interrogator, as well as the devices used to enable remote access to the data, i.e., a gateway or router and a server. All the elements in the Monitoring Module must be physically placed at the location of the structure being monitored.

The Analysis Module includes a computer with specifically developed algorithms used to pre-process, analyse and post-process the sensor data received from the Monitoring Module. Thereafter, both the pre-processed and post-processed results are transferred and stored in a database from where data can be served to an external client on demand.

The Interface Module includes the elements that enable users to access and interact with the digital twin. In this study, a web application has been developed using different open-source frameworks and libraries to implement the front-end and back-end. The system's architecture showing the interconnection between the three modules and its components is schematically depicted in Fig. 1.

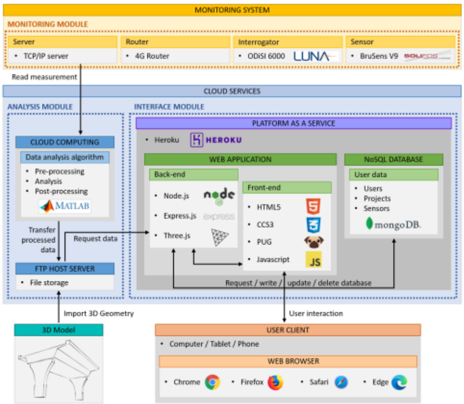

Figure 1. Schematic representation of the web-based asset management system's architecture.

2.3. Data analysis and visualization

A case study of a reinforced concrete beam subjected to flexural loading similar to the elements used in the structural engineering lab at Chalmers University of Technology is described to show the applicability of the presented system.

2.3.1. Beam geometry, loading and sensor deployment.

In Fig. 2, the geometry, test-setup and sensor deployment are carefully depicted for the reinforced concrete beam used in this case study. Further Digital Image Correlation was used as a reference system to validate the proposed methodology.

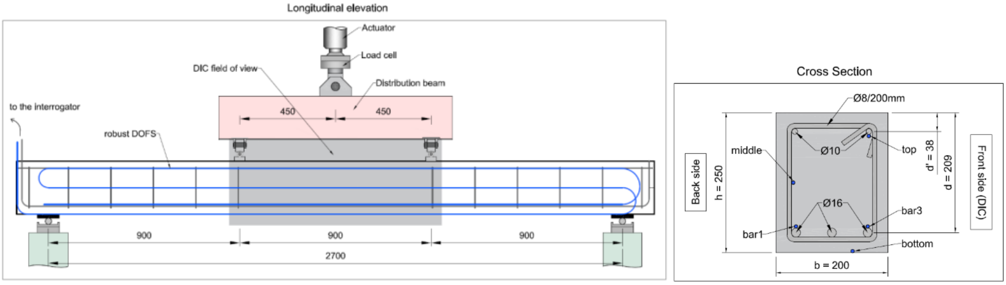

Figure 2. Geometry, loading setup and DOFS installation configuration for the RC beam specimen.

2.3.2. Analysis of sensor data

In most cases, raw sensor data do not provide useful information that can be directly interpreted. Therefore, the collected data must be processed and analysed to increase data value. For this concept, based on Euler-Bernoulli beam theory, the curvature distribution of a beam can be obtained by deriving two times the deflection with respect to the spatial coordinate along the beam axis. Consequently, a method has been implemented to back-calculate the beam deflections by integrating the curvatures twice, obtained from the strains measured by DOFS, and applying the right boundary conditions, i.e., zero deflection at the supports.

Further, it has been previously shown that the existence of cracks is evidenced in the strain measurements of DOFS embedded in concrete by the presence of strain concentration peaks, as illustrated in Fig. 3, and compared to the DIC measurements. The gradual merging of the strain peaks is likely due to the progressive deterioration of the steel-concrete bond with increasing load. This observation suggests that crack detection should be performed as a recurrent process taking the load history into account.

Subsequent to crack detection, the estimation of the crack width is addressed. A method proposed by the authors in (Berrocal et al., 2021), which is based on the mechanical models included in current structural design codes, is used in this study. The proposed method can be effectively used to estimate the crack width of individual cracks provided those are correctly identified and isolated by the DOFS.

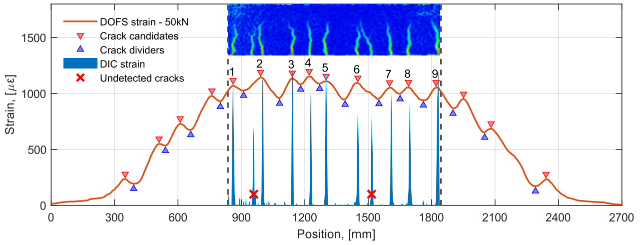

Figure 3. Determination of crack location based on DOFS.

2.3.3. Data post-processing for improved visualization

For this method to be useful to the students and the data to be of practical use, the analysed data must be conveyed in a clear and accessible way. One of the most straightforward and intuitive ways to present this type of data is through contour plots. The development of such contour plots requires that DOFS measurements are available in at least two levels, or in this case heights of the beam, where the greater number of levels will produce more accurate contour plots. In this case three different contour plots were considered relevant for the comprehensive behaviour of the beam behaviour: 1) strain distribution along the beam, 2) deflection distribution along the beam and 3) crack distribution and propagation. The first two can more or less be obtained directly from the DOFS measurements, i.e. assuming Bernoulli Theory as previously described, both strains and deflections can be computed as a linear interpolation in the direction of the beam height for each longitudinal coordinate. The later requires transforming the strain profiles into crack profiles, which hold the relevant information about all the cracks, i.e., their position and width. This is achieved through "crack functions" the value of which is zero everywhere except in the vicinity of the cracks, where they present a peak of value equal the width of each crack. Further information about this procedure can be found in (Berrocal et al. 2021).

The crack contour plot obtained after completing the entire post-processing of the cracks is shown in Fig. 4. As observed, the result of the described procedure provides a quick and straightforward way to read critical information about the cracking condition of RC elements.

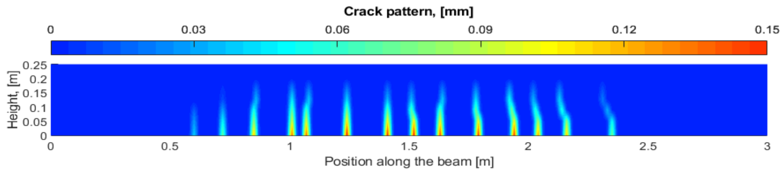

Figure 4. Visualization of crack width and position in the beam

2.4. Augmented Reality

In recent years the interest in Augment Reality (AR) for different applications has significantly increased, mainly driven by new hardware, such as Microsoft Hololens, as well as availability of feature-rich AR frameworks for mobile phones and tablets, such as ARKit (Apple) and ARCore (Google). Additional recent efforts have devoted to bring AR to the web through a new web-based AR framework called WebXR, which opens for the possibility to support a wide range of devices with a single source code.

Therefore, a web-based solution based on WebXR was chosen in this application for the AR-tool. In order to render the plots, the web-rendering framework Three.js was implemented. An important challenge when using AR and data visualization overlayed is the alignment between real element with its virtual representation in order to present and augment accurately the sensor data. In this particular case, the WebXR framework utilises three aspects that allows the tool to locate the user/camera in the space and therefore identify objects for further interaction.

Anchors. Modern AR systems use a technique called simultaneous localization and mapping (SLAM) to construct an internal 3D representation of the environment. Instead of a fixed position in space, anchors provide virtual positions in relation to physical locations. That is, relation between physical and virtual object are prioritized before absolute positions in space.

Image and marker tracking. WebXR provides functionality to track images or more typically “markers”, like a QR code. During the session, WebXR will identify the previously stored images and provide information when detected such as position and orientation.

Alignment. Placement and alignment of virtual objects can be done in several different ways. A common approach to proceed with the alignment is to control where a virtual object should be placed by using a “marker”/image. The WebXR session will then detect and track this image and report a position in 3D-space where a virtual object should be positioned and rendered.

3. Results and discussion

In order to simplify the 3D plotting in the real-word space, a marker-based solution was chosen. As illustrated in Fig. 5(a), this approach requires two markers to be placed equally apart from the edges of the beam, so that a mid-point between the markers identifies the origin of the global coordinate system. Theoretically a single marker would also work well, in practice it would be more sensitive to any tilting of the images and therefore two markers were preferred due to the length of the specimen. Hence, once the two markers are identified, the virtual beam can be positioned at the real-world origin. So, in order to align the virtual and physical beam, the user only needs to make sure that the mobile device detects the two markers, as seen in Fig. 6. Upon detecting the images, two anchors are created internally, and the virtual beam is aligned to the real one, hence a wireframe 3D model of the beam is displayed, see Fig 6(right).

A user interface was specifically developed in order to be able to plot the relevant data. WebXR was chosen as framework for the AR interface as it allows the use of conventional Hypertext Markup Language (HTML) and Cascading Style Sheets (CSS) to define and style a web interface and then renders all the graphics as an overlay to the AR interface. As illustrated in Fig. 5(b), the simplified interface makes is possible to display strains, cracks, or deflections using a contour plot overlay with max and min values presented. In addition, it is possible to select a specific timestamp using a slider in order to retrieve time-history data. Using this interface, it is then possible to walk around freely and inspect any part of the beam at the same time as strains, cracks, or deflections can be visualized for specific load levels.

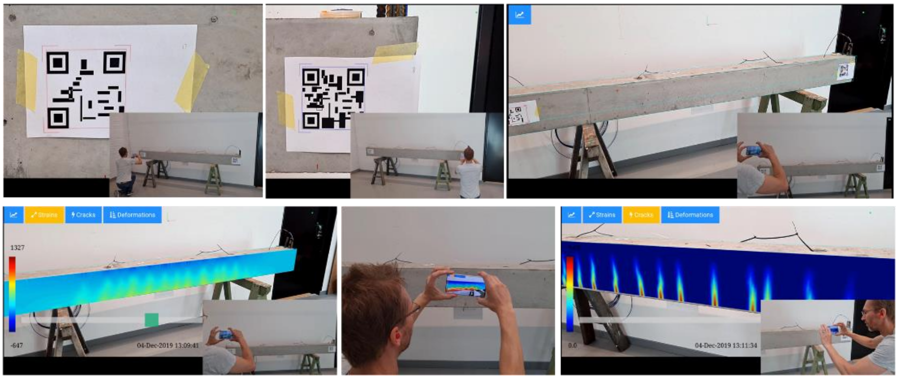

Figure 5. (a) Procedure to align the real and virtual beams in the AR tool using two markers. (b) The AR Tool interface (https://youtu.be/y8yFHzpmzI8)

4. Conclusions

This work explored the possibility to enhance traditional educational lab activities with novel enabling technologies to increase the student's learning of structural engineering courses. The following conclusions can be made:

- The incorporation of AR in educational lab activities opens for a vast number of possibilities in order to convey better the different learning outcomes, to establish stronger links theory/reality and in summary to maximize investments (both time and economic).
- In the current iteration of the tool, deflections, strains, and crack development are quasi real-time visualized and overlayed on the beam through AR. This already allows to show aspects of the structure behavior that were not possible to see else. However, the possibilities to show more detailed aspects such the sectional behavior of critical cross-sections, in combination with the material response together with the actual beam are huge.
- Even though that the activity has only been conducted once and no direct assessment comparing the lab with and without the AR implementation is carried out, the students showed appreciation and a better understanding with on-site questions about the different observations.

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