# Development of VR/AR applications for experimental tests of beams, columns and frames

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## Abstract

This paper depicts a set of virtual reality (VR) and augmented reality (AR) applications conceived for the enrichment of laboratory experiences within the field of structural engineering. The experimental program correspond to the study of beams, columns and frames of austenitic stainless steel subjected to different types of static loading. The development of these applications encompasses the use of measured data from sensors, the use of 3D modelling tools, the use of game engines, and the corresponding mathematical treatment and post-process of the structural tests in a real-time fashion. The developed applications provided new possibilities for structural engineering laboratory experiences. In both cases (VR and AR), the developed applications were meant to enhance the experimental program experience to a variety of target users (researchers, technicians, students) by adding customized information related to the structural behavior of all elements during the tests as well as to basic concepts of health and safety in structural engineering laboratories.

**Keywords:** Virtual Reality, Augmented Reality, Tests, Structural elements

## Introduction

The role of structural engineering laboratories in the development of research, design and education within the Architecture, Engineering and Construction (AEC) fields is paramount. Research on new materials and/or structural configurations, the use of design assisted by testing or the relentless development of structural monitoring and control are only few of the needs that are routinely addressed and solved worldwide in those facilities. Historically, instrumentation and control in structural engineering laboratories has included cutting-edge high-precision measurement techniques from which strains, displacements, forces, accelerations, pressures and several other physical magnitudes are gathered. Routinely performed tests on structural elements include sensors, data acquisition systems and classical visualization of measurements in the form of plots, bars or numbers. Usually, during the tests, the gathered data is recorded and the analysis of the results is only performed afterwards via post-processing.

Measurement techniques and the degree of sophistication of the tests performed in structural engineering laboratories as well as in construction sites have evolved considerably. The data acquisition has experienced a surge both quantitatively and qualitatively. Classical tests on structural elements, are nowadays infused with data-intensive techniques such as digital image correlation (Lee et al. 2012), ubiquitous and innovative sensors (Sony et al. 2018), terrestrial laser scanning (Olsen et al. 2010), or tests based on hybrid simulations (Del Carpio Ramos et al. 2015). Therefore, a need of massive data-management tools as well as of massive data-visualization techniques emerges not only for laboratory facilities but also, for structural control at construction sites. Several technological players are providing potential frameworks for the creation of both standard data-management hubs as well as for the creation of data-visualization interfaces.

For data-management, Building Information Modeling (BIM) tools are becoming main players when it comes to centralize information related to design (different information layers interact in the same model). Centralizing data at design stages for the corresponding interoperability in construction has been a great challenge in recent years (Hardin and McCool 2015, Cerovsek 2011). Integrated models encompassing all stakeholders present manifold aspects such as 3D modeling, constructability, structural analysis, material management and post occupancy evaluation. These fields are increasingly interacting throughout platform-neutral specifications such as Industry Foundation Classes (IFC), a data model intended to describe building and construction industry data or the Linked Building Data.

For data-visualization, endless alternatives are available in many fields. The level of sophistication when it comes to data-visualization techniques increases relentlessly in other areas and thus, the AEC sector is continuously infused with such possibilities. Particularly in construction, Digital Twins (Kaewunruen and Lian 2019), Serious Games (Rüppel et al. 2011), Virtual Reality (VR) (Kim et al. 2013) and Augmented Reality (AR) (Behzadan and Kamat 2013) applications are data-visualization techniques that have been continuously explored.

In this paper, a set of VR and AR applications aimed at enriching tests on structural elements are developed and assessed. These applications were conceived and assessed as potential experience- and cognitive-enhancers for different user groups. The experimental program on which the application were developed correspond to real tests on beams, columns and frames of austenitic stainless steel subjected to different types of static loading. The development of the applications encompassed the use i) game engines in the development of VR/AR applications ii) the use of measured data from sensors and the corresponding mathematical treatment and post-process of the structural tests in a real-time fashion and iii) 3D BIM tools able to centralize data in adequate standard form. The observations performed during the development and the corresponding appraisal allow pinpointing advantageous and challenging remarks in the potential of VR/AR in structural engineering experimental environments.

## Literature review

### *VR/AR in research and education*

VR and AR technologies are relatively well-established tools with a diversity of applications spanning many fields. VR is an interactive simulated environment generated with computers (Sherman and Craig 2018) which replaces the user's physical world with a fully synthetic environment. The interaction between such environment and the user is typically generated with special screens, sound systems and joysticks embedded in customized helmets or glasses. AR is a real-world environment enriched with layers of information that are perceived by the user by means of multiple modalities. Screen-infused glasses with embedded hardware are one typical application of AR systems. In such scenario, the user's awareness of the real environment is preserved by compositing physical/virtual worlds in a blended space (Craig 2013). The user sees the real environment and layers of graphical information (or text) that is added and updated in real time. Although both VR/AR technologies are decades old in their simplest forms, the societal perception of these technologies is not as mature as the technologies themselves. The level of sophistication has increased with the relentless improvement in Hardware and Software and consequently, better CPUs, GPUs, data-storage facilities and cloud computing have enabled the use of more affordable gear to all kinds of developers. One of the uncontested contributions of VR/AR is their potential to enhance sensorial perception as well as to trigger advanced learning to users by means of immersive experience since realistic immersive creations represent tools for visual communication of massive data. In the particular case of VR/AR, benefits from 3D visualizations can be highlighted at educational (Chi et al. 2013), design (Dong et al., 2013) and construction stages (Behzadan et al. 2015).

From a pedagogical point of view, the cognitive-enhancement capabilities provided by VR/AR technologies have been studied in many fields such as economics (Innocenti 2017) neurosurgery (Pelargos et al. 2017), cultural tourism education (Chiao et al. 2018) and pedagogy (Rau et al. 2018), to cite a few. In the AEC field, attention has also been paid to the pedagogical benefits that VR/AR technologies provide. Research aimed at assessing the cognitive effects of VR/AR techniques on the increase of spatial abilities in engineering graphics courses has been presented (Chen et al. 2011). Systematic reviews on this topic are also available (Keenaghan 2014). Attempts for infusing AR mobile-based tools as information delivery tool have successfully been implemented in classroom-scale experiments to enhance traditional lecture-based instruction and information delivery methods (Shirazu and Behzadan 2015, Behzadan & Kamat 2013).

At the analysis/design stage of AEC projects, VR/AR tools have been developed in several forms (Kim et al. 2013). From systems that integrate real-time simulations based upon Finite Element (FE) models and AR technologies (Huang et al., 2015) to systems that provide enriched information to designers in processes of piping assemblies (Hou et al. 2015), VR/AR technologies prove usefulness at decision-making levels of design. In (Turkan et al., 2017), advanced interactive 3D visualization techniques were piloted for enhancing students' perception and understanding of load effects, load paths and in general, the ability to understand the deformed shape of simple structures. Moreover,, in (Ge and Kuester, 2015), an integrative data analysis environment for conceptual structural analysis is presented. Design, modeling and simulation are integrated together with sensors, devices and interfaces. The results presented in these papers suggest that standard framework are desired when integrating sensor measurement, Finite Element Analysis (FEA) simulation, design and scientific visualization into AR-based environment. This integration facilitate data post-processing and interpretation of results.

At the construction site, as well as in all aspects related to construction (including safety management), a fairly varied ecosystem of VR/AR tools has been presented in academia. In particular, AR tools aimed at enriching the construction discussion have been presented in academic journals and conferences in the field (Fernandes et al. 2006, Lin et al. 2015, Kassem et al. 2017). One of the fields in which VR/AR have been explored considerably is the one related to safety management. VR/AR-based experience- and cognitive enhancers aimed at generating multi-modal levels of awareness for workers/researchers and students alike can be found in (Li et al. 2018, Park and Kim 2013, Rüppel and Schatz 2011). VR serious games have been developed for hazard management and evacuations during disasters (Lovreglio et al., 2018).

In the particular topic of laboratories, experimental tests infused with augmented reality have been documented in academia in recent years. AR applications have been developed in science laboratories for the sake of enriching cognition (Andújar et al. 2010, Akçayir et al., 2016, Smith et al. 2016). These studies were fundamentally focused on studying the effect of AR on skills and attitudes towards experimental testing. Examples of use of AR in laboratories of chemistry (Yee et al., 2018), earth sciences (Vaughan et al, 2017) and medicine (Hanna et al., 2018) are documented. In the particular case of structural engineering, information is less abundant. (Basías et al., 2018) developed experiments in simply supported and cantilever beams provided with perspective projection video cameras and markers to track the beam motion during different types of loading. The goal of this study was to embed reduced order modeling in physical experiments for the sake of augmenting video streams through numerical simulations. These models proved interesting for such visualizations since they provide cost-effective numerical solutions of highly nonlinear problems with less computing capacity. In such research, neither sensors nor 3D rendering engines were used.

### *VR/AR in BIM environments*

Moreover, the development of VR/AR applications that infuse real-time measurements generally implies intensive use of i) 3D modeling tools, ii) the use of multi-user platforms capable of rendering data-infused real-time applications and iii) the use of data in standardized form. BIM-based technologies allow centralizing all types of information in data-hubs. The parametric abilities, the multi-purpose nature of BIM-based platforms and their data-aggregation and analysis satisfy the needed requirements for their use of VR/AR in construction. Applications of VR/AR in the AEC field are not only meaningful due to their visualization capabilities but also, to their contribution to all workflows, processes, technologies and behaviors that BIM increasingly offer. Although the topic of data-driven analysis in BIM platforms is out of the scope of this case study, it is observed that the evolution of data-standardization in recent years is paramount for the development of integrated interoperable tools (Cerovsek 2011, Hardin and McCool 2015, Li et al. 2017). The navigation from BIM platforms to/from game engines implies working on problems such as latency (Du et al. 2018), model updating, data-flow and real-time rendering (Yan et al. 2011) of the applications. Usually, tracking and sensing technologies such as radio frequency identification (RFID), laser pointing, sensors and motion tracking are needed for the sake of increasing the effectiveness of such applications (Wang et al. 2013).

To tackle the interoperability issue, academic consensus suggest the adoption of Industry Foundation Classes (IFC) as the data exchange schema between BIM and other computerized maintenance management systems (Shalabi and Turkan 2017). Monitoring and control BIM tools, which heavily rely on proper data-acquisition from sensors, are increasingly based on standards defined by IFC (Theiler and Smarsly 2018, Ding et al. 2017). Cloud services for ubiquitous sensing in AEC are generally based on JavaScript Notation Formats (JSON) which represent a popular lightweight data-interchange format for numerous AEC-related Software and web applications (Afsari et al. 2017). Notwithstanding, other initiatives based upon semantic web ontologies such as the Linked Building Data also provide conceptual frameworks for the development of BIM-based interoperable applications (Gómez-Romero et al. 2015, Radulovic et al. 2015).

### *Summary*

Summarizing, the literature review allows pinpointing some remarks:

- VR/AR applications are found in the AEC in particular, at construction stages as cognitive enhancers for workers. Health and safety regulations infused with VR/AR is an active research topic. On the other hand, at design stages, academic papers are less abundant. Some authors suggest that standard framework are desired when integrating sensor measurement, Finite Element Analysis (FEA) simulation, design and scientific visualization. This integration facilitate data post-processing and interpretation of results. In addition, developing frameworks following BIM allow considering data flow in a standard fashion.

- Education-wise, VR/AR applications have been developed and academically documented in numerous fields (Akçayir & Akçayir, 2017, Ibañez & Delgado-Kloos, 2018). Nevertheless, academic record related to the use as a cognitive enhancer is mainly focused on the use of VR/AR based on static information (layers with meaningful yet asynchronous information that is uploaded and stored prior to its usage).

- Laboratory applications in which VR/AR tools are developed can be found in some fields. Sciences, medical and chemistry laboratories are among those in which academic papers can be found. VR/AR applications in civil engineering aimed at enriching laboratory experiences (both research- and education-wise) are, however less abundant.

In this paper, an integrative set of VR/AR applications encompassing simulation and laboratory applications infused with sensors is developed. This approach includes systems and parts of systems that are found in the literature but in this case, the novelty stems in its integration within the field of experimental structural engineering. These applications are conceived for various target users (researchers, students and technical staff) belonging to a vast experimental program on beams, columns and frames described in the following sections.

## Experimental program

The experimental program on which the VR/AR applications have been developed corresponds to a series of tests on EN 1.4301 austenitic stainless steel beams, columns and frames. The test were performed at the structural and materials technology laboratory LATEM at the Polytechnic University of Catalonia, Spain. The experimental program belongs to a research project aimed at studying the behavior of stainless steel frames under accidental actions both experimentally and numerically. The experimental program covers the study of stainless steel structures at material, member and structure levels including variations of cross-section (compact, semi-compact, slender) and global slenderness (sway, non-sway frames). The numerical program covers a broader range of studies including the behavior of frames subjected to static, seismic and fire loading. The experimental study includes both traditional high-precision measurement techniques for loads, displacements and strains as well as novel measurement and data-gathering techniques such as DIC, real-time visualization of the results in the form of digital twins, the use of cloud-based platforms for data storage and VR/AR immersive tools for the enhancement of the tests experiences. In this case study, only the general organization of the tests and results related to VR/AR applications are depicted. Figure 1 shows lateral views of the tests whereas Table 1 displays nominal geometries of all elements as well as some particular observations of each test. Further details about the experimental program on members and frames can be found in (Arrayago et al. 2019[a], Arrayago et al. 2019[b], Arrayago et al. 2019[c]).

The tests on stainless steel beams consisted of 4 simply supported 1700 mm long specimens. Two concentrated loads were symmetrically applied as shown in Fig. 1 (a). The variation between elements was related to cross-sectional properties. The elements cross-sectional behavior ranged from compact to slender. The tests consisted on static incremental loading of the specimens. Sensor-infused VR applications were developed for visually enriching the experiments. For this purpose, the vertical deflection $\delta_{\text{beam}}$ at mid-span was measured by using a distance sensor. Under the assumption of elastic beam theory and neglecting all geometrical and material nonlinearities, the behavior of the structure was characterized by this single magnitude at this stage.

The tests on stainless steel columns consisted of 8 pinned-pinned 1500 mm long specimens. The variations between elements were related to cross-sectional properties as well as to the position of the element during the test (since both major and minor axes were tested). The tests consisted on incremental axial loading of the specimens. VR applications were developed for these experiments. For this purpose, the horizontal deflection $\delta_{\text{column}}$ at mid-span was measured by using a distance sensor. Under the assumption of elastic buckling theory in beams and neglecting all geometrical and material nonlinearities, the behavior of the structure was characterized by this single magnitude. Fig. 1(b) displays lateral view of the test deployment.

The tests on stainless steel frames consisted of 4 one-bay one-story specimens as indicated in Fig. 1(c) . Two frames were designed as sway whereas the other two frames were designed as non-sway. All tests followed the same procedure. First, a vertical load $P_v$ was applied up to a pre-determined value (and held constant during subsequent steps). Second, a horizontal load was applied incrementally until failure. The application of this horizontal load was performed by means of a hydraulic jack that pushed a rigid beam laterally. The rigid beam was connected to both bottom ends of the frame whereas the upper beam-to-column joint was fixed. It is worth noticing that due to laboratory requirements, the imposed displacement $\delta_{frame}$ was located at the bottom part. The main reason of this arrangement is the vertical load application, since hydraulic jacks were fixed in a vertical line. The horizontal displacement $\delta_{frame}$ of the rigid beam was measured by using a distance sensor. Under the assumption of elastic buckling theory in frames, neglecting all geometrical and material nonlinearities and using the vertical load as a known of the problem, the behavior of the structure was characterized entirely by $P_v$ and $\delta_{frame}$. AR applications were developed for these experiments.

## Design of the system

All VR/AR systems were developed entirely from scratch. Three premises were set when developing these systems: i) the system ought to provide platform inter-operatibility, ii) the system addresses all parts of the information (from sensor to visual perception by end-users) and iii) the tools must be as versatile and replicable as possible. Figure 2 shows the basic parts of the system as well as the identified data-flow that was used for the conception of all parts. From left to right, one can observe how data is generated by sensors and transmitted to web servers. In this particular study, data was sent in JSON format to a game engine as well as to adequate mathematical post-processing (coding platforms). Post-processed data was also sent from mathematical post-processing in JSON formats to game engines. In addition, 3D models were rendered in platforms based on standard BIM capabilities and exported to game engines. Finally, at the game engine stage, all acquired data was used for the development of real-time visualizations of information in both VR and AR applications. Versatile data-formats are thus required in order to provide smooth data-exchange. Detailed description of all parts are separately presented.

### *Data measurement and transmission*

Sensors were installed in order to measure $\delta_{beam}$ and $\delta_{column}$ intended for the development of VR applications as well as $\delta_{frame}$ for the development of AR applications. All measurements followed a similar principle. Data was gathered from sensors connected to electronic prototyping platforms and sent subsequently to other platforms and/or web servers. For all cases, distance was measured using a HC-SR04 ultrasonic sensor. The principle of this sensor is to generate high frequency sound and then calculate the time interval between the sending of signal and the receiving of echo. The measurement range of the sensor (5cm-100cm) was broad enough for the designed applications (in other applications, more precise laser sensors may be needed).

In beams and columns, the sensor was connected to a Arduino Nano board (Arduino 2018), which was connected to a laptop directly. Data was gathered and sent both locally to a game engine (Unity, 2018). Simultaneously, data was also sent to a platform developed at the School of Civil Engineering as a Cloud Service for civil engineering laboratories and academic use (Smartlab 2018).

In frames, the sensors were connected to a ESP32 prototyping board provided with Bluetooth and Wi-Fi capabilities (Expressif Systems 2018). The vertical load $P_v$ was provided directly by the actuator (and held constant during the test). $P_v$ was introduced manually to the app interface at the beginning of each test. Data was sent from the board to the server via Wi-Fi from which other applications retrieved the info under request. Figure 3 shows basic connections, circuitry and implementation of the devices for beams, columns and frame tests.

### *Data processing*

In beams and columns, the mathematical treatment of data was straightforward. Both $\delta_{beam}$ and $\delta_{column}$ were used for inferring characteristics of the structural behavior of the members (applied loads and deformed shape). On the one hand, $\delta_{beam}$ allowed obtaining information about the deformed shape of the beam as well as of the applied load. Under the assumption of linear elastic bending according to a Bernoulli formulation, the set of equations is presented in (1) to (6). Figure 4(a) shows the structural model of beams. From this formulation, the deformed shape z(x) is expressed as a function of the characterizing magnitude $\delta_{beam}$ as well as of the geometric proportions *a* and *L*.

$$z\left(x\right)_{a-c} = \frac{P\cdot x}{6EI}\cdot\left(3\cdot a\cdot L - 3\cdot a^2 - x^2\right) \tag{1}$$

$$z\left(x\right)_{c-d} = \frac{P\cdot a}{6EI}\cdot\left(3\cdot L\cdot x - 3\cdot x^2 - a^2\right) \tag{2}$$

$$z\left(\frac{L}{2}\right) = \delta_{beam} = \frac{P\cdot a}{24EI}\cdot\left(3\cdot L^2 - 4\cdot a^2\right) \tag{3}$$

$$P = \frac{24EI\delta_{beam}}{a\left(3\cdot L^2 - 4\cdot a^2\right)} \tag{4}$$

$$z\left(x\right)_{a-c} = 4\delta_{beam}\cdot x\frac{\left(3\cdot a\cdot L - 3\cdot a^2 - x^2\right)}{\left(3\cdot a\cdot L^2 - 4\cdot a^2\right)} \tag{5}$$

$$z\left(x\right)_{c-d} = 4\delta_{beam}\frac{\left(3\cdot L\cdot x - 3\cdot x^2 - a^2\right)}{\left(3\cdot a\cdot L^2 - 4\cdot a^2\right)} \tag{6}$$

On the other hand, $\delta_{column}$ allowed obtaining information about the deformed shape of the column. Under the assumption of linear elastic buckling according to the Euler formulation for ideal members, the set of equations with which these magnitudes are connected is presented in (7) to (12) and illustrated in Figure 4(b). The deformed shape z(x) is expressed as a function of the lateral deflection $\delta_{column}$ and the total length L.

$$EI\cdot z''\left(x\right) + N\cdot z\left(x\right) = 0 \tag{7}$$

$$k^2 = \frac{N}{EI} \tag{8}$$

$$z(x) = A\cos(kx) + B\sin(kx) \tag{9}$$

$$BC \quad A = 0 \qquad B \neq 0$$

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$$z(x) = B\sin\left(\frac{\pi}{L}x\right) \tag{10}$$

$$z\left(\frac{L}{2}\right) = B\sin\left(\frac{\pi}{L}\frac{L}{2}\right) = B = \delta_{column} \tag{11}$$

$$z(x) = \delta_{column}\sin\left(\frac{\pi}{L}x\right) \tag{12}$$

In both cases, one single measurement provides enough information for characterizing the shape of the members. The data processing allowed generating animated objects based on shapes resulting from classical theories and enriched with real measurements.

In frames, the mathematical treatment of data presented a slightly higher degree of sophistication. Both $P_v$ and $\delta_{frame}$ were introduced in a structural planar model of a frame implemented in Matlab (Matlab 2018) using a classical stiffness formulation solved by means of linear algebra. Under the assumption of linear elastic bending according to a Bernoulli, the pair of values [$P_v$ ; $\delta_{frame}$] generated results related to all reactions at fixed points [$R_x$, $R_y$, $M_z$] as well as to the distribution of internal axial, shear forces and bending moments in all elements [N,V,M]. Figure 4 (c) displays schematics of the frame to be solved according to the test setup. The set of variables are solved in matrix form and the displacement $\delta_{frame}$ of both ends is introduced as a known boundary condition within the formulation.

It is worth pointing out that for all cases, the constitutive equation of the material was considered to be linear. This assumption facilitated the mathematical processing of the results at this stage. Full generality may be achieved if the non-linear behavior of the material largely depicted by (Arrayago et al., 2017) is included in all formulations. Likewise, it is interesting to point out that more sophisticated tools such as FEM can be linked t

### *Data visualization*

Finally, treated post-processed data was sent to a game engine in JSON format. The visualization of the data was different for VR and AR applications. Firstly, in beams and columns, an immersive 3D model intended to recreate the laboratory facilities was developed in Revit, a commercial fully functional BIM-infused platform (Revit 2018). This virtual synthetic facility was exported to Unity. At this stage, the render of the 3D lab was *static*. With the usage of a VR headset, users located anywhere are able to navigate throughout the whole facility by means of tele-transportation, a popular feature that is usually used in VR applications when appropriate remote controllers are connected to the VR headset. The user of the synthetic lab may or not be subjected to physical restrictions that are present in laboratory facilities such as safety ribbons, obstacles or similar features. Figure 5 displays general views of the reproduced synthetic environment and corresponding similar pictures of the same view. Furthermore, animated objects were also rendered.

At this stage, the animation transformed the render of the 3D lab was *dynamic*. The principal feature of these animations was related to the capabilities for acquiring data that shaped both beams and columns according to mathematical relationships. These objects were specifically designed in the form of rectangular hollow sections RHS. These Revit objects were thus generated and sent to Unity. Though imperceptible, a certain degree of latency was noticed when this procedure was used. When animated objects were directly created in Unity, no latency was observed. The animated beams and columns were thus scaled in shape according to the measurement performed throughout the incremental loading as seen in Figure 6. In this case, users need to connect the Unity environment to the web server from which real-time data is retrieved.

In the case of frames, augmented reality glasses (Hololens) were used for visualization purposes. These glasses provide regular vision of the environment but on top of that, layers of information are added. In the particular case of frames, the user needed to be located near the test area during the experience as shown in Figure 7.

Data obtained at the post-processing stage was stored in vector forms including all reactions and internal forces of the whole structure. This information was formatted in JSON format and used for the creation of customized layers of data in the form of diagrams, arrows, buttons, lines and floating text boxes. Thus, the AR application was conceived as a tool that allows the user to understand in real-time, the static behavior of a frame subjected to a particular set of loads and boundary conditions. The AR visualization was conceived for its implementation in the system embedded in Microsoft Hololens glasses using Vuforia (Vuforia 2018), a Software Development Kit (SDK) that allows operation between the Hololens OS and Unity. These glasses communicate via Wi-Fi and/or Bluetooth with the server. Figure 8 displays four elements that are included as information layers: i) buttons, ii) lines, iii) text and iv) arrows. Moreover, the tool was provided with other objects such as safety ribbons. These objects defined the boundaries of a limited area in which the user was not allowed to enter during the test (alarms and warnings were set to appear in such a case).

Figure 9 shows a screen capture of the Unity work space in which the enclosed area of the test limited by the safety ribbon is shown. Other objects can also be seen in this figure (text boxes, lines, arrows).

## Implementation of the system during the tests

VR and AR applications were gradually implemented in all tests depicted in section 3. The number of tests (4 beams, 8 columns and 4 frames) allowed exploring different aspects of design in terms of functionality as well as in terms of usefulness of the applications. An iterative design was performed throughout the development of the experience. Details related to the whole system (from measurement to visual applications) were enhanced slightly from one experiment another. More realism, better synchronization and enhanced quality were added at each iteration. Beams, columns and frames were tested following this order resulting in first developing VR applications and subsequently, AR tools.

### *VR applications in beams and columns*

Tests on beams and columns were provided with sensors and microcontrollers located at key points. Figure 10 displays the location of the ultrasonic sensor under the beam (measuring vertical deflection at mid-span) and next to the column (measuring horizontal deflection at mid-span). Following the information path depicted in section 4, measured data fed continuously the 3D model. The result was a real-time reproduction of the test within a synthetic environment. Non-present users provided with any VR headset connected appropriately to the web server may remotely though synchronously recreate the experimental test. Figure 11 displays graphical comparisons between the real test in beams and the corresponding 3D reproduction. Figure 12 shows a similar comparison but in this case, in columns.

### *AR applications in frames*

Tests on frames were also provided with sensors and microcontrollers located at key points. An ultrasonic distance sensor was located next to the sliding surface on which the supports were located as shown in Figure 13(a). In addition, recognition markers were needed to anchor the spatial location of the floating objects with respect to the actual location of the tests as displayed in Figure 13(b). These elements allow for the AR glasses to develop a spatial recognition of the working space. Markers are arbitrary images with clear patterns defined by the developer. The markers must be located within the testing premises (with the available equipment, these premises were limited to an imaginary square of 4 meters width). Once properly recognized, layers of information are placed correctly on top of the desired objects . As the user moves around the location of the frame, all layers adapt and float accordingly on the right spatial position.

Following the information path depicted in section 4, measured data fed continuously the animated objects. The result was a real-time augmentation of the test reality for both experience enhancement. Present users provided with Hololens were able to recreate synchronously the experimental test with added layers of information such as axial, shear and bending moment diagrams or the resulting values of reactions at supports. Figures 14 to 16 display several captures of the visual enhancement the user may get when experiencing the AR application. Diagrams, values and drawings are located spatially in such a way that moving users perceive these information layers as existing on top of the frame geometry (automatic adaptation of the spatial location).

### *Discussion*

The developed applications provided insightful information to users during the development of the tests. One aspect of the developments of such applications was to use a framework integrating sensor measurement, simulation, design based on BIM environments and scientific visualization of results. For this proof of concept, the mathematical problems that were solved were linear and based upon simple closed-form solutions. The system was conceived in way more sophisticated tools such as FEM can be also embedded as mathematical engines.

VR applications were meant for users that are not necessarily present within the laboratory facilities whereas AR applications were meant for users that are necessarily present within the laboratory premises. In VR, any user at any place with a synchronous connection may experience the development of the test remotely. Immersive 3D reproductions of laboratories coupled with animated representations of the tested specimens can be blended in a virtual reality space. In AR, users can experience an enriched version of a structural test *in situ* without losing awareness of the real environment. Both applications are complementary and can be used simultaneously. A systematic appraisal of the deployed applications is presented in the following section.

## Appraisal of VR/AR applications in structural engineering laboratories

Both VR and AR applications were successfully implemented in the depicted tests. The focus of the development was concentrated in data acquisition, data processing and data visualization. From a mathematical perspective, in both cases, all formulations were linear and derived using closed-form analytical solutions. The visualization of these results was related to deformed shapes and response magnitudes in the form of diagrams and reactions. In the following, a comparison between systems as well as between users' perception is presented.

### *Comparison between VR/AR systems*

VR is an interactive fully synthetic environment generated with computers that replaces the user's physical world. AR is a real-world environment enriched with layers of information. In the latter, the user's awareness of the real environment is preserved by compositing physical/virtual worlds in a blended space.

From the perspective of the laboratory experience, AR showed greater potential as experience- cognitive enhancer. It is pinpointed that the resources required to add layers of information are not excessive (Software and interoperable platforms) but the necessary equipment (Hardware) is presently rather expensive for the deployed modality. AR Hardware is still under development which is reflected in the market availability. Other AR modalities including other interfaces may be

On the other hand, the resources required to recreate a realistic VR scene (Software) are larger than those required in AR applications but the necessary equipment (Hardware) is considerably more accessible. VR Hardware can be found in numerous forms and affordable prices nowadays. The amount of time needed to replicate a realistic VR environment is longer than the amount of time needed to recreate layers of information in AR. Notwithstanding, VR systems can be used as a way of recreating experimental experiences to remotely located users, which represents a major advantage. The amount of participants that may access to such events may be fairly larger considering that any user connected to a web server with an adequate VR gear can be immersed in such test.

### *Appraisal of the applications provided by different user groups*

Participants belonging to different user-groups were polled after testing the applications. 3 full professors, 3 associate professors, 2 post-doctoral researchers, 6 students (graduate and undergraduate) and 4 laboratory technicians participated in the interviews during the tests. A reduced yet systematic scrutiny of the applications were performed by i) users with high expertise in the subject (professors and post-doctoral researchers), ii) users with high expertise in structural engineering laboratories (technicians) and iii) civil engineering students. Conclusions related to the potential use of such tools in these facilities are thus separated for user groups:

- Users with high expertise in the subject (the developers of the structural tests themselves), expect more sophisticated visualization of the results. Real-time data-processing with more advanced formulation is necessary when providing other layers of information. In the case of beams, columns and frames, several forms of plastic-hinges visualizations or visualization of the accumulated history of the tests were suggested by scrutinizers as potential enhancers for these particular applications.

- Users with high expertise in structural engineering laboratories expect clear visualization of results associated with control of the test as well as with the overall safety of the experiment. These users are interested in monitoring the correct development of measurement as well as any potential malfunction of the set-up.

- Users under training (civil engineering students) found that results were meaningful and useful for understanding purposes. Some of them were attracted by the use of technology as a cognitive-enhancer. In particular, students showed a quick understanding of the phenomenon visualized with AR applications. Notwithstanding, for these cases, the visualization was associated with internal force diagrams and reactions. It is required to scrutinize the cognitive enhancement these applications provide when more sophisticated visualizations are used in pedagogical terms.

*Identification of the potential and of technical issues in VR/AR tools for structural engineering laboratories.*

From a general perspective, in structural engineering laboratories, experiments with other materials as well as with other types of structural tests can be infused with VR/AR immersive environments. Improvement in the formulations (e.g., accounting for the material non-linearity) and/or visualization of more sophisticated results are enhancements one may include in similar tests. Notwithstanding, the sophistication of the mathematical formulation involving highly nonlinear components adds latency to the system due to the required computational time with incremental/iterative procedures. In the deployed tools, a certain degree of latency was observed in VR applications (a temporal lag from the measurement to the moment the rendered imagery is presented to the user). The synthetic 3D environment, which needs to be refreshed in real time, consumes considerable CPU graphical resources. On the other hand, the AR applications were computationally treated in external CPUs. Subsequently, processed data was sent to the Hardware (Hololens) in the form of layers of information that required limited amount of graphical resources. In such cases, latency was not an issue.

Moreover, in AR applications, a recognition marker is required. When users enable the system, the AR glasses need to be placed close to the marker in order to locate spatially the layers of information (Figure 13 (b)). In static tests, in which the duration may exceed a certain time (minutes to hours), the system is usually restarted during the test. It is recommended to place the marker in an accessible point within the premises of the test outside the safety ribbons.

### *Future research*

The present case study has been developed as a proof of concept in real scale structural tests with a particular emphasis in including all the needed steps. An integrated framework including measurement, transmission, processing and visualization have been treated in all examples. In particular, several aspects related to structural engineering applications need further deepening (other technological aspects involving the equipment itself are also a matter of research but are not discussed herein). Throughout the development of the applications, some research trends have been identified:

- Development of VR/AR multivariable models in redundant structures. Redundant structures tested in laboratories are more complex to measure and analyze. Enriched visualizations of the results provide to test operators with more tools for decision-making and for safety control in such complex tests.

- Development of more sophisticated FEM models that predict the behavior of the tests up to failure. This development may provide enriched phenomenological insight to operators related to important events such as remaining life, failure, excessive deformation, etc during the tests.

- Development of AR application in which reduced order methods are used for calculations. This development may provide enriched phenomenological insight to operators with complex calculations that may be developed with less computing capacity. Latency may be reduced considerably using such models.

- Development analyses using cloud computing for the sake of optimizing calculations and avoid undesired latency.

- Development of VR/AR applications in real scale load tests. Routinely performed load tests in bridges are one example in which both remotely located users (VR) as well as users present in the field (AR) may need. The development of such applications including experimental (EMA) and operational modal analysis (OMA) is at development stages by the research group (Chacón et al. 2019).

## Conclusions

In this paper, a set of VR and AR applications were successfully implemented in the form of experience-enhancers in structural engineering routine tests. Several experiments on beams, columns and frames in stainless steel were performed at the laboratory facilities. Immersive tools were successfully deployed in such tests, which cover several structural elements. These applications encompass the use of measured data from sensors, the deployment of synchronous data transmission and post-processing and finally, a real-time visualization of results. These visualizations were specifically conceived and developed for these tests as potential experience- and cognitive enhancers. The developed applications have allowed enriching the perceptive experience for different users.

VR applications were meant for users that are not necessarily present within the laboratory facilities whereas AR applications were meant for users that are necessarily present within the laboratory premises. For the former case, any user at any place with a VR headset and a synchronous connection to servers may experience the development of the test remotely. Immersive 3D reproductions of laboratories coupled with animated representations of the tested specimens can be blended in a virtual reality space. From data, not only animations but also text, plots, numbers or any other interface can be added as experience enhancers. As a result, tests on structural elements, often limited and expensive, can be recreated by an unlimited amount of persons synchronously. For the latter case, users provided with AR headset can experience an enriched version of a structural test *in situ*. Without losing awareness of the real environment, users receive additional layers of information that enrich overall experimental experience. Although both applications are complementary and can be used simultaneously, considerable differences between both are pinpointed. VR applications require more computational resources than AR applications. Conversely, VR tools are more affordable and accessible nowadays than the AR counterparts.

Moreover, different user groups such as researchers, technical staff and civil engineering students were designated as scrutinizers of the applications. Qualitative suggestions were provided by different types of users. Researchers with high expertise suggested in adding complex post-processed information. Technical staff suggested that clear visualization of results at any time as clear warning about malfunctions or safety-related issues are of utmost importance. Students considered these applications as interesting technology-based cognitive enhancers even for simple cases such as beams and columns.

All applications were performed following some of the latest trends in AEC sector related to interoperability and data exchange. Since data-exchange was synchronously performed from sensors to real-time renders, standard protocols facilitated its implementation. Issues related to latency in VR and operability in AR were pinpointed. The development of environment-controlled laboratory experiences showed their conceptual applicability but interestingly, showed replicability in real structures infused with sensors that feed BIM models. Routinely performed load tests in real structures represent a starting point for the development of more ambitious applications for a broader range of users such as constructors, administrations and consultant engineers.

## Data availability statement

Some data, models, or code that support the findings of this study are available from the corresponding author upon reasonable request. (Measurement and structural analysis codes).

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Table 1. Geometrical and organizational characteristics of the tests.

| Type | Number | RHS Cross-Section | Geometry | Observations |
|---|---|---|---|---|
| **Beams (VR)** | S1-B | 120 x 80 x 6 | Length = 1700 mm<br>Span=1500mm | Compact |
| | S2-B | 100 x 80 x 4 | | Compact |
| | S3-B | 120 x 40 x 4 | | Semi-Compact |
| | S4-B | 120 x 100 x 3 | | Slender |
| **Columns (VR)** | S1-C1 | 120 x 80 x 6 | Height = 1500 mm | Major axis. FB |
| | S1-C2 | 120 x 80 x 6 | | Minor axis. FB |
| | S2-C1 | 100 x 80 x 4 | | Major axis. FB |
| | S2-C2 | 100 x 80 x 4 | | Minor axis. FB |
| | S3-C1 | 120 x 40 x 4 | | Major axis. FB |
| | S3-C2 | 120 x 40 x 4 | | Minor axis. FB |
| | S4-C1 | 120 x 100 x 3 | | Major axis. FB |
| | S4-C2 | 120 x 100 x 3 | | Minor axis. FB |
| **Frames (AR)** | S1-F | 120 x 80 x 6 | Height = 2000 mm<br>Span = 4000 mm | Fixed supports |
| | S2-F | 100 x 80 x 4 | | Fixed supports |
| | S3-F | 120 x 40 x 4 | | Pinned supports |
| | S4-F | 120 x 100 x 3 | | Pinned supports |