Can model-making makes better architects?

A French and Australian comparative case-study

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Abstract—The review of the different types of models that are developed and tested for architectural courses displays the challenges faced by the students in terms of structural issues and new technologies. Through a comparative case study in France and Australia, our research aims at assessing the contribution of model-making to improve engineering skills in architecture curriculum. The ultimate goal is to assess the efficiency of this specific pedagogical approach in order to contribute to the emerging demands of the industry, such as more collaborative and integrated work for a better sustainable built environment.

Keywords—component; model-making, architecture education, engineering skills

I. INTRODUCTION

The use of physical models comes from a long-time tradition in architecture education and it is a way for students to test and express the design intentions of their projects at a smaller scale, usually up to 1:10. Depending on the countries and their educational approach, physical models have also been used more or less recently in the courses that address building sciences. This is intrinsically related to the place given to engineering knowledge within an architecture program. In France, for example, due to the long-time impermeability between engineering and architecture training, it was only in the 1960s that emphasis on engineering knowledge came back [1]; while in Germany the pedagogy has existed efficiently since the late 19th century [2].

However, the pedagogical intent of the model-making in engineering courses for architecture students is initially quite different from the one required in design studios. Although both aim at testing and correcting the different stages of conceptualization, model-making in engineering course particularly focus on developing the technical side of the project, that is to try its structure, controlling its details and calculating its feasibility. The response of the structure to applied forces, “perceiving the interrelationship of material, form, and structure” [3] is observed and has its influence in the development of the project. It is also very relevant to the industry since it is even used in the conception of real projects by architects [4]. This is without doubt a minor version of the 1:1 scale model testing that is usually an intrinsic part of the curriculum of an engineering student.

Among what we will call 'the technical models', two approaches are usually acknowledged, a qualitative and a quantitative approach also recognized as the “analogue model” or “direct model” in literature [3]. The first type of structural models or qualitative models are used to explain a concept, based on the analogy between two phenomena. The second type, the quantitative or direct model, behaves like the actual structure it represents, authorizing even the prediction of stress, strain or deformation of the structure without any other calculation. The second type was particularly usual between 1930 and 1970, when numerical calculation methods were not developed enough to verify certain very audacious structures at that time, like the long span bridges in Germany by Karl Schaechterle in 1934 or the German Pavilion, Expo '67 by Frei Otto [4].

Today, the creation of models with the help of computer assisted programs and 3D simulation has drastically changed professional practices and definitively opened new doors in the architectural design process ([5], [6], etc). Arguably this 3D simulation model reduces the frontier between analogue and direct models, yet several questions still arise: does it reinforce student understanding of the analyzed structure and does it participate in creating a better global conception and/or to a better project? Our paper precisely examines the role of model-making, physical and digital, with the help of two case studies; one in France, and the other in Australia. In both cases, architectural students were asked to design a bridge where steel was set as the predominant material to use. Our research aims at assessing the contribution of model-making to improve engineering skills in architecture curriculum. The ultimate goal is to assess the efficiency of this specific pedagogical approach in order to contribute to the emerging demands of the industry, such as more collaborative and integrated work for a better sustainable built environment.

II. METHODOLOGY

In the present context of climate change and request to sustain our environments, knowledge sharing as defined by Hubers [7] is becoming more and more relevant, even more in the construction industry. In the educational sector, several experiences, learning and teaching innovations and implementations have been made in this direction. For example, some have combined architecture and engineering teachers in architecture courses to develop the engineering

aspect within the design development [2]; some have mixed architecture and engineering students for a common course [2] [8]; some have redeveloped part of the curriculum to offer integrated courses [9], etc.

In order to address the questions of skills and pedagogical efficiency, we have decided to develop a comparative study-case methodology based on the same brief for two different classes. Third year architecture students from the French National Institute of Applied Sciences in Strasbourg (INSAS) and the Australian Griffith University (GU) were challenged to design a footbridge, with their own choice of material, over a three-month period. However, in the French case, steel was favored by the teaching team because, as underlined by Frapier [1], the earliest engineering interventions that took place in France and modified the technical teaching in architecture programs are highly related to the emergence of new materials, new limits for older materials or new audacious realizations. This is for example the case with aluminum taught by Jean Prouvé at the Paris Beaux-Arts in 1961 [1]. As such, architecture programs often follow closely the evolution of technologies and lately, steel has been quite challenging as a material in the construction of bridges (Kurilpa Bridge in Brisbane- Australia- or Helix Bridge in Singapore by Cox & Rayner, Simone de Beauvoir Footbridge in Paris, etc).

The brief was set in the context of the City of Gold Coast (Australia) which proposed three real sites for investigation. Students were asked:

- To design and detail a green bridge for pedestrian and bicycle access for one of three chosen sites in the Gold Coast City area.

- To demonstrate the ability to undertake a thorough contextual analysis to propose appropriate architectural intentions about connection and integration.

- Deep strategic thinking to generate coherent architectural ideas for an appropriate and sustainable bridge.

- To present a well resolved proposal demonstrating clear design ideas, structural resolution and integration with the existing context.

More specifically, their submission required a site analysis; one base model of bridge site (1:500); conceptual diagrams/ vignettes showing ideas, inspiration, process and intent; architectural drawings; physical model of bridge either to fit to base model scale 1:500 or to convey insight on the structure (1:100, 1:50, etc.); large-scale section through the bridge showing detailed structure, form and intent (1:20).

The selected criteria to evaluate the student's potential increase of skills are the following:

1. Data on his/her scientific level prior to architectural studies
2. Grade on this project
3. Observation on his/her engagement during the design studio and particularly on the produced outcomes (types of produced models, calculations, references, and testing)

Criteria (1) and (2) are analyzed against each other to assess whether a scientific background plays a fundamental role in acquiring engineering knowledge. The limits of our survey are of several types. First, the choice of both institutions was made by genuine convenience, since both research leaders are former colleagues and now part of one of the two institutions. In that sense, there was no choice by similarities in students recruitment or percentage of engineering courses in both architecture programs. Yet, thanks to the long-term relationship between the two investigators and a common pedagogical approach (e.g. exchange of course material, equal face-to-face investment, tradition of reciprocal learning and teaching benchmarking), distance did not alter the analytical process.

The second limit concerns the criteria which we defined to assess a potential increase of engineering skills. Criteria (1) and (3) are quite plain, but (2) encompasses more than the acknowledgement of engineering skills. For example, it also relates to the qualitative relationship the design proposal offers with its local context; it also takes into consideration the aesthetics of the project as well as the potential it may offer to the community. In that sense, engineering skills represent a sub-class of this criterion. However, to regulate this, we set up the postulate that a design proposal that is not structurally working cannot achieve a good grade. We are also aware that criterion (1) presents some limits since Australian and French students do not have the same high school prerequisites in their sciences education. As such, we are not comparing their pre-university scientific level against each other. It has its flaws in the sense that one student in France might be considered of a high scientific level in Australia, and vice-versa.

Finally, the fact that the teaching team was different for each class presumably impacts the results. At INSAS, the teaching team is composed of a good representation of engineers and architects (50%), whereas at GU one third were professional engineers and the other two thirds were architects. We are aware of the different flaws these limits might produce but this paper represents the first stage of our research, which is under current refinement.

III. THE CONTEXT OF ARCHITECTURE EDUCATION

Architecture students traditionally encounter difficulty with aspects of structure that involve the calculation of forces and mathematical modeling [7]. For example, architecture students can easily integrate the concept of fibers that expand or retract within one material and identify this to the stresses, and tensile or compressive stress. But it is not the same for more complex phenomena, that are combined or internal (Figure 1). In particular, the construction of internal shear and bending moment diagrams is an especially abstract exercise for non-engineering students. Yet the insight that can be gained from the graphical representations of structural member forces makes them an invaluable aid to understand structural behavior.

Figure 1. Analogue physical models zero state, under traction loads and flexion; photo: C. Gress.

At INSAS, building sciences represent 22% of the overall architecture program, against a small 10% at GU. However, in the two involved institutions, students are expected to acquire three types of skills through model-making:

1. Qualitative skills with analogue models

With these type of models, students build a library like system in the first stage, as well as “a pool of experiences through the perception of the physical world and the accumulation of procedural knowledge and know-how” [14]. This ‘pool’ helps to build up competences and performances (“the use the person makes of that knowledge in concrete situations” [15]. As such, this stage concerns mainly the activation of memory but in an active way. It questions how to best memorize these physical phenomena. A test was used to study these aspects on architecture students. It consists in the study of one truss represented on paper and as a physical model. At first, the architecture students observe the paper version and must indicate the bars under tension, compression and which ones are the most solicited bars. Then the correct answers are given to the students before they observe and manipulate one uniform color physical model and start again to locate the different bars and efforts. Finally, they repeat the same experience with one 3D model which has colors. This experience shows (1) the skill acquisition to recognize efforts in a truss; (2) the manipulation of physical model fixes the skill better than 2D does; (3) colors especially affect the visualization of phenomena and help to improve memorization.

2. Quantitative skills

It concerns essentially direct and digital models, but analogue models are also very helpful since every original design is bound to a material and technological reality.

3. Analytic & reflexive skills while developing the design process

This approach is similar to the problem-solving strategy which is in use in aviation: it recommends the use of the physical model by opposition to verbal strategies [16].

Surprisingly, both at INSAS and GU the same pedagogical approach is used to develop these skills. For the first aspect, to emphasize certain behaviors such as beam deflection or buckling, the choice is made to experiment a phenomenon with reduced proportions of the original section of the elements. The concept had to appear clear and evident to the student,s while remaining realistic. Most of the time, this experiment is made with steel models (e.g. fine plates of cross section 18mm x 0,5 mm and 1meter length metal rulers). Usually, the depth to span ratio is approximately 1:55 compared to the typical ratio of 1:20, which shows that the observed behavior could only be qualitative. This also reveals the type of deflection under different types of loads or cross sections, or material (like plastic, wood or steel). Other aspects of the deflection, such as the influence of the connections on a structure allow to visualize the joints' rotation or the points where the curvature reverses in case of built-in structures (Figure 2).

Figure 2. Basic model of a rigid portal with a hinged base, photo: C. Gress.

All in one, this approach draws similarities with the architectural process of design where trial and error forms a large part of “learning by doing” [8]. In both institutions it has then been observed that, once the students have had experience with analogue models, they instinctively develop structural models. Emphasis on this development is proper to each architectural program in general, but both at INSAS and GU students are highly encouraged to do so (Figure 3).

Figure 3. a) Concept photograph b) Concept physical model c) Structural model d) Digital model – stress diagram ; photo: C. Gress.

Specifically at INSAS, it has been observed that the use of structural models in design studio plays a consequent role in the following points:

- to identify attributes of form which might contribute to architectural intentions
- as a means to visualize how the forces are applied on the structure, and assess their effects on the design
- to help the decision-making process regarding the size or depth of the elements of the structure; the choice of connections and support condition types, or even whether to use flexible or rigid elements

Admittedly, digital models often go hand-in-hand with either analogue or structural models because the introduction of computer analysis has simplified the process for architecture students. Digital structural models that can be 'tested' are easy to create using current software. Once the basic parameters of a structural model (joint type, reaction type, member section, load representation and placement, and overall geometrical configuration) are known, it is a straightforward process to model and test a structure using any of the new graphically oriented structural applications. Using a program such as RDM6 for example, a basic truss can be modeled in a few minutes and, with loads identified and placed, an analysis will instantly produce performance measurements in the form of member forces/stresses, reactions, and accurate deflection profiles indicating the predicted movement of the structure in an exaggerated, and thus, visually enhanced plot.

If desired, these shear and moment diagrams can be displayed for any member in the structure. Varying a single parameter (e.g. eliminating half the loads) will produce new results that can be compared to the first and so forth, thus leading to insights into the behavior of the structure and the potential for improvement. The model is interactive and the designer can test any number of assumptions about the geometry of the truss, the effect of pin versus rigid joints, the efficiency of the member sections, or the effect of alternative materials. The interactive nature in using structural analysis software in this way offers many interesting pedagogical applications. Black and Duff [12] have introduced a series of

exercises in structural behavior that is reminiscent of *reverse engineering*. In a lab class, Black provides his students with a partial analysis of a simple structure in the form of load, shear, moment and deflected shape diagrams. From this output information students are asked to work backwards to 'discover' the configuration and support conditions of the original (and unknown) structure. It is a challenging puzzle that induces students to consider the relationships between load, shear, moment, member deflection, and the types of connections or supports involved. The computer model can quickly test hypotheses in an informed trial and error process. This method has shown excellent results at INSAS [13].

IV. RESULTS

Table 1 sums up the results of this survey. First, and very interestingly, the initial scientific level of the students seems to play a role in the progress of the students. Students from INSAS, who have an overall stronger scientific background, are using more of the 'engineering tools' such as calculations, references and testing. Although the difference between the values in average seems quite small (0.5), precise scrutinization among each category gives evidence of a wider gap. This, for example, was really evident in the testing category where the difference is 1.4 between INSAS and GU students, and at a minor scale with the calculations (0.30 gap). As such, it reveals that a certain level of skills acquisition has already been achieved and thus empowers the students to the next level of acquisition. It is also visible in the model-making process where a vast majority of the INSAS students tested their project with the three forms of models (analogue, structural and digital). This was not the case with GU students.

TABLE I. RESULTS OF THE COMPARATIVE CASE-STUDY

Institutions	Average entry grade (max. 100)	Average grade for the bridge project (max. 100)	Number of produced models (up to 3 categories)	Calculations average : 0-5 (lower to best)	References average : 0-5 (lower to best)	Testing average : 0-5 (lower to best)	Average average : 0-5 (lower to best)
INSAS	77.44	71.9	2.7	2.5	2.6	3.3	2.8
GU	75.8	76.2	1.9	2.2	2.8	1.9	2.3

Secondly, although our table does not display a fine grain regarding the produced models, the study addressed their categorization and, as expected, in both cases, analogue and digital models were predominant, while structural models were usually lacking for students with lesser scientific backgrounds (GU students in general). Furthermore, even if all the GU students produced a physical model, only one tested 1:50 scale (and it was partial), whereas all the other students built a 1:500 model for the site model (Figure 4). The quality of these latter models also varied from 'conceptual' models (without any structural awareness) to structurally-oriented models. In France all the students, without exception, produced a final 1:200 model.

Figure 4. Site model, photo: K. Dupre.

Thirdly, and more surprisingly, a high level of scientific background did not guaranty the best results in terms of overall project design. This was acknowledged when comparing INSAS and GU students but also, internally, in each class. Different dynamics were observed. For INSAS students, over 64% did perform under their scientific level, whereas it concerned less than 44% for GU students. Seemingly, around 36% at INSAS increased their grades against nearly 55% at GU. At such it could be concluded that the pedagogical approach benefits mostly the average students and that new methods should be developed for the more advanced students.

However, as set in our methodology, many criterion might limit this way of thinking and, as previously demonstrated, results might be lower but engagement greater. In both places, the average grade for the bridge project was well above 70% (out of 100), thus showing evidence of the overall quality of the projects (Figure 5).

Figure 5. top: Project from an INSAS student (A. Caron-Gingras; J. Li, I. Valentin, R. Verna); bottom: Project from a GU student (M. Booth)

A closer examination of the three top students in each class also shows evidence of a strong scientific background, a high level of engagement but discrepancy did occur regarding model-making. The top GU students did not physically test their design, developing a rather conceptual 1:500 physical model. However, their digital models were highly developed, using advanced representation software such as Rhino and

Grasshopper that allowed them to come closer to the structural aspect and features of their design (Figure 6).

Figure 6. Example of the top GU student project, (Sasha Wales).

Finally, when the impact of our approach is difficult to measure in terms of the progressive percentage of the structural knowledge of the architecture students, the teaching evaluations showed, in the same manner in both France and Australia, the positive impact on the student engagement, motivation and their feeling of having improved their skills in understanding structural behavior (by more than 80% of the students at INSAS and 56% at GU).

The choice of steel as the dominant material for the design project was also non negligible in the learning process for students as they engaged in modeling, using both a wide variety of materials to simulate steel (spaghetti, small iron or timber sticks for example) and software. They additionally became aware of the limits of physical models, such as the influence of the chosen materials used to represent steel and respect mechanic analogy, the scale of the model that might affect the visualization of the wanted phenomenon and, the importance of connections that are frequently difficult to realize.

V. CONCLUSION

Our research aimed at examining the contribution of model-making for architecture students to increase their understanding of structural and material properties and the advantage of steel in this approach. Through the comparative case-study, it can be assessed that this specific pedagogical approach appears quite efficient, because it 'lifted up' the

general level of the students with less scientific backgrounds and engaged the best students with further technical developments and a deeper understanding of steel as a material.

The presented examples of the students' structural bridge models also underline that sometimes such a model can reveal more of the design intentions than a design model can, especially if the design project involves structure or structural performance as a predominant aspect (e.g. cases of the bridges where the influence of long span and structural forms is evidence).

The experience presented in this paper has also shown that the digitization process is simple and straightforward, but the next step, which is 3D modeling, was more troublesome. In order to contribute to the emerging demands of the industry, with more collaborative and integrated work for a better sustainable built environment, it seems relevant to investigate further the development of the pedagogical approach to develop these engineering skills for architecture students.

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