Adding a dimension to pedagogy through 3D printing

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Abstract — **In this article, it is intended to describe the process of design and materialization of three-dimensional models using Computer Aided Design (CAD) and 3D printing to support the teaching of "Resistance of Materials" of the Integrated Master in Civil Engineering (MIEC) of the Faculty of Engineering of the University of Porto (FEUP).**

Learning is always easier with the right tools and 3D printing adds a new dimension to the pedagogical experience, allowing problems to "jump" from the blackboard to the student's hand, materializing elements or experiences that are difficult to visualize on paper or too complex/expensive to perform at full scale. The use of visible and palpable models allows teachers and students to contextualize concepts through the immediate application of skills and learning using simulations and demonstrations, relating theory with real situations of their day-to-day making experience as the basis of learning.

After mastering the process of designing and printing the models by the teacher, he intends to extend the use of the means acquired to students, so that this revolutionary technology can motivate and promote innovation, giving them tools to develop concepts and products based on their ideas. Certain of the success of this project, the results obtained with the use of this "tool" in the academy will be disseminated, motivating students and teachers from other curricular units to use it as a pedagogical strategy.

The project "Adding a dimension to pedagogy through 3D printing" was one of the winners in the annual competition (2020/2021) of "Pedagogical Innovation Projects" at the University of Porto, through the Pedagogical Innovation and Educational Technologies Unit of the Rectory.

Keywords — 3D printing; Computer Aided Design (CAD); Resistance of Materials, Civil Engineering

I. INTRODUCTION

The author of this article has been teaching for 20 years the curricular units (UC) of Material Resistance 1 and Material Resistance of MIEC of FEUP, where students have their first contact with structural problems in the scope of Civil Engineering, the knowledge transmitted is based on an understanding of fundamental concepts that are not always easy to explain.

Despite the constant evolution of everything that surrounds us, these UCs work in the classic way, where in theoretical classes the subject is exposed on a board and in practical classes exercises are solved. Lately, the face-to-face hours of UCs have considerably decreased, keeping the subject to be taught, so it is urgent to optimize the efficiency of classes, through the resourcefulness of the teachers and the motivation of the students. One way to achieve this goal is the use of three-dimensional didactic models, however, there are few models on the market and they are usually expensive and not always perfectly adjusted to the content that is intended to be taught. On the other hand, due to a series of specificities of the sector itself, there is a huge inertia of the civil construction to change and, consequently, to innovation, so radical action is needed to ensure that the next generation of engineers is prepared to deal with a new technological age - the "fourth industrial revolution" - of robots, artificial intelligence and 3D printing.

It was in this context that the idea to conceive and materialize 3D didactic models to support these UCs, using emerging technologies, such as CAD and 3D printing, emerged. Although CAD is already fully implemented in civil construction and the potential for 3D printing in the sector is enormous, see Figures 1 and 2, for many a 3D printer is "something that exists in the International Space Station and that prints the pieces that astronauts need it". There is an urgent need to change this point of view.

Fig. 1. 3D-printed steel bridge [1]

Fig. 2. 3D-printed concrete house [2]

Although there are several authors who have already looked into 3D printing as a pedagogical tool [3] [4] [5] [6], its use is not frequent in connection with the design and manufacture of pedagogical models linked to the teaching of Civil Engineering. Even so, it is hoped that through this project to obtain 3D models pedagogically suited to the subjects taught and to present students with important technologies for their development as Engineers, increasing awareness of the relationship between curricular units and engineering in the real world.

II. The Objectives

In pedagogical terms, the most obvious advantage of 3D printing is that it quickly transforms an idea into something visible and palpable, this not only facilitates the teaching and learning processes but also inspires creativity and student involvement in learning. In addition to creating models to help illustrate concepts in a physical way, the use of 3D printing gives an opportunity to learn to use technology which can help in the process of understanding other concepts. Combining computer skills with problem solving and imagination, 3D modelling gives students a hands-on experience with fun and interactive technology and arousing a curiosity that might not otherwise have happened.

Advantages of using 3D modelling/printing:

- Quickly transform an idea into something physical, thus facilitating the teaching and learning process, inspiring creativity and actively involving the student in learning;
- Create 3D printed objects with which students can process complex information through their analysis;
- Store, consolidate and perfect the models developed, in order to increase applicability and reuse;
- Instead of drawing a structure and its deformed structure on a board, it will be possible to take a small scale structure to class and let students test it and observe its operation;
- Use libraries of existing and validated models, for example www.cults3d.com, www.thingiverse.com or www.youmagine.com, which can be used tout court or adapted to the objective of the course.

In terms of teaching methodologies, the aim is to:

- Closer the link between theory and practice;
- Make educational, appealing and certified 3D models available to students and the community in general;
- Promote the analysis, discussion and critical interpretation of results, highlighting the potential of 3D models;
- Promote opportunities for autonomous, but guided study, encouraging self-regulation of student learning;
- Develop students' critical spirit through access to tools that allow them to validate or correct their reasoning, promoting skills testing opportunities;
- Encourage and support the development, by students and teachers, of 3D models within the scope of Civil Engineering;
- Collect and coordinate the development of new 3D models within the scope of MIEC UCs and, at the same time, disseminate the work developed among teachers, students of MIEC and other potential stakeholders.

III. The Process

Several steps are necessary until obtaining a usable didactic model:

- Define the concept to be explored and the objectives of the model;
- Conceive the model/experience;
- Draw the model in three dimensions;
- Prepare the three-dimensional model to be printed;
- Print the model;
- Test and fine-tune the physical model.

After the conception of the model/experiment to be built, which depends only on the inspiration of the creator, it is necessary to materialize it, initially in a digital environment and later physically. Since all professors and students at the University of Porto have access to the necessary software for the development of 3D models, it was only necessary to acquire the printing hardware and the respective printing material: the filaments.

In this case, the software Fusion 360 was used to model the elements to be printed, which is a cloud-based 3D CAD, Computer-Aided Engineering (CAE) and Computer Aided Manufacturing (CAM) design tool from Autodesk. In Figure 3 one can see the model developed with Fusion 360 to the study of buckling, that will be presented in detail in the next chapter.

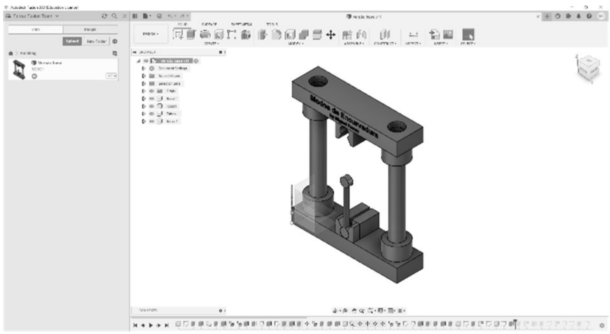

Fig. 3. Computer aided design software “Fusion 360” from Autodesk

Once the three-dimensional digital model is completed and “tested”, often composed of several parts, it is necessary to convert this model into specific instructions for the printer using a software called slicer, see Figure 4.

The slicer first divides the object as a stack of flat layers, followed by describing these layers as linear movements of the 3D printer extruder, that together with some specific printer commands, are finally written in the g-code file, that can afterwards be transferred to the printer. Some of the commands mentioned above are the extruder temperature, the extrusion speed, the temperature of the printing bed, the filling, the creation of temporary supports or the use of rafts, skirts and brims. Although it is not a simple process, there are currently numerous good manuals available for free on the internet that help substantially in this task.

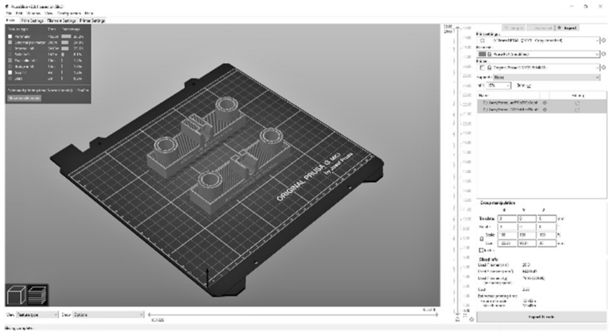

Fig. 4. Slicer software "PrusaSlicer" from Prusa

We have now reached the stage of materialization of the model, which is why we need a 3D printer. There are several types of 3D printing, which include:

- Fused Deposition Modelling (FDM)
- Stereolithography (SLA)
- Selective Laser Sintering (SLS)
- Fused Deposition Modelling (FDM)
- Digital Light Process (DLP)
- Multi Jet Fusion (MJF)
- PolyJet
- Direct Metal Laser Sintering (DMLS)
- Electron Beam Melting (EBM)

In this project, for economic and simplicity reasons, we opted for Fused Deposition Modelling (FDM), also known as Fused Filament Fabrication (FFF), which works through a 3D printing innovation that uses a cycle called Material Extrusion. In these printers, a spool of fibre made of strong thermoplastic material is used, which is pushed by a motor through a heated nozzle, where it liquefies. The printer's ejection head at that point moves along the predefined directions while releasing material which, after being deposited, cools and hardens, forming a strong item. When a layer is completed, a printer defines another layer, until the object is completed.

There are several ways to obtain a FDM 3D printer, among them: building your own printer, buying a ready-to-use printer and buying a kit printer and assembling it. The first option, despite being the most economical, is not advisable for beginners, because if the assembly of the board is not normally very difficult, obtaining the correct alignments, the assembly of the extruder and the electronics can be quite complicated. The easiest way to start printing in 3D is by purchasing a ready-to-use printer however it is also the most expensive option. The option to purchase a kit is usually a good compromise solution between the previous two, in terms of difficulty and costs.

After some investigation the choice fell on the printer assembly kit of the Prusa i3 MK3S + printer, see Figure 5, as its cost was affordable by the available funds, the critics referred to print quality, profitability and longevity with a performance and usability widely demonstrated. In addition to regular updates, ideas and official and community-generated support, the fact that some colleagues at FEUP already had experience with these particular printers weighed considerably in the decision.

Fig. 5. Original Prusa i3 MK3S+ 3d printer [3]

In fact, the assembly of a 3D printer kit requires some expertise and a lot of attention, see Figure 6. The total time spent in assembling the printer was about 10 hours, because despite the manual that accompanies it being very complete and detailed, this did not prevent the making of some errors that prolonged the assembly in a few hours.

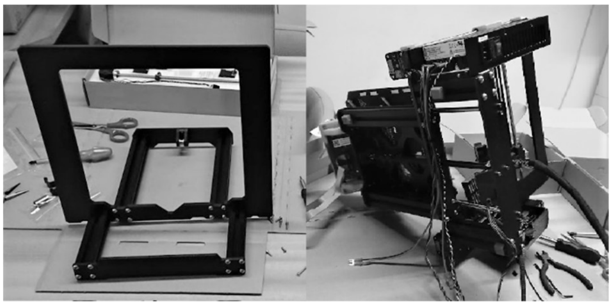

Fig. 6. Assembling the 3D printer

As mentioned above, FDM printers use strong thermoplastic filaments that can be of different materials, of which some have been chosen depending on the intended use:

- Generic models: Filament in acrylonitrile styrene acrylate (ASA) as it is a rigid material, resistant to chemical exposure, heat and changes in shape and colour. Since printing on ASA sometimes presents some difficulties, filaments in lactic polyacid (PLA) will also be used since it is easy to print; it exists in a wide variety of colours / styles and is biodegradable, however it is relatively more fragile than ASA.
- Metallic elements: "Steelfill" filament, is a mixture of powdered metal with lactic polyacid (PLA) or acrylonitrile butadiene styrene (ABS), has the appearance, texture and weight of the metal.
- Wood: "Wood" filament, is a mixture of powdered wood with lactic polyacid (PLA), in which the aesthetic and tactile attractions are opposed by the reduced flexibility and resistance.
- Tie Rods: Polycarbonate filament, is extremely strong, durable and resistant to physical impact and heat.

In the first printing tests, ASA filament was used, but it was quickly realized that, despite all its good mechanical characteristics, printing with ASA filament requires a series of special care. One of the problems detected is related to the poor adhesion of these filaments to the printing base and, even using special additives, such as the printing lacquer, and a heated printing base, several impressions had to be interrupted by detaching of the piece. Problems with layer separation, splitting and warping also arose, mainly related to the high temperatures required with the melting of this material, around 260ºC, and the cooling process, in which the piece shrinks. One way to reduce these problems is through the use of a heated enclosure that can help regulate the temperature of the entire build volume. Since a heated enclosure was not available, it was decided to use another material, namely PLA. In fact, the PLA is much more user friendly in terms of 3D printing and no problems were detected during the actual printing and, although the mechanical characteristics are not as good as those of the ASA, the final product proved to be very satisfactory.

IV. THE FIRST APPLICATION

The first model to be designed and built was a model for the study of buckling of compressed bars in structures, called “Bending modes”. Despite being a relatively simple model, the design process and realization was extremely interesting and enriching as it implied the domain of all stages of the process.

The developed model allows the application of axial forces on a bar while simulating different support conditions. It consists of a fixed base that supports two tubes over which a top slides and a bar that connects to the base and the top, see Figure 7. All parts were printed in 3D with the exception of the tubes, which are metallic, they could be printed in 3D, but it was felt that it would make no sense to print parts easily obtained at a very low cost.

Fig. 7. Finished buckling model parts

Since the 3D printing process was already relatively mastered and the right choice was made of the material to be used, the printing process of this model went without any kind of hiccup and all the pieces resulted in the first attempt. The final appearance of the printed parts is excellent, which gives the model a very professional look.

After assembling the different parts, a model was ready to rehearse. In figure 8 it is possible to visualize the final model in use, using the conditions of fixed at the base and articulated at the top for the bar, it is possible to observe the bending mode of the bar with two inflection points.

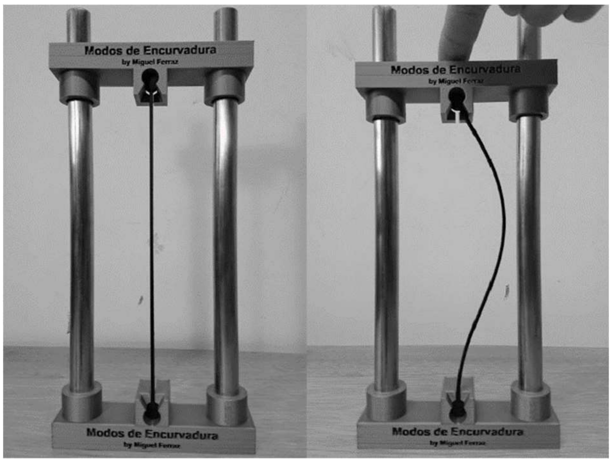

Fig. 8. Using the buckling model

The only part that had to be perfected was the bar, having been tested various thicknesses and materials in order to better calibrate the forces to be applied to the model and diameter of the ends in order to fine-tune the clearance in the fitting, see Figure 9. At the end, it was decided to take advantage of all the specimens since the rigidity and length of the bar are a factor to take into account during the analysis of buckling and thus the use of bars with different characteristics makes the experience much more enriching.

Fig. 9. Compression bars

Unfortunately, the existing restrictions due to the Covid-19 pandemic have not yet allowed the use of the "Buckling Modes" model in classes, where students could try it out with their hands. However, the receptivity of everyone who had the opportunity to try the model, both students and teachers, found it very didactic, easy to use and were extremely motivated by the use of 3D printing.

V. CONCLUSIONS AND THE FUTURE

After the materialization of the first models in the scope of this project it was possible to conclude:

- The process of creating a piece using 3D printing is multidisciplinary because it involves drawing a three-dimensional model and mastering the technology of 3D printers. Despite the immense potential of the process, the use of it implies an initial investment in economic terms and considerable time;
- The motivation presented by the students in the use of the models made was enormous, not only in the analysis of the phenomena under study but also in their curiosity about the manufacturing process, namely in three-dimensional modelling and 3D printing;
- The model aroused the curiosity of several colleagues who now intend to develop three-dimensional didactic

models to help in their classes, in areas as diverse as hydraulics, reinforced concrete or physics;

- The possibilities opened by 3D printing in the creation of didactic models are immense.

Among the many new approaches within this context, taking advantage of the experience acquired in terms of 3D printing, the author, together with Fernando Miguel Moreira Nogueira, responsible for the Infographics service at the Faculty of Letters of the University of Porto (FLUP), has been developing three-dimensional maps to support the study by colour blind and blind people, see Figure 10.

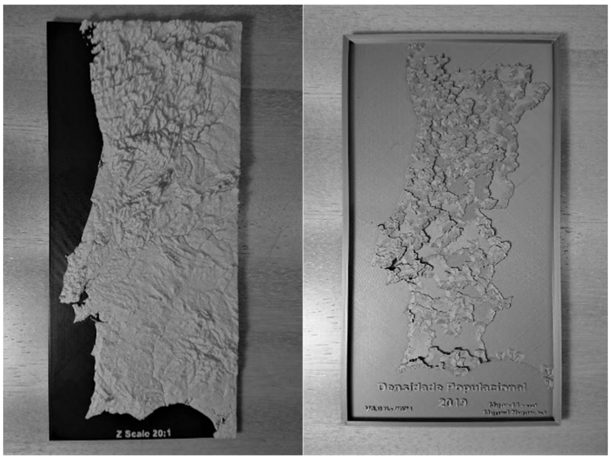

Fig. 10. Altimetric map, on the left, and population density map, on the right

Finally, as an example… The author has been a collaborator for several years in the "Spaghetti Bridges Competition" promoted by the International Civil Engineering Students Association (IACES - LC Porto). Although the contest is a success at all levels, such as motivation, resourcefulness and companionship, it may be time to take the leap into the 21st century and replace spaghetti with 3D printing, see Figure 11.

Fig. 11. Printed bridge contest, Gdansk University of Technology [8]

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