From physical to digital in structural engineering classrooms using digital fabrication

Rolando Chacón, David Codony, Álvaro Toledo
School of Civil Engineering
Universitat Politècnica de Catalunya, Barcelona, Spain

Revision submitted to Computer Applications in Engineering Education

Abstract

I*n this paper, a set of digital artifacts related to simple examples of structural engineering are presented. The artifacts are real-time applications and visualizations of typical problems students from the architecture, engineering and construction (AEC) schools are acquainted with. The real-time nature of the examples allow a high level of interaction between humans and the classic visualization of results, namely, bending and shear force diagrams, internal stresses distributions and contour plots. These artifacts may provide in AEC a twofold educational target: i) for users, to provide visual understanding in real time of typical problems that must be understood in classic lectures of structural engineering; ii) for developers, to provide meaningful applications of applied digital fabrication using sensors, microcontrollers and GUI's and their potential in the development of tools related to Structural Health Monitoring (SHM) and the Internet of Things (IoT) among students of the AEC sector.*

1. Introduction

Education takes many forms when it comes to teaching structural engineering in civil engineering schools worldwide. The educational spectrum, similarly to other engineering fields is fairly wide. Methods range from classical master lectures to software- and project-based environments. Broadly speaking, it can be stated that structural engineering is taught at four different levels: i) via an in-depth theoretical mathematical background involving linear algebra, partial differential equations and numerical methods for solving structures in a computational fashion, ii) via a practical approach aimed at using and understanding the theory behind national guidelines and codes for the design of structures of various construction materials, iii) via a software-based design in which the provided theoretical background is aimed at generating conscious users of such packages and also, to a lesser extent iv) via experimental experiences in laboratories involving different structural configurations, materials and scales. Admittedly, the depth of each one of these levels depends on schools' educational targets, to their corresponding curricula as well as to economical issues.

The level of computational skills acquired by students is occasionally high with a particular focus in programming complex phenomena in discrete or continuous structural systems. Similarly, skills associated to the use of Software (commercial, or open-source) with a highly professional component (use of CAD, BIM, FEM and the like) have improved considerably the level of understanding of more complex structures with stronger and more varied materials. On the other hand, experimental full- or scale-reduced structural systems built by students offer hands-on experiences related to the whole construction process but its use in education is limited due to time and economic constraints. In any case, a considerable amount of educational research available for the levels of computational skills [1-3], software-based learning [4-6] and experimental resources [7-9] proves a long record of academic activity in the field.

Educationally, little attention has been paid though, to the potential use of prototyping electronic platforms in structural engineering classrooms. Broadly speaking, these electronic artifacts involve the usage of sensors, microcontrollers, actuators and occasionally, simple graphical user interfaces (GUI). In particular, these devices may be assembled in a way they provide relevant information related to the response and behavior of simple structures. These platforms have gained popularity in other engineering fields for developing both applications and educational frameworks. Formally, academic educational research related to Robotics [10-11], Architecture [12], Electronics [13-14] and Control engineering [15-16] similarly prove an increasing record of academic activity in several other engineering fields with particular educational targets.

In this paper, several computer applications using open-source electronics, open-source Software coupled with illustrative structural problems are developed. The aim of these applications is to show the potential of such artifacts in educational frameworks within the field of structural engineering. For the sake of developing these tools, three different aspects are studied: i) the use of sensors, actuators and electronics, ii) the implementation of different theoretical and numerical solutions of structural problems and iii) the development of a simple GUI using open-source Software for visual understanding of the structural phenomena. The artifacts are built from scratch by students acquainted with the aforementioned concepts of structures but with little to no-background in electronics.

The results show how these tools together with other digital fabrication technologies may be useful for generating digital artifacts by students in structural engineering classrooms. These devices may be used in many forms educationally for the sake of structural engineering but also, they may help to bridge the existing physical-to-digital gap in civil engineering classrooms, by adding an educational layer that involves the internet of things and the vast array of possibilities it may generate within the field of automation in construction. In this paper, both the development of such tools (section 4) as well as the potential application in the classroom (section 5) are discussed.

2. Digital fabrication and architecture, civil engineering and construction education (AEC)

Digital fabrication is an amorphous term that encompass a vast array of technologies and practices:

- At first, digital fabrication and modeling has been understood as a process in which computer-aided design is joined with production of objects by means of additive and subtractive technologies (3D printing, laser-cutting, etc). The open-source nature of 3D modeling Software as well as the massive development of 3D technologies foster creativity and open a vast array of new possibilities in education due to their accessibility both technically and economically [17]. As a matter of fact, students in the architecture, engineering and construction fields (AEC) are increasingly using these technologies at several levels.

- At second, in addition to 3D technologies, open-source low-cost prototyping electronics joined with open-source visual programming Software allow developing endless possibilities when it comes to automation, control, monitoring and development of objects within the realms of the Internet of Things (IoT). The accessibility to these tools in recent years (both economically and technically) has fostered a new wave of DIY enthusiasts which under the umbrella of the maker movement are exploiting these technologies at various educational levels [17-21].

Some authors pinpoint potential academic trends related to engineering education and social innovation in which the convergence of 3D printing, open Hardware and open Software may revolutionize the educational experimental training nowadays provided in high schools as well as in technical universities [22]. Others, from the business perspective, pinpoint potential social changes due to this wave [23]. The academic activity worldwide related to automation in construction and digital fabrication is increasing at a fast pace. Research groups joining both fields have presented interesting examples in recent years [24-27].

Within the educational framework that is presented in this paper, the term digital fabrication is circumscribed to the realm of development of educational tools in architecture, civil engineering and construction classrooms. The academic activity involving education, digital fabrication and the AEC sector is, however, less abundant [12][28]. Students at schools of the AEC sector are often acquainted with 3D modeling and production but rather seldom with the development of electronic circuitries and programming. However, these skills are increasingly interesting for AEC students since in the years to come, a considerable proportion of the infrastructure to be built will be provided with additional layers of automation, graphical user-interfaces and human-computers interaction. As a matter of fact, one active field of research in AEC is Structural Health Monitoring (SHM) in which basically i) sensors, ii) data acquisition systems and iii) Software for analysis are coupled together for the sake of providing real time understanding of the structural integrity of bridges, buildings, efficient architecture, energy systems, sustainable transportation, or other relevant infrastructures.

3. Tools.

In these examples, digital twins of real experiments are built using three different open-source technologies: Sensors, microcontrollers and visual programming Software. Figure 1 shows the Software and Hardware tools employed.

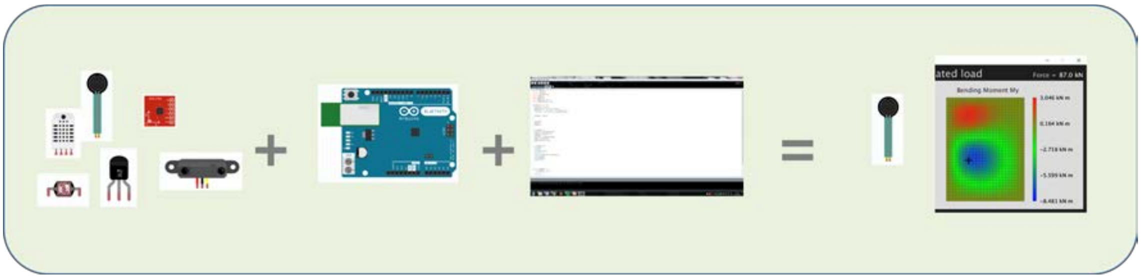

Figure 1. Hardware and Software tools used in all artifacts (a) Sensors, b) Arduino UNO and C), Processing IDE.

a. For the case of sensors, pressure, distance and light dependent sensors are used. The pressure sensor is a touch-activated module. It consists of a pad that is activated with a finger. The more pressure is applied, the more signal it sends out. The distance sensor is an infrared (IR) module useful for measuring distances without actually touching a surface. The light dependent resistor (LDR) gives out an analog voltage when connected to 5V. This signal varies in magnitude in direct proportion to the input light intensity on it. That is, greater the intensity of light, greater will be the corresponding voltage from the LDR.

b. For the case of microcontrollers, the open-source electronic prototyping board Arduino/Genuino UNO [29] is chosen. Arduino/Genuino Uno is a simple microcontroller board based on the ATmega328P. It has 14 digital input/output pins (of which 6 can be used as Pulse Width Module outputs), 6 analog inputs, a USB connection, a power jack as well as other functionalities. The boards allows starting with electronics in a intuitive fashion. The Arduino Integrated Development Environment IDE allows the user to code and upload programs aimed at obtaining magnitudes from sensors and/or controlling actuators such as motors, LEDs or servos. The Java-written IDE consists of mainly two functions: void setup() for initial arrangements, which is executed once and void loop(), which is executed repeatedly according to the instructions given by the user. Educationally speaking, this platform is suitable for the development of tools by students that are initially not familiar with electronics.

c. For the case of developing simple graphical interfaces, the open-source visual programming Software Processing [30] is chosen. Processing is used in classrooms worldwide, often in art schools and visual arts programs in universities, but it's also found frequently in high schools, computer science programs, and humanities curricula. It is also based in Java syntax and follows an object-oriented programming scheme that allows seamless communication with Arduino IDE. Similarly, the Java-written Processing IDE consists of mainly two functions: void setup() for initial arrangements, which is executed once and void draw(), which is executed repeatedly according to the the instructions given by the programmer. Data is collected from serial ports in real-time and thus, visual applications can be developed in an intuitive way.

4. Prototypes

a. Beams and Frames

- Artifact

The device consists of a scale-reduced steel beam as well as a steel frame to a which concentrated loads are applied by means of a movable pressure sensor (see figure 2). Forces may be applied vertically downwards or horizontally leftwards in specific members of the beam/frame. The distance at which the forces are applied by the users are automatically read by distance sensors (both vertically and horizontally). The frame aims at providing a useful structural engineering example well known by students. Beams and frames are mathematical models widely described in structural engineering books that reproduce the physical behavior of several constructional elements such buildings, trusses, bridges, and similar structures of various materials.

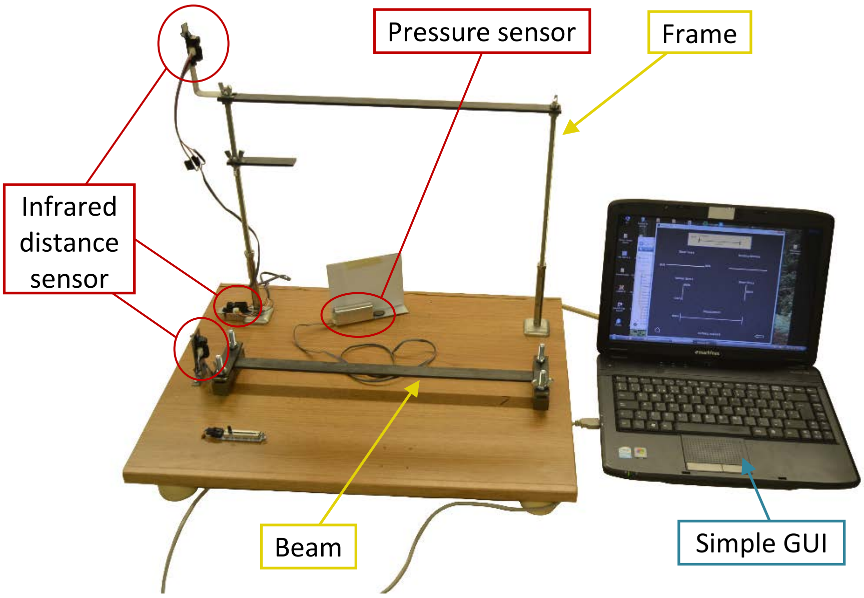

Figure 2. Lateral view of the beam-frame artifact

- Theory Review

The mathematical formulation for beams and frames is based upon the one-dimensional *Euler-Bernoulli* beam theory. This formulation describes the relationship between deflections of members subjected to bending and the corresponding applied loads. Under the assumption of linear behaviour of materials, small strains and no transverse shear deformation, a coupled set of equations involving equilibrium (eqs. 1-3), compatibility (eqs. 4-6) and the constitutive relationship between stresses and strains provide closed-form solutions at both internal and external levels of members with simple geometries and boundary conditions. For the former, stresses and their corresponding integrations as forces and moments are obtained. For the latter, reactions, shear forces and bending moments can be derived in closed-form solutions. Fig. 3 shows schematic diagrams from which all equations may be derived.

Accordingly, and after some mathematical simplifications, equilibrium equations read:

$$\sum F_{e_1} = 0, \qquad \text{then} \qquad \frac{dN}{ds} + p_1 = 0 \tag{1}$$

$$\sum F_{e_2} = 0, \qquad \text{then} \qquad \frac{dQ}{ds} + p_2 = 0 \tag{2}$$

$$\sum M = 0, \quad \text{neglecting second order infinitesimals} \quad \frac{dM_f}{ds} + Q + m = 0 \tag{3}$$

in which p_1 and p_2 are the axial and shear external forces, respectively, and m is the external bending moment.

Subsequently, compatibility equations read:

$$\mathrm{d}\varphi = \frac{\mathrm{ds}}{\rho} = \chi_2 \cdot \mathrm{ds} \tag{4}$$

$$\chi_2 = \frac{d\varphi}{dx_1} \qquad (5)$$

$$d\varphi = \chi_2 \cdot ds = \frac{\varepsilon_1(x_3) \cdot ds}{x_3}, \qquad \text{then} \qquad \boldsymbol{\varepsilon_1(x_3) = \chi_2 \cdot x_3} \qquad (6)$$

where $d\varphi$, ρ and χ_2 are the angle of rotation, the radius of curvature and the curvature, respectively.

Finally the constitutive equation reads:

$$\sigma_1(x_3) = E \cdot \varepsilon_1(x_3) \quad \Rightarrow \quad \boldsymbol{\sigma_1(x_3) = E \cdot \chi_2 \cdot x_3} \qquad (7)$$

with E as the Young's modulus.

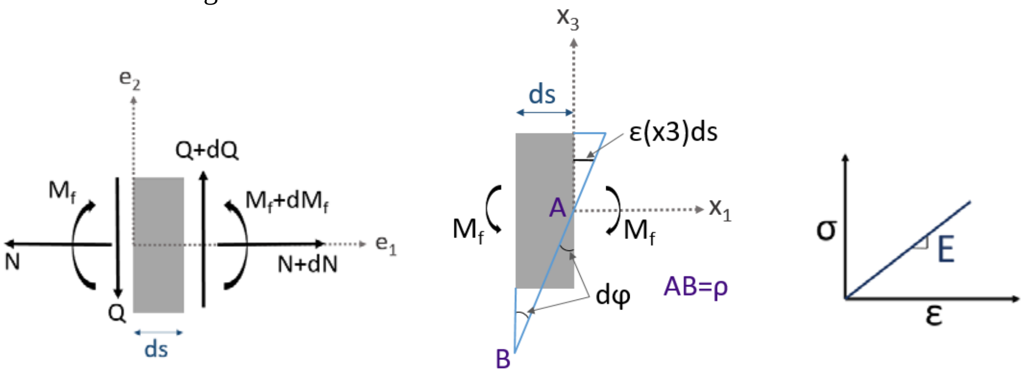

Figure 3. Equilibrium, Compatibility and Constitutive schemed of the Euler-Bernoulli beam theory.

- Electronics and circuitries

The Arduino UNO board is the core of the electronics of this device. Analog sensors are attached to it providing an analog signal that it brought to the computer through serial communication. Signals generated by the infrared sensors (see fig. 4) provide information about the position of the load and signals coming from the pressure sensor provide information related to the magnitude of the load. All sensors must be powered and grounded accordingly.

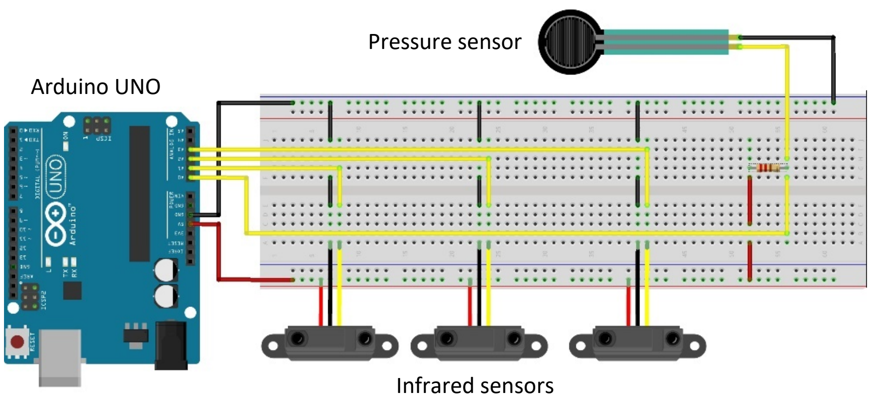

Figure 4. Sketch of the electronics attached to the physical artifact

- The simple GUI (Graphical User Interface)

The GUI of the device displays at real-time external forces (shear, bending and reactions) by means of linear plots that are directly understood by students acquaninted with structural engineering. The user may choose among several structural cases (displayed in Fig. 5) for both beams and frames. On the other hand, results showing stresses and strains at sectional levels are also visualized. Both plots are displayed in the same screen and thus, a real-time student-structure interaction may be achieved. Fig. 6 shows screenshots of the simple GUI including user-definition of the problem and user-visualization of results. The included options encompass simple cases of both isostatic and redundant beams and frames.

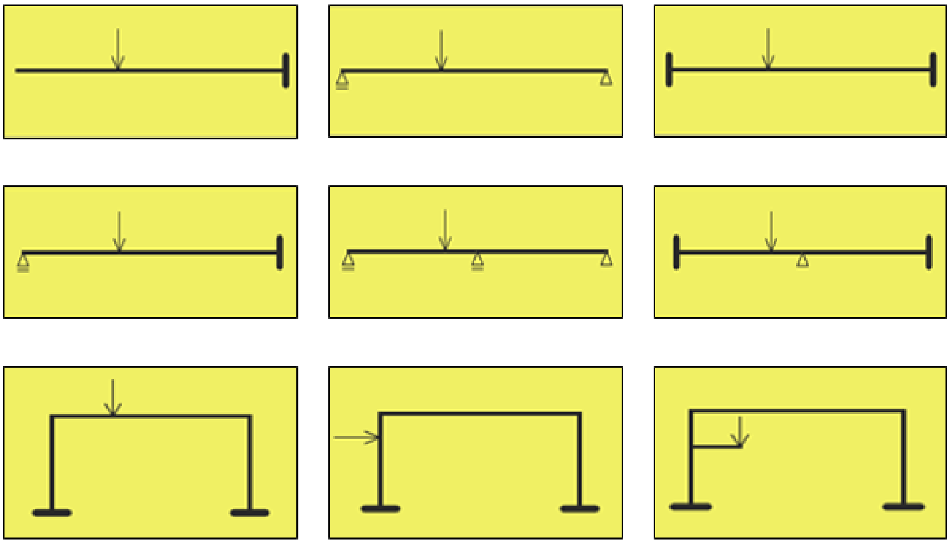

Figure 5. Variation of cases that may be solved and visualized by the GUI

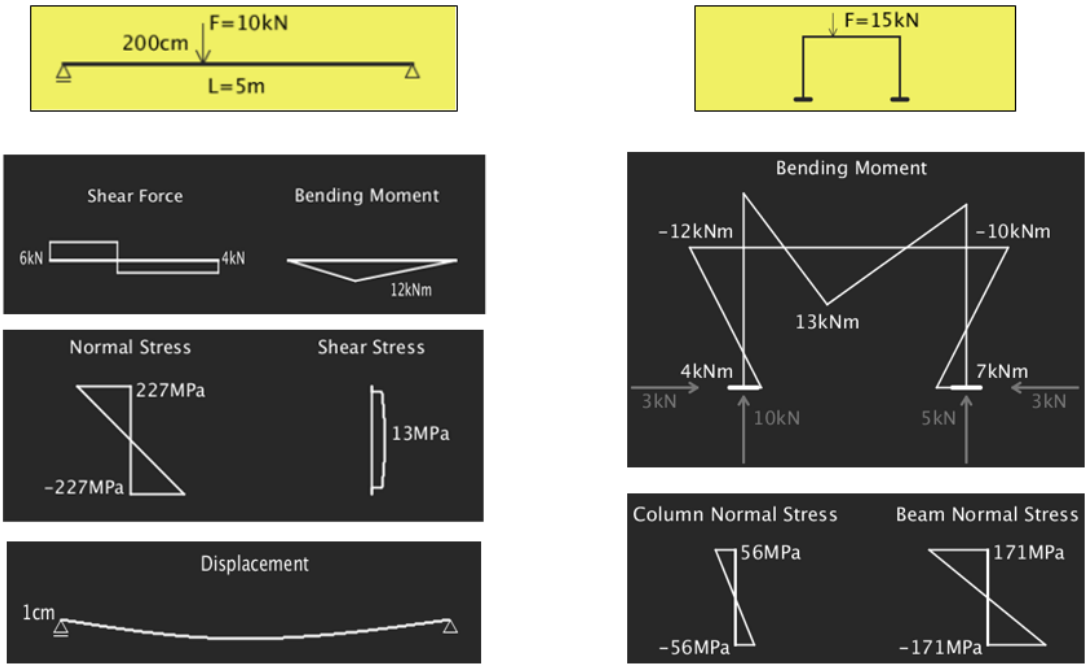

Figure 6. Visualization of results for one example of beams (left) and one example of frames(right)

b. Plates

- Artifact

The device consists of a wooden plate to a which a concentrated load in a determined location is applied with a pressure sensor (see figure 7-left). The plate aims at providing a useful structural engineering example well known by students. Plates are mathematical models widely described in structural engineering books that reproduce the physical behavior of several constructional elements such as concrete slabs or web or flange panels in steel members. The sensor provides an analog input that can be generated by the student using his/her fingers in a small but sufficient range of numbers ranging from 0-1023. The model is built on four cylindrical supports located at each edge of it, allowing the electronics be hidden underneath (see figure 7-right). For the sake of determining particular positions, a system of LDRs detecting light is installed following a triangular arrangement. Three small cylindrical holes are made through the plate in order to permit the sunlight reach the light sensors located within. If light does not reach a particular LDR, it means that the pressure sensor blocks it. The systems sends a signal to the Arduino with the (x,y) coordinates of the concentrated load position.

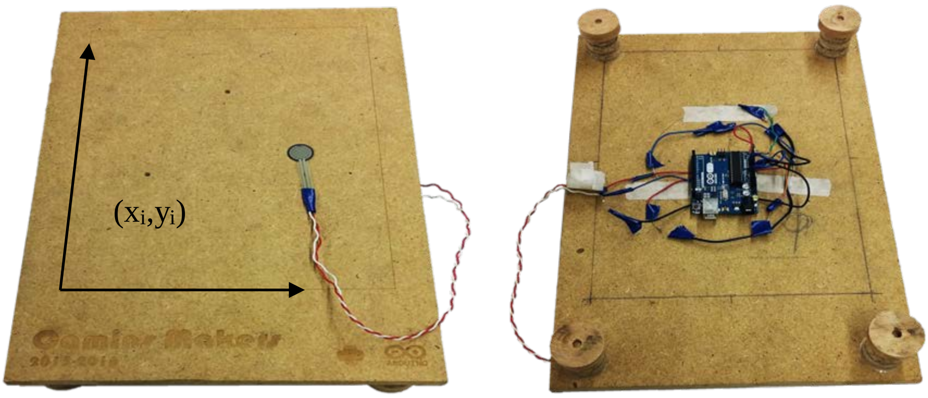

Figure 7. Front and rear views of the plate prototype.

- Theory Review

The one-dimensional *Euler-Bernoulli* beam theory can be extended to a two-dimensional mathematical model for thin plates, which is called the *Kirchhoff–Love theory of plate* [31]. It considers the mid-surface plane of a plate to represent its full geometry, considering the displacement $w(x,y)$ along the normal direction of the mid-plane as the only unknown. The simplicity of this model is given by the assumption of several hypotheses, such as neglecting shear stresses and vertical strains and stresses. Thus, the model is valid only in the range of small strains and thin plates. In practical structural engineering applications, this model reproduces the behaviour of thin-walled plates (such as steel panels).

The particularization of this theory to elastic, isotropic and homogeneous materials leads to the equilibrium differential equation [32] given in (8):

$$\Delta\Delta w(x,y) = \frac{q(x,y)}{D}, \qquad \text{with} \qquad D = \frac{E \cdot t^3}{12 \cdot (1-\nu^2)}; \tag{8}$$

where $q(x,y)$ refers to the loading of a unit force normal to the mid-plane, and D to the rigidity of the plate. In addition, E and ν refer to the Young's modulus and the Poisson's ratio, respectively, and t to the thickness of the plate.

A wide range of approaches can be considered in order to solve this PDE. For the sake of simplicity, the **Navier** direct method has been considered, which is restricted to rectangular geometries with simply-supported edges. The main idea is to express both the load and the displacements field in terms of sinusoidal Fourier series as read in eqs. 9 and 10:

$$q(x,y) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} q_{mn} \cdot \sin\left(\frac{m\pi x}{a}\right) \cdot \sin\left(\frac{n\pi y}{b}\right); \quad (9)$$

$$w(x,y) = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} w_{mn} \cdot \sin\left(\frac{m\pi x}{a}\right) \cdot \sin\left(\frac{n\pi y}{b}\right); \quad (10)$$

where a and b are the x and y-dimensions of the plate, and m and n are the indices of each term in the Fourier serie in each x and y-direction. Note that (9) implicitly holds the simply-supported boundary condition. Since $q(x,y)$ is known, the q_{mn} coefficients can be found using the orthogonality of Fourier components:

$$q_{mn} = \frac{4}{ab}\int_0^a\int_0^b q(x,y) \cdot \sin\left(\frac{m\pi x}{a}\right) \cdot \sin\left(\frac{n\pi y}{b}\right) \cdot dx \cdot dy. \quad (11)$$

We restrict $q(x,y)$ to be a point load P, in order to simplify the computations and in order to allow the user to apply load to the plate interactively with his/her finger. Thus, eq. (12) leads to:

$$q_{mn} = \frac{4}{ab} \cdot P \cdot \sin\left(\frac{m\pi x_p}{a}\right) \cdot \sin\left(\frac{n\pi y_p}{b}\right), \quad (12)$$

being (x_p, y_p) the application point.

Inserting (9), (10) and (11) into equation (8 and deriving it, we reach a set of equations that allows finding w_{mn} for each mn term:

$$w_{mn} = \left[D \cdot \pi^4 \cdot \left(\frac{m^2}{a^2} + \frac{n^2}{b^2}\right)^2\right]^{-1} \cdot q_{mn}. \quad (13)$$

The obtained value w_{mn} is introduced into (10) to retrieve the analytical solution of the plate. Note that these sinusoidal Fourier series are composed by infinite terms ($m = 1 \ldots \infty$, $n = 1 \ldots \infty$). In order to get a real solution, the series have to be truncated to a finite number of terms in each direction ($m = 1 \ldots M \in \mathbb{N}$, $n = 1 \ldots N \in \mathbb{N}$). Internal forces within the plate (e.g. bending moments and shear forces) can be easily derived from the displacements field w_{mn} as explained in [32]. Figure 8 shows a scheme of equilibrium and compatibility from which all equations are derived.

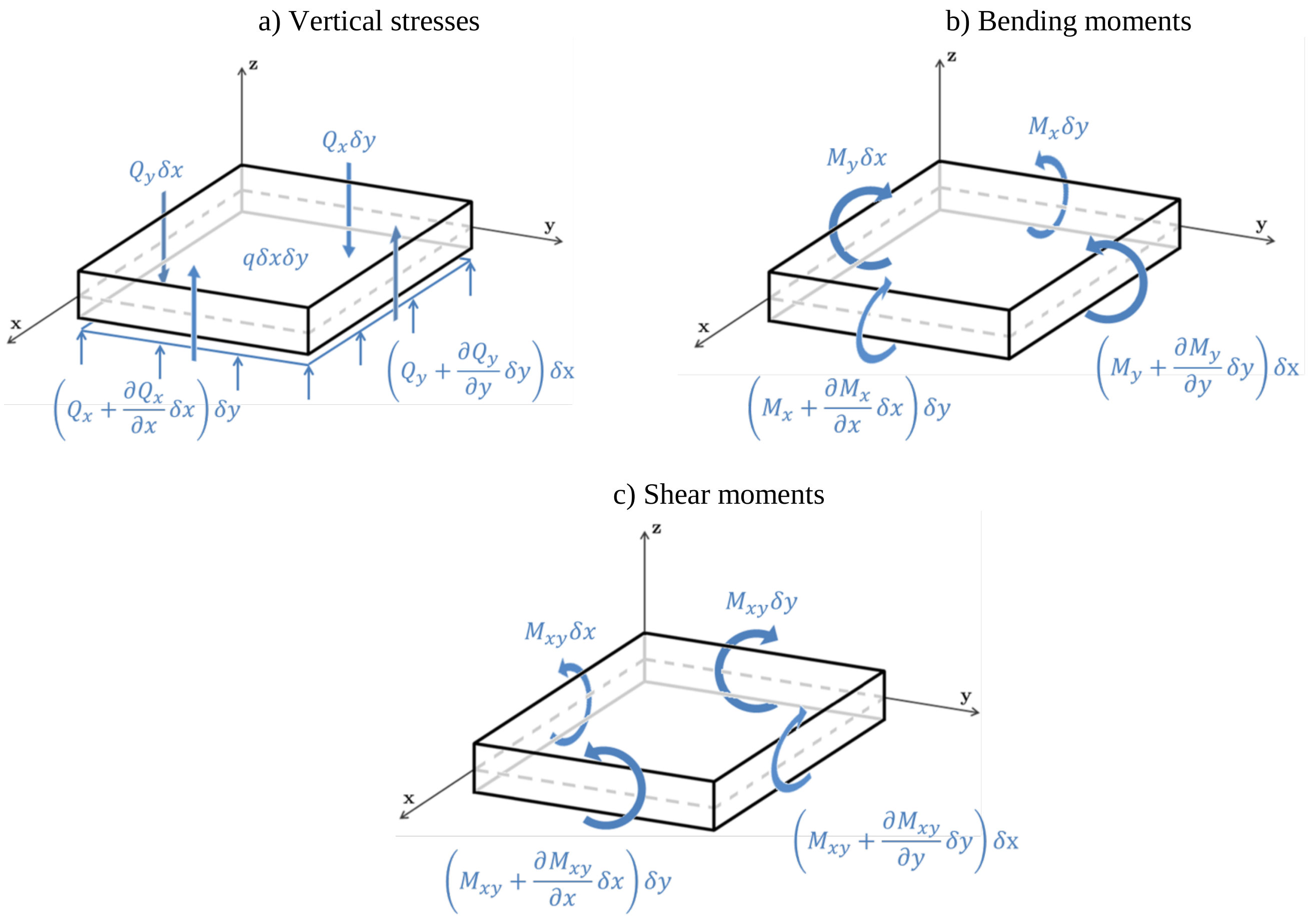

Figure 8. Equilibrium of a differential slice of plate in the Kirchoff-Love plate theory.

- Electronics and circuitries

The Arduino UNO board is the core of the electronics of this device. Analog sensors are attached to it providing an analog signal that it brought to the computer through serial communication. These sensors are a) one pressure sensor and b) three LDRs, to catch the value of the load and its location respectively. Figure 9 displays a schematic circuitry including a breadboard, LDR, resistors and a pressure sensor. Since the LDR cells are located below each hole in the plate, they are fixed, and therefore the plate is only loadable at those specific points (more complex devices may be conceived by adding LDR or other devices).

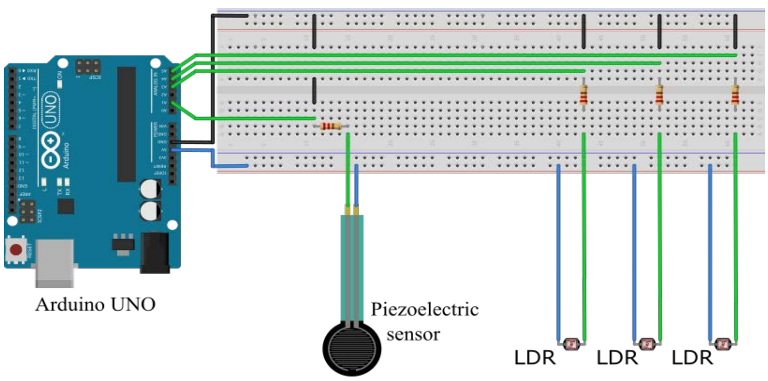

Figure 9. Sketch of the electronics underneath the plate prototype.

Both setup() and loop() functions are uploaded to the board. Analog magnitudes from the pressure sensor and (x_i,y_i) coordinates of the application of the load are obtained many times per second and sent to Processing, the code in which all calculations are performed and also, the results are visually displayed. At the computer level, the vertical displacement as well as the corresponding plate internal forces are calculated by means of the aforedescribed theory for plates. The input data is, many times per second, the data coming from the Arduino board (pressure and position). This process is repeated accordingly and provides to an interactive device: the results of the computation depend on the user's loading at practically real-time.

- The simple GUI (Graphical User Interface)

The GUI of the device displays at real-time the vertical displacements and x and y-bending moments by means of colored contour plots (see figure 10). To this purpose, a color bar beside each plot maps the colors with the values of the output. This color bar is fixed, and ranges between the maximum and minimum values of the represented physical magnitude, which are given when the maximum point load is applied.

All constant parameters of the simulation (such as the elastic parameters of the plate, the number of terms of the Fourier series in the x and y- directions, the force mapping and the spatial resolution of the solution) are set at the first lines of the code, before running the program and may be tuned by the user.

When the program is run, the contour plots are empty. The software is constantly comparing the values of the different light sensors, and only starts computing when the values differ above a given tolerance. This difference is given since the pressure sensor covers one of the three holes. In this case, the computations are done with a unit point load applied at the location of the covered hole. The results are afterwards multiplied by the value of the point load given by the pressure sensor, which is amplified by a given constant factor in order to reproduce loads of a relevant order of magnitude in civil engineering studies.

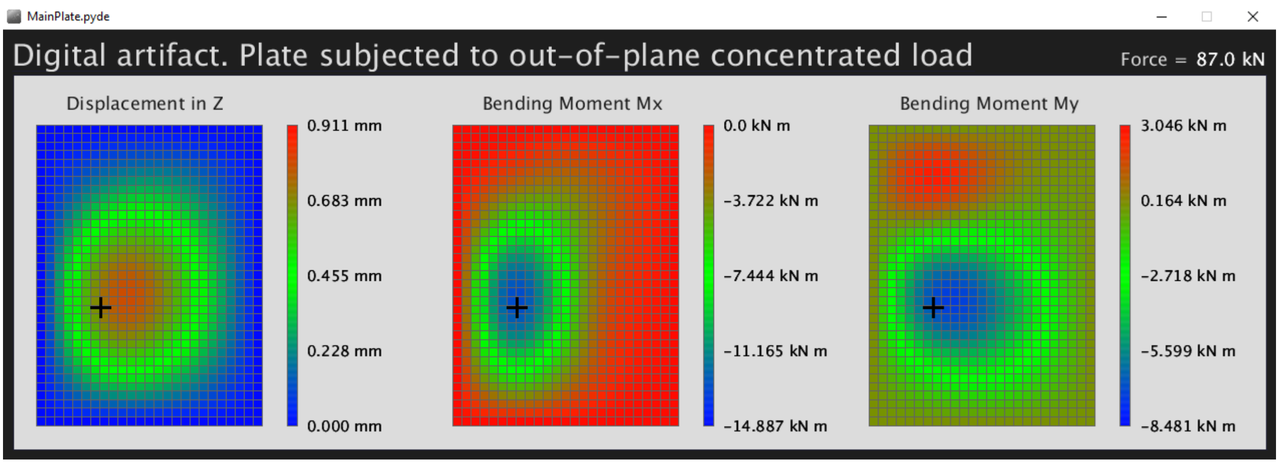

Figure 10. GUI of the point loaded plate. Vertical displacement and bending moments in both x- and y- axis are represented by colored contour fills. The load is interactively applied by the user's hand, pressing the plate prototype at one of the three loadable locations (Load amplification factor = 10^5).

5. Educational potential in structural engineering classrooms

Figure 11 displays the schematic path the measured data follows from the physical object to screen visualization throughout sensors and microcontrollers.

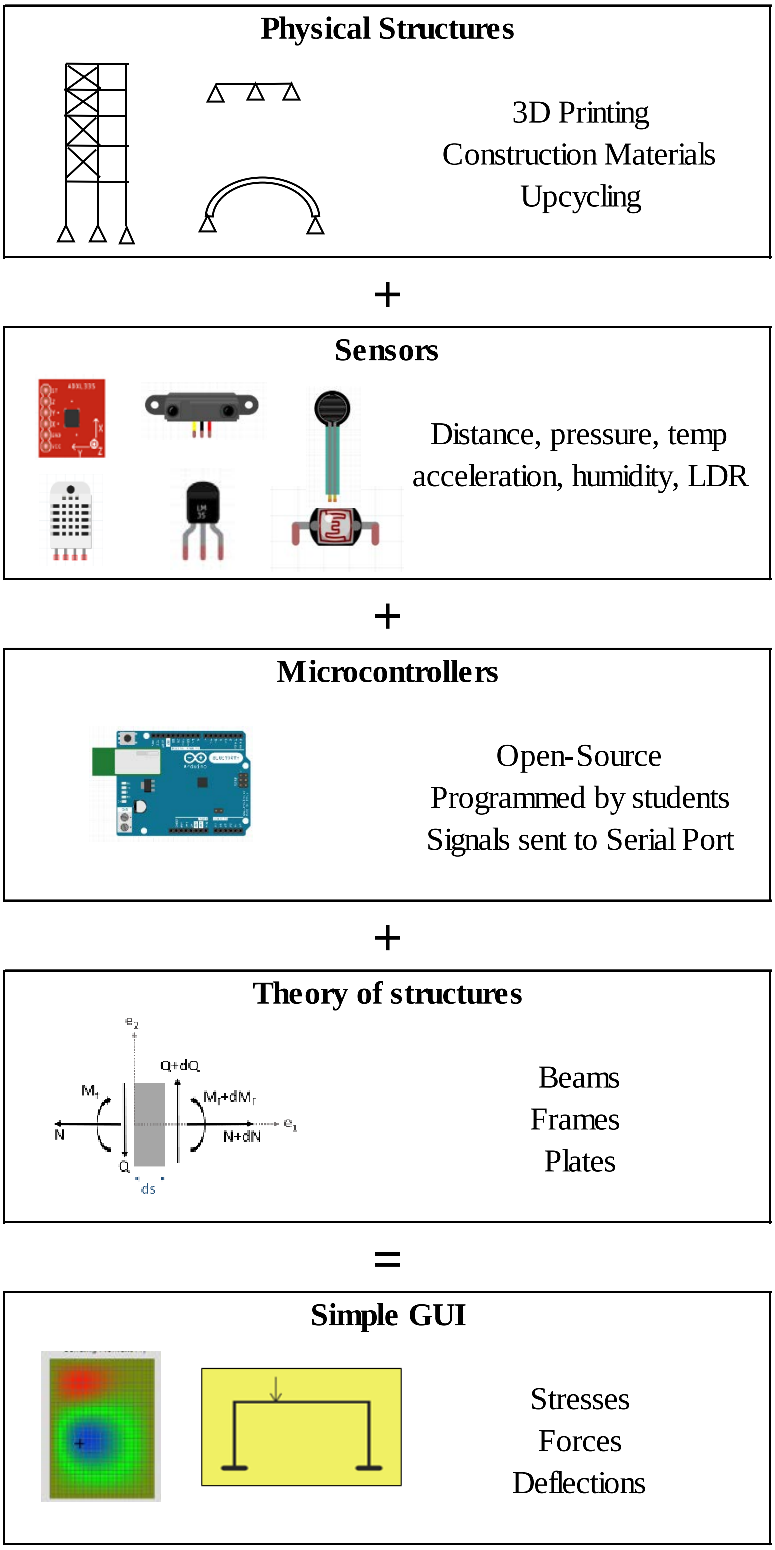

Figure 11. Information path. From physical-to-digital in structural engineering classrooms.

Structural engineering classrooms may benefit by the addition of digital fabrication layers within the curricula by many means, some of which are listed herein:

- Students may develop hands-on experiences related to the construction of meaningful structures. The construction of such structures generally imply decisions related to boundary conditions, application of forces and materials that are studied thoroughly from the theoretical perspective. Feedback obtained so far shows the benefits of hands-on experiences for the understanding of problems associated with real construction. Questions such as how the structure should be fixed or loaded fundamental and easily solved with physical devices. On the other hand, 3D printing provides a vast array of new possibilities. More advanced and complex structures can be fabricated and thus studied.

- These structures must be solved theoretically. The mathematics behind these solutions are as cornerstone as in other educational frameworks. The solution of such simple (or complex structures) includes that the user must assess the level of stress, strain and deformation of the physical bodies. This is a classic objective in structural engineering curricula. The hands-on experience reinforces the accomplishment of such primary objectives.

- In addition, presently, it is important for civil engineering students to understand the mechanics of Structural Health Monitoring (SHM). Real structures are increasingly monitored with both short- and long-term deployments including sensors, data loggers and data visualization. The development simple tools, in which data coming from sensors is visualized in simple GUIs may prepare these students for more advanced courses related to high-precision, cutting-edge courses devoted to monitoring of real structures.

- Similarly, a simple introduction to sensors and microcontrollers facilitate more advanced courses related to automation and robotics in construction, which are increasingly enriching civil and construction engineering curricula.

6. Educational potential in civil engineering classrooms

The information path depicted in Fig. 11 may be extrapolated to other modules in civil engineering schools such as those related to fluid mechanics, soils, transportation, environmental engineering and the like. The available array of sensors is vast as well as the potential application in the development of digital twins with various applications. As a matter of fact, one of the ongoing projects of the educational research group is related to the fabrication of simple digital twins in courses such as experimental techniques in construction, soils mechanics and marine engineering. The developed devices present a low level of complexity but students are highly rewarded by the achieved results. Hands-on experience foster intrinsic motivation since results are tangible, meaningful and visible by students and peers. However, scaffolding methods integrating these technologies in civil engineering curricula are still in their infancies and have neither been systematically nor objectively assessed within the school.

Promisingly, digital fabrication technology is gradually becoming better and more accessible. Worldwide institutions of the AEC educational sector may afford including such technologies both economically and technically. This is particularly appealing for low-income schools. In addition, since these technologies are being embraced at early educational stages (high schools and even elementary schools), students are increasingly acquainted with tinkering and making digital craft before starting college. These technologies foster creativity related to "building", "constructing", "making", which are concepts that underpin the philosophy of all courses in the AEC educational sector. The creation of digital twins from scratch using sensors, microcontrollers and GUI’s in other units provide similar benefits to those discussed in section 5. In addition, more philosophical advantages related to the educational experience may be listed:

- Generally speaking, digital fabrication allows fostering active methodologies in classrooms. Digital fabrication labs can enact project-based, student-centered, constructionist learning and similar methodologies.

- Particularly in AEC sector, digital fabrication enables to create a technical framework related to the Internet of Things and how it works. This is interesting for the development of tools related to automation in construction, structural health monitoring, efficient buildings and other disruptive trends within the sector. The use of sensors, microcontrollers, actuators and the development of simple GUI's allows understanding the technical parts of physical-to-digital or digital-to-physical systems, which will be of the utmost importance in the AEC field in the years to come. Unfortunately, in most AEC schools, this gap has not yet been educationally bridged within the incumbent curricula.

7. Conclusions and on-going development

In this paper, computer applications related to structural engineering and digital fabrication to be used in classrooms are depicted. The applications are developed with the aim of joining the use of sensors, the use of theoretical mathematical concepts behind the structural problems and the use of simple graphical-user interfaces. All applications are developed following an open-source philosophy when it comes to Hardware and Software. The devices are portable and may be used directly in classrooms as educational tools related to structural engineering. Simple GUI's show relevant information related to the behavior of such structures in real-time and thus, meaningful magnitudes such as stresses, strains, deflections and deformations are analyzed in a rea-time basis by students and facilitators. In addition, it is found that the development of this sort of applications is particularly interesting for AEC students from the digital fabrication perspective, that is to say, creating project-based methodologies in structural engineering classrooms, in which such applications are briefed to students as structural projects, may enrich such courses by adding two extra layers:

- The application of abstract concepts by means of a constructionist student-centered approach. Hands-on development of tools that involve experimental, numerical and physical modeling foster creativity, self-esteem, tinkering and ultimately, engineering.

- The mechanics of the Internet of Things (from physical-to-digital or viceversa) are developed in a hands-on fashion. The availability and accessibility of low-cost electronics and 3D technologies nowadays allow implementing in school labs such deployments. Understanding such concepts is crucial for those AEC students interested in the realm of automation in construction, structural health monitoring and intelligent infrastructure.

Acknowledgments

The authors acknowledge the AMD grants provided to *Camins Makers* by the School of Civil Engineering during 2015-2016 and 2016-2017.

References

[1] Lee, J. Y. and Ahn, S. Y. (2014), Finite element implementation for computer-aided education of structural mechanics: Frame analysis. *Comput Appl Eng Educ*, 22: 387–409. doi:10.1002/cae.20563

[2] Young, B., Ellobody, E., and Hu, T. (2012). 3D Visualization of Structures Using Finite-Element Analysis in Teaching. *J. Prof. Issues Eng. Educ. Pract.*,138(2), 131-138 10.1061/(ASCE)EI.1943-5541.0000093

[3] Lee, J. Y. (2015), Interactive simulation of finite element equation processing for educational purposes. *Comput Appl Eng Educ*, 23: 157–169. doi:10.1002/cae.21586

[4] Paultre, P., Lapointe, E., Carbonneau, C. and Proulx, J. (2016), LAS: A programming language and development environment for learning matrix structural analysis. *Comput Appl Eng Educ*, 24: 89–100. doi:10.1002/cae.21675

[5] Katsanos, E. I., Taskari, O. N. and Sextos, A. G. (2014), A matlab-based educational tool for the seismic design of flexibly supported RC buildings. *Comput Appl Eng Educ*, 22: 442–451. doi:10.1002/cae.20568

[6] Wang, N. and Adeli, H. (2012), Web-based tutor for interactive design of connections in steel buildings. *Comput. Appl. Eng. Educ*., 20: 568–577. doi:10.1002/cae.20487

[7] Gao, Y., Yang, G., Spencer, B. F. and Lee, G. C. (2005), Java-powered virtual laboratories for earthquake engineering education. *Comput. Appl. Eng. Educ.*, 13: 200–212. doi:10.1002/cae.20050

[8] Unterweger, H. (2005). Simple Structural Models for the Education of Structural Engineers at Graz University. *J. Prof. Issues Eng. Educ. Pract.* 131(4): 227-230 10.1061/(ASCE)1052-3928

[9] Chacón, R., Uribe, N. & Oller, S. (2016). Numerical Validation of the Incremental Launching Method of a Steel Bridge Through a Small-Scale Experimental Study. *Exp Tech* 40: 333. doi:10.1007/s40799-016-0037-5

[10] Basso, M. and Innocenti, G. (2015), Lego-bike: A challenging robotic lab project to illustrate rapid prototyping in the mindstorms/simulink integrated platform. *Comput Appl Eng Educ*, 23: 947–958. doi:10.1002/cae.21666

[11] A. Cruz-Martín, J.A. Fernández-Madrigal, C. Galindo, J. González-Jiménez, C. Stockmans-Daou, J.L. Blanco-Claraco, (2012). A LEGO Mindstorms NXT approach for teaching at Data Acquisition, Control Systems Engineering and Real-Time Systems undergraduate courses.. *Computers & Education*. 59(3):974-988, http://dx.doi.org/10.1016/j.compedu.2012.03.026.

[12] Kensek, K. M. (2014). Integration of Environmental Sensors with BIM: case studies using Arduino, Dynamo, and the Revit API. *Informes de la Construcción,* 66(536): e044, doi: http://dx.doi.org/10.3989/ic.13.151

[13] Rodriguez-Sanchez, M. C., Hernandez-Tamames, J. A. and Borromeo, S. (2015), An embedded system course using JavaME and android. *Comput Appl Eng Educ*, 23: 294–303. doi:10.1002/cae.21599

[14] Collins, T., Woolley, S. I., Rawson, N. C. and Haroon, L. (2016), Final-year projects using open source OpenEEG. *Comput Appl Eng Educ*, 24: 156–164. doi:10.1002/cae.21682

[15] Martin Kalúz, Ľuboš Čirka, Richard Valo, Miroslav Fikar. (2014). ArPi Lab: A Low-cost Remote Laboratory for Control Education, *IFAC Proceedings* 47(3), 9057-9062, http://dx.doi.org/10.3182/20140824-6-ZA-1003.00963

[16] Antonio Visioli, Manuel Berenguel, P. Reguera, D. García, M. Domínguez, M.A. Prada, S. Alonso (2015). IFAC Workshop on Internet Based Control Education (IBCE15). A low-cost open source hardware in control education. Case Study: ARDUINO-FEEDBACK MS-150, *IFAC,* 48 (29): 117-122, ISSN 2405-8963, http://dx.doi.org/10.1016/j.ifacol.2015.11.223

[17] Smith R.C., Sejer Iversen O., Hjörth M. (2015). Design thinking for digital fabrication in education. *International Journal of Child-Computer Interaction*. 5:20-28. http://dx.doi.org/10.1016/j.ijcci.2015.10.002

[18] Ole Sejer Iversen, Rachel Charlotte Smith, Paulo Blikstein, Eva-Sophie Katterfeldt, Janet C. Read (2015). Digital fabrication in education: Expanding the research towards design and reflective practices, *International Journal of Child-Computer Interaction*. 5: 1-2, ISSN 2212-8689, http://dx.doi.org/10.1016/j.ijcci.2016.01.001.

[19] Lee M. (2015). The promise of the Maker Movement for Education. *Journal of Pre-College Engineering Education Research* (J-PEER). 5(1)-4. http://dx.doi.org/10.7771/2157-9288.1099

[20] Fox S. (2014). Third Wave Do-It-Yourself (DIY): Potential for prosumption, innovation, and entrepreneurship by local populations in regions without industrial manufacturing infrastructure. *Technology in Society*. 39 (11): 11-30. http://dx.doi.org/10.1016/j.techsoc.2014.07.001

[21] Blikstein, P. (2013). *Digital Fabrication and 'Making' in Education: The Democratization of Invention*. In J. Walter-Herrmann & C. Büching (Eds.), FabLabs: Of Machines, Makers and Inventors. Bielefeld: Transcript Publishers.

[22] Pearce J. (2014). *Open-Source Lab. How to Build Your Own Hardware and Reduce Research Costs*. 1st Edition. Elsevier. USA-UK-The Netherlands. 2014

[23] Rayna T, Striukova L. (2016). From rapid prototyping to home fabrication: How 3D printing is changing business model innovation, *Technological Forecasting and Social Change*, 102: 214-224, http://dx.doi.org/10.1016/j.techfore.2015.07.023.

[24] Lloret E., Shahab A, Linus M, Flatt T, Gramazio F, Kohler M, Langenberg S (2015). Complex concrete structures: Merging existing casting techniques with digital fabrication, *Computer-Aided Design*, 60: 40-49, http://dx.doi.org/10.1016/j.cad.2014.02.011.

[25] Willmann J, Knauss M, Bonwetsch T, Apolinarska A, Gramazio F, Kohler M (2016). Robotic timber construction — Expanding additive fabrication to new dimensions, *Automation in Construction*, 61: 16-23, http://dx.doi.org/10.1016/j.autcon.2015.09.011.

[26] Oxman N, Ortiz C, Gramazio F, Kohler M (2015). Material ecology, *Computer-Aided Design*, 60: 1-2, http://dx.doi.org/10.1016/j.cad.2014.05.009.

[27] Gattas J.M., You Z. (2016). Design and digital fabrication of folded sandwich structures, *Automation in Construction*, 63:79-87, http://dx.doi.org/10.1016/j.autcon.2015.12.002.

[28] Chacón R., Oller S. (2016). Designing experiments using Digital Fabrication in Structural Dynamics. J. Prof. Issues Eng. Educ. Pract (ASCE). Vol. 143(3). July 2017 http://ascelibrary.org/doi/abs/10.1061/%28ASCE%29EI.1943-5541.0000315

[29] Arduino. www.arduino.cc Retrieved in November 2016

[30] Processing. www.processing.org Retrieved in November 2016

[31] Timoshenko S. (1955). Strength *of Materials, Part 1, Elementary theory and problems*. Third Edition. CBS Publishers. New Delhi. ISBN-13: 81-239-1030-4

[32] Love A.E.H. (1944). *A treatise on the mathematical theory of elasticity*, Dover Publications, Inc. , ISBN 0-486-60174-9

[33] Timoshenko S. and Woinowsky-Krieger S. (1959). *Theory of plates and shells*, McGraw-Hill New York, ISBN 0-07-064779-8