Published: 16 October 2019

Citation in BibTeX format

TEEM'19: Technological Ecosystems for Enhancing Multiculturality
October 16 - 18, 2019
León, Spain

RESEARCH-ARTICLE

3D printed models-based lab activities to enhance learning-teaching processes in Structural Engineering courses

LUIS CELORRIO-BARRAGUÉ, University of La Rioja, Logrono, La Rioja, Spain

SERGIO CALVO-SIMÓN, University of La Rioja, Logrono, La Rioja, Spain

MARCELO GASPAR, Polytechnic Institute of Leiria, Leiria, Leiria, Portugal

MARIANO VIDAL-CORTÉS, University of Zaragoza, Zaragoza, Zaragoza, Spain

PABLO MARTIN-RAMOS, University of Zaragoza, Zaragoza, Zaragoza, Spain

TEEM'19: Proceedings of the Seventh International Conference on Technological Ecosystems for Enhancing Multiculturality (October 2019)
https://doi.org/10.1145/3362789.3362819
ISBN: 9781450371919

3D printed models-based lab activities to enhance learning-teaching processes in Structural Engineering courses

Luis Celorrio-Barragué
Dept. Mechanical Engineering
Universidad de La Rioja
C/ San José de Calasanz 31
26004 Logroño, Spain
luis.celorrio@unirioja.es

Sergio Calvo-Simón
Universidad de La Rioja
Logroño, Spain
sergio.calvos@alum.unirioja.es

Marcelo Gaspar
Instituto Politecnico de Leiria
Leiria, Portugal
marcelo.gaspar@ipleiria.pt

Mariano Vidal-Cortés
EPS, Universidad de Zaragoza
Carretera de Cuarte s/n
22071 Huesca, Spain
vidalcor@unizar.es

Pablo Martín-Ramos
EPS, Universidad de Zaragoza
Carretera de Cuarte s/n
22071 Huesca, Spain
pmr@unizar.es

ABSTRACT

Three-dimensional (3D) printing is a promising tool in Engineering education, as it can facilitate learning, contribute to the development of key skills and competences, increase the engagement and interest of students, and promote their creativity. In this work, a set of laboratory activities aimed at enhancing the learning–teaching experience of sophomore and junior students of engineering degrees related to structures is presented. To improve their understanding and their ability to calculate the stability, strength and rigidity of built structures, the use of 3D printed models is put forward. These printed models can be used as specimens in lab tests and also as visualization objects to improve students' comprehension in lectures. Moreover, they offer interesting advantages in terms of their lower cost, easy manipulation, low weight and short time of production. Five lessons, designed for Strength of Materials and Theory of Structures courses, which cover tensile testing, the analysis of truss and plane frames, bolted and welded joints, and constructive details in reinforced concrete structures are discussed.

CCS CONCEPTS

• Applied computing → Engineering; • Applied computing → Education; • Applied computing → Computer-assisted instruction; • Hardware → Printers; • Hardware → Emerging tools and methodologies

TEEM'19, October 16–18, 2019, León, Spain

ACM ISBN 978-1-4503-7191-9/19/10...$15.00
https://doi.org/10.1145/3362789.3362819

KEYWORDS

3D printing, Additive manufacturing, Lab activities, Structural Engineering, Steel structures.

ACM Reference format:

Luis Celorrio-Barragué, Sergio Calvo-Simón, Mariano Vidal-Cortés, Marcelo Gaspar and Pablo Martín-Ramos. 2019. 3D printed models-based lab activities to enhance learning-teaching processes in Structural Engineering courses. In *Proceedings of the Seventh International Conference on Technological Ecosystems for Enhancing Multiculturality (TEEM 2019) (León, Spain, October 16-18, 2019), ACM, New York, NY, USA*, 7 pages. https://doi.org/10.1145/3362789.3362819

1 Introduction

3D printing, based on the Fused Deposition Modeling (FDM) technique, has become very popular in recent years. This technology uses filaments of materials such as Polylactic Acid (PLA), Acrylonitrile Butadiene Styrene (ABS), Copolyester (PETG), translucent co-polyester filament, etc. to create three-dimensional objects. These materials are affordable and are also very suitable to manufacture scaled 3D models or prototypes of mechanical parts for educational purposes.

3D printing technologies have been in the market for several decades. However, it has not been until the last decade when 3D printing has become widespread, reaching the general public and making it possible to have a printer at home. This expansion may be ascribed to the expiration of the patents that protected these inventions and also to the appearance a multitude of 3D printer manufacturers, which has resulted in a remarkable reduction of production costs. Assembly kits have been popularized, and users can nowadays buy or manufacture the parts of the 3D printer and make it up by themselves. In fact, open design projects such as RepRap (rep*licating* rap*id prototyper*) have developed low-cost 3D printers that can print most of their own components, in what can be regarded as an excellent example of the "Do It Yourself" (DIY) movement that has been so beneficial from the educational point of view.

3D printing and Additive Manufacturing (AM) technologies present a fundamental advantage over conventional manufacturing technologies, summarized in the motto "complexity and variety are free" [1]. Complexity refers to the fact that 3D printers do not care about the features of the model, while variety refers to the fact that designers can create a copy of each design. They do not need to mind about traditional economy of scale and they can manufacture very short series, or even unique copies, of each model.

Recently, practical applications of 3D printing have gone beyond prototyping, and, for instance, it is increasingly finding a place in the aerospace, healthcare and tooling industries, and even in the construction of real-scale structures. For example, concrete bridges have been manufactured using a type of 3D printing technology [2], and metallic AM has been used to develop the MX3D bridge [3].

In view of the wide-range applicability of this technology and owing to the fact that FDM–based printers are accessible and easy to use, the goal of this study has been to explore the applications of 3D printing in Structural Engineering education through several appealing activities for second- and third-year Engineering students. Applications of other 3D printing technologies, such as Additive Manufacturing or Metallic Additive Manufacturing, have not been considered herein due to their high cost and provided that are mainly applied to the manufacturing of industrial products [4].

2 3D Printing in Higher Education

The use of 3D printing in education is a varied and extensive field of study due to its numerous benefits. Although students may have their first contact with the basic operation of 3D printing at a Secondary Education level (for instance, in Spanish secondary schools, students may be exposed to 3D printing as part of the "Technology" compulsory subject or in the optional A-levels course on "Industrial Technology"), in this section emphasis will only be placed on some of its most common uses in Higher Education.

2.1 Teaching of 3D Printing as a Manufacturing Technology

3D printing is a subject of study with important applications in the field of manufacturing and industrial design. Thus, there is great demand for specialized technicians in 3D printing. Many Institutions that offer Mechanical Engineering studies and Schools of Arts and Design offer specific courses on 3D printing or on AM as part of their curricular program. Also, some Polytechnic Schools have services, libraries or classrooms dedicated to 3D printing, in which students can book printers and create their own models. In some cases, Universities offer multidisciplinary postgraduate degrees about AM. Regarding distance education, mention should be made to massive open online courses (MOOCs) dedicated to 3D printing and AM available in platforms such as Coursera, EdX or MiriadaX, which also represent an excellent source of knowledge for these technologies.

2.2 Supporting Active Learning by Using 3D-printed Specimens in Tests and Experiments

This application is typical of Mechanical Engineering [5-7], Structural Engineering [8,9], Industrial Engineering and Architecture degrees. For example, specimens made from different materials (e.g., PLA, ABS, etc.) may be used to perform the tensile test, determining the mechanical properties. In some cases, students already have knowledge of 3D modelling and 3D printing, acquired in subjects or courses from previous years and can design and print their own specimens for testing.

2.3 Supporting Active Learning by Using 3D-printed Models for Visualization Purposes

It is the most common application in education of 3D printing, especially in STEM courses. The teacher shows in class artefacts or 3D models that help the visualization of complex objects composed of several components. As an example, in Geometry, 3D printed models are used to visualize polyhedral and other geometric figures; in Chemistry and Pharmacy, to conceive complex molecules; in Anatomy, to image skeletons; in Dentistry, to visualize implants and teeth; in Surgery, prosthesis are manufactured by 3D printing. More cases of this type of applications may be found in the recent review paper by Ford and Minshall [10].

In the field of Structural Engineering, 3D printing can help to understand stiffness methods and the physical meaning of stiffness [11]. It has also proven useful to promote the comprehension of constructive details in steel structures and reinforced concrete structures: Chacon et al. [9] materialized steel connections and plate girders by 3D printing in order to help students' understanding of such elements. The authors claimed that physical reproductions of connections added realism and enriched the lectures and helped to visualize details that could be hidden in the graphical representation.

2.4 Advantages and Disadvantages of 3D Printing in Higher Education

Several studies have highlighted the benefits of the application of 3D printing in teaching. These studies concluded that 3D printing facilitates learning, develops skills, increases engagement and interest of students, brings realism, increases creativity and improves the students' opinion about technical careers. Furthermore, it also increases the engagement and interest of the teacher [10].

As mentioned above, FDM-based 3D printing can be regarded as very affordable: a 3D printer with an excellent performance can be bought for less than 700 € and a 1 kg spool of FDM material costs *ca.* 25 €, so the cost of 3D printed models is much lower than that of steel structures.

From the point of view of health hazards, 3D printing is an activity that involves a very low risk for the students and teachers. However, some basic safety recommendations must be considered, such as avoiding touching hot parts of the printer, being careful of moving parts, and ventilating the lab room. Measures of prevention, e.g., covering the printer with a transparent box, are advised.

The main drawback associated with 3D printing would be that the mechanical properties of the materials used (PLA, ABS and others) differ from those of the materials used in realistic structures, such as steel, aluminum or concrete. However, 3D-printed materials have an elastic zone in their stress–strain curves (shown for PLA and ABS specimens in Figure 1), in which the applicable equations are the same as those that apply to conventional engineering materials. Hence, 3D-printed scaled structures can still be deemed as very useful to conduct elastic analyses of structures.

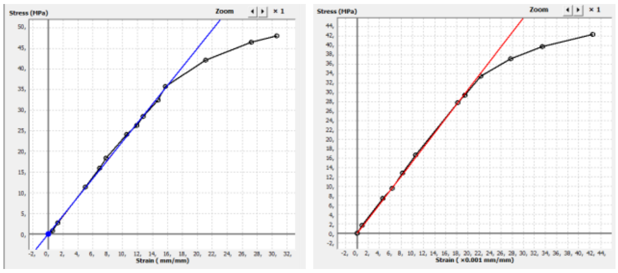

Figure 1: Experimental stress-strain curves obtained for PLA (left) and ABS (right) specimens in the tensile test.

Another possible limitation that can arise is that, if the number of students in the class is very large, several sets of specimens are needed for the lab activities, which can be time-consuming, provided that the 3D printing of certain models can take a long time. For example, for some of the models presented in section 4, printed with a 100% infill percentage to maximize stiffness and strength, the 3D printing process took up to 7 hours.

3 Context of the Proposed Teaching Experience with 3D-printed Models

The advantages and benefits of 3D printing discussed in previous sections have encouraged the introduction of 3D printing in several subjects related to the Structural Engineering field at University of La Rioja, continuing other teaching innovation projects conducted by some of the co-authors [12, 13].

In particular, in this initial stage, the main goal has been to prepare lab classes based on 3D models for two subjects: Strength of Materials, a second-year course in Industrial Engineering degrees (Mechanical Engineering, Electrical Engineering and Electronic Engineering), and Theory of Structures, taught in the third year of Mechanical Engineering undergraduate degrees. In the first course there are *ca.* 100 students enrolled, while the second course counts with approximately 50 students. All the students have previous knowledge of 3D modelling, as they have received training on the use of AutoCAD 3D and SolidWorks software packages [14] in the compulsory subject "Graphic Expression and Computer-Aided Design" in the first year and some of them have basic hands-on experience in 3D printing, acquired in secondary school.

The proposed activities are based on FDM 3D printing, and involve the manufacturing of small 3D models that are then used either as specimens for lab tests or as 3D objects for the visualization of structural details during lectures. The models are printed using an open-source PRUSA i3 MK3S printer, manufactured by the Czech company Prusa Research, part of the RepRap project. This low-cost printer has additional refinements to the extruder body and filament sensor as compared to the popular MK2, MK2S and MK3 models. It features a print volume of 200 mm × 200 mm × 200 mm, which is a constraint on the 3D models. Thus, realistic structures need to be scaled.

Due to the skills and competences acquired in previous courses, students are able to design their own models. Therefore, the teacher can propose a basic model with a common configuration for all students, but with variations in topology, geometry or configuration of the structure for each group of 2-3 students. Then, those groups carry out tests with those individualized models. Alternatively, in order not to burden the students with extra work if the time schedule is tight, the instructor can provide the 3D models necessary to conduct the laboratory activities.

4 Description of Lab Activities

Proposed laboratory activities, designed to enhance the learning process and complement the lectures, and the learning objects prepared with 3D printed models are discussed in this section.

Since some of the 3D models are to be used as specimens for testing, certain settings of the 3D printer and the 3D model g-code file have to be modified in order to obtain a specimen with the expected mechanical properties. Hence, parameters such as the fill pattern, the layer thickness or the fill density need to be tuned accordingly. As regards the latter parameter, it is recommended to set it to 100%, so that the 3D printed models have the highest possible strength and stiffness.

4.1 Tensile Testing

As explained above, FDM-based 3D printers can use different types of materials (viz. PLA, ABS, PETG, FLEXIBLE, etc.), which allows to prepare test specimens with different tensile strengths. The students can then mount them in the tensile testing machine and determine their mechanical properties: modulus of elasticity, elastic limit and ultimate tensile strength. This introductory activity is instructive by itself and provides information on the mechanical characteristics of the materials that will be used in subsequent activities.

Materials needed for the activity: 3D printer, different types of filaments, tensile testing machine, and several software packages (Solidworks or AutoCAD, the proprietary software of the tensile testing machine and MdSolids) [15]. Figure 2 shows the tensile testing machine and some testing specimens before and after the experiment.

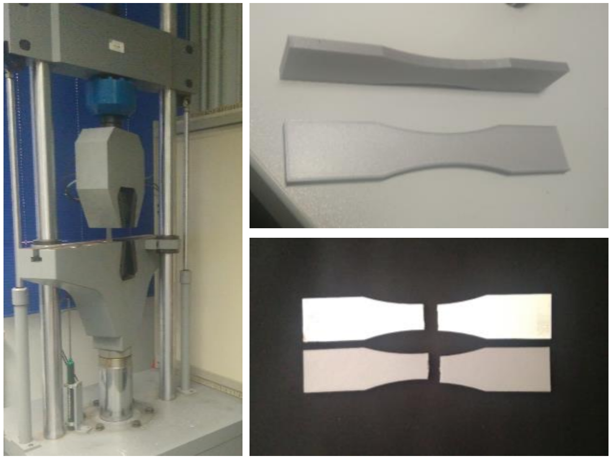

Figure 2: Tensile testing equipment (left) and 3D-printed specimens, before (upper right corner) and after (bottom right corner) the test. Grey specimens are printed with PLA and white ones are printed with ABS.

4.2 Analysis of Trusses

Trusses are structures that consist of all straight members, connected together with pin joints, only at the ends of the members. External loads are applied only at the joints and members are only subjected to axial (tensile or compressive) forces.

The second activity proposed to the students involves building a simple truss, applying loads on the nodes and determining the displacements. Students can design their own structure, or they may print a pre-defined structure from a 3D model repository such as Thingiverse [16]. Figure 3 shows a simple truss bridge being tested.

Figure 3: Truss bridge, composed of two identical trusses, symmetrically loaded.

A more challenging exercise is that students compete in groups –under the same terms and conditions– to design the most efficient truss [6]. That is, the structure with the largest ratio between the applied loads and its own weight in the moment that the failure of the structure occurs. One condition could be to limit the weight of the material used. Competition between students usually encourages them and increases their interest and creativity (in fact, competitions about building bridges with ice-cream sticks are very popular in Structural Engineering Schools).

4.3 Analysis of Plane Frames

Stiffness method or matrix analysis of structures, part of the Theory of Structures syllabus, requires a solid mathematical background. Students usually build the stiffness matrix of a structure from the stiffness matrix of the elements (beams and columns) for the simplest frame structures. However, they need to understand the physical meaning of stiffness and how stiffness varies for structures with different geometrical configurations, and this physical meaning may sometimes be hindered by the algebra of the mathematical method.

3D printing allows to obtain relatively slender plane frames with different geometries. This third activity, focused on learning the physical meaning of stiffness, requires testing several 3D printed models of single-bay plane frames. As proposed by Virgin [16], frames should have the same boundary conditions (fixed supports) and different geometries: for example, columns length can be two times or one time the beam length, the thickness of the cross section for the beam can be four times or the same than the column thickness, etc.

In this activity, plane frames printed with two types of materials are assayed. Each type of plane frame is tested using both PLA (grey plane frames in Figure 4) and ABS (white frames in Figure 5). Their properties, determined in the tensile testing activity, should be considered here to characterize them in Finite Element Analysis (FEA) packages.

Other stiffness enhancements can be integrated into the frame: a bracing system, additional cross beam members and so on. For example, Figure 6 shows a PLA plane frame with a bracing bar to increase stiffness.

Students are given the specimens, they apply loads and are requested to measure displacements. Then, they compare the experimental results with the displacements calculated with any FEA software (e.g., SolidWorks) [14] or Structural Analysis software (e.g., CESPLA) [17]. Alternatively, students can apply the force method (also called the flexibility method or method of consistent deformations) to determine these displacements, which is part of the Strength of Materials syllabus.

This activity requires a support with a magnetic grip and an arm to hold the digital dial indicator probe; standardized masses, a support for the masses on the hole of the frame and two clamps to fix the frame to a rigid solid (Figure 7). The cost of this equipment is reasonable: the instruments cost less than 60 € and the materials cost less than 20 €.

Figure 4. Displacement tests for 3D-printed single-bay frames using PLA.

Figure 5. Displacement tests for 3D-printed single-bay frames using ABS.

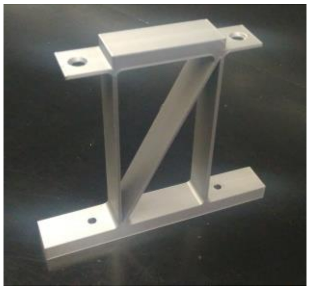

Figure 6. PLA plane frame with a bracing member.

Figure 7. Magnetic stand (left), digital indicator probe (center) and clamp (right) used in the analysis of plane frames.

4.4 Visualization of 3D Models of Bolted and Welded Joints

3D printing may also be helpful in the study of beam-column joints [9]. This activity consists in visualizing the different elements of beam-column joints: screws, welds, plates, stiffeners, angular profiles of equal sides or type L profiles, etc.

The goal of the session is that students can differentiate between rigid joints, semi-rigid and simple or pinned joints. To this end, different models of beam-column connections are printed. Two models represent the extreme cases. The first model is a beam-column joint printed as a continuous block, with thick areas representing the weld (see Figure 8). This joint can be classified as a rigid joint. The second model is a beam-column joint in which the beam, the column and the angular profiles are printed separately. Then, these printed pieces are drilled. The beam-column joint is formed by screwing the angles to the beam web and one flange of the column (see Figure 9). Thus, this joint can be classified as a pinned joint. Semi-rigid joints (not shown) are intermediate cases between these two extremes, as they permit a relative rotation of the members in addition to a certain bending moment transmission.

It is important to note that the printing of a rigid beam-column joint as a continuous solid implies using 3D-printed supports because one flange of the beam will be printed like a cantilever, that is, one flange will be parallel to the printer base, but separated from it.

Students can grab both members of the joint and try to rotate them in order to check their rigidity. They will appreciate that the first model (Figure 8) is more rigid than the second one (Figure 9). 3D-printed models make it easier to perceive this difference than steel ones.

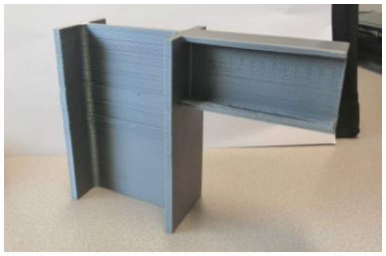

Figure 8. 3D-printed rigid beam-column joint.

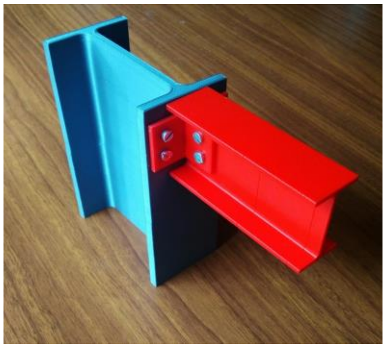

Figure 9. 3D-printed pinned beam-column joint.

Another objective of the activity is to visualize constructive details of the joint. 2D graphical representations of joints may not be clear enough for the students to perceive all the details. On the other hand, a 3D model gives a clear spatial view and helps to identify stiffeners, plates, bolts, welds, etc. The use of these 3D-printed physical models of the joints adds realism to the lectures, provided that the teacher can take them to the classroom and hand them around to the students.

4.5 Visualization of 3D Models of Constructive Details in Reinforced Concrete Structures

An interesting feature of modern 3D printers is that they can use transparent or translucent filaments. One can take advantage of this to facilitate the comprehension of concepts related to coating, reinforcement thickness, bonding, steel reinforcement bars, steel stirrups, ties, footing, concrete slab foundation, etc. In this activity, typical constructive details of reinforced concrete structures such as joints, shallow foundations, slabs, etc. are represented using an opaque filament for steel reinforcement bars and stirrups, and a transparent or translucent filament for concrete. Further enhancements in the representation can be obtained if a 3D printer with three extruders is available, as three filaments with different colors would then be available. Figure 10 shows a cut of a 3D model representing a reinforced concrete column.

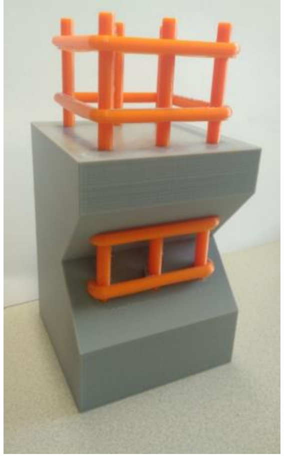

Figure 10. 3D model of a reinforced concrete structure printed with a combination of filaments of different colors: concrete and reinforcement bars have been printed in grey and orange, respectively.

5 Feedback and future lines of action

In the pilot tests conducted as part of the teaching innovation project, the volunteer students received enthusiastically the novel approach to improve the teaching–learning process. From the teacher's perspective, it was a very rewarding experience: throughout the lab sessions, it became apparent that they were engaged in learning and motivated by the step-by-step increase in the complexity of the activities.

No pre- and post-tests were conducted in this stage. Instead, they will be delivered during the actual deployment phase, projected for 2019-2020 academic year, with a view to gaining insight into the real effectiveness of this approach on the students' performance and also in order to diagnose lessons plans that should be revised, detecting the topics that they students have (or have not) mastered.

Moreover, additional activities are being prepared using 3D printing technology in the field of dynamic of structures, buckling and impact loads. It is envisaged that these new activities, together with those presented in section 4, will also be conducted in other centers, provided that several faculty members who have heard about the project have already expressed their interest in using the 3D models in their classes.

6 Conclusions

FDM-based 3D printing is a technology that is receiving increasing attention in Higher Education. The materials used as filaments and the printing processes result in objects that feature suitable mechanical properties for their use as test specimens.

This work describes five lab activities that cover key topics of the syllabus of two Structural Engineering courses, and which help to build important skills and competences. Students design and print different 3D models, some of which are then used as specimens for tests (gauges, frames and simple structures), while others are used only for visualization purposes, facilitating the comprehension of elements in structural details.

The choice of 3D-printed models entails noticeable savings over the use of traditional lab kits, allows to the students to design and produce by themselves a large variety of specimens and structures in a facile manner, and does not involve hazard or health risks.

ACKNOWLEDGMENTS

This work has been sponsored by Universidad de La Rioja under the teaching innovation project entitled "Mejora del proceso de enseñanza - aprendizaje de Resistencia de Materiales utilizando prototipos de estructuras y elementos estructurales elaborados mediante impresión 3D".

REFERENCES

[1] C. Anderson. 2014. *Makers: The New Industrial Revolution.* CROWN PUB INC. London, UK
[2] F. Bos, R. Wolfs, S. Ahmed and T. Salet (2016). Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing. Virtual and Physical Prototyping, 11(3), 209–225, DOI: https://doi.org/10.1080/17452759.2016.1209867
[3] MX3D Bridge. https://mx3d.com/
[4] Renishaw, 2016. *Fabricación aditiva metálica.* Downloadable from https://www.renishaw.es/es/impresion-de-metales-3d--32084P.
[5] Minetola, L. Iuliano, E. Bassoli, A. Gatto (2015). Impact of additive manufacturing on engineering education - Evidence from Italy. Rapid Prototyping Journal, 21 (5), 535-555. DOI: https://doi.org/10.1108/RPJ-09-2014-0123
[6] N. A. Brake, F. A. Adam (2016). Integrating a 3-D printer and a Truss Optimization Project in Statics. 2016 ASEE Annual Conference & Exposition. New Orleans. USA, DOI: https://doi.org/10.18260/p.25776

[7] M.C. Gaspar, A. Pikkarainen (2017). FINPORTECH: Cross-Border Cooperation and Knowledge Transfer in Engineering Design across Europe. ECS2017 - 4th International Conference on Education, Culture and Society. Wroclaw. Poland.
[8] R. Chacón, D. Codony, Á. Toledo (2017). From physical to digital in structural engineering classrooms using digital fabrication. Comput. Appl. Eng. Educ. 1-11. DOI: https://doi.org/10.1002/cae.21845
[9] R. Chacon, E. Mirambell, E. Real, I. Arrayago, S. Martínez (2018). On the use of 3D printing in steel structures education. IV International Conference on Structural Engineering Education without Borders.20-22 June 2018, Madrid, Spain.
[10] S. Ford, T. Minshall. (2019). Invited review article: Where and how 3D printing is used in teaching and education, Additive Manufacturing. 25, 131-150, https://doi.org/10.1016/j.addma.2018.10.028.
[11] L. Virgin (2017). Enhance the teaching of linear structural analysis using additive manufacturing. Engineering Structures 150, 135-142. https://doi.org/10.1016/j.engstruct.2017.07.054
[12] L. Celorrio-Barragué, A. Lopes-Ramalho, M.R. Calvete Gaspar (2016). Development of generic and strategic skills through a wiki platform in industrial engineering programs. Multidisciplinary Journal for Education, Social and Technological Sciences. 3 (1) 152-168. DOI: https://doi.org/10.4995/muse.2016.4486
[13] L. Celorrio-Barragué (2016). A case study of mobile learning in a strength of materials course. Proceeding TEEM '16 Proceedings of the Fourth International Conference on Technological Ecosystems for Enhancing Multiculturality.543-547. Salamanca, Spain DOI: https://doi.org/10.1145/3012430.3012571
[14] Solidworks. https://help.solidworks.com/2019
[15] MdSolids, MDSolids: Educational Software for Mechanics of Materials. https://web.mst.edu/~mdsolids/
[16] Thingiverse. Thingiverse - Digital Designs for Physical Objects. https://www.thingiverse.com/
[17] J. T. Celigüeta (2011). Cálculo de estructuras con Cespla 7. Universidad de Navarra - Servicio de Publicaciones. Pamplona. Spain.