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Students' difficulties and remedies with the structural design for their final master project

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ABSTRACT

What difficulties do architecture students encounter in the structural design for their final master project? How do they address these difficulties? This paper presents the topic and focuses on these two research questions by examining the students' experience, using thematic analysis with a qualitative approach. We obtained the data through surveys administered to architecture students during their final master project. The results show 11 categories of students' difficulties in designing the structure. The five most frequent are integration between structure and architecture, pre-sizing, long spans, complex geometries and floor systems. To deal with their difficulties, the students employed seven strategies, which we have grouped into three components: documentary, social and experimental. We found that the final master project students participating in our study possessed and practiced the following skills: self-directed learning, constructive investigation with problem-solving skills and positive social interaction. This study can help instructors understand the difficulties faced by the students learning structural design in the context of real world, authentic projects. Our findings confirm the positive effects of social learning, analogical thinking and design alternatives for structural design education.

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KEYWORDS
Final master project; structural design education; learning difficulties; architectural engineering education; project strategies

Introduction

Final master project

The present study examines the difficulties faced by final year students doing their final master thesis at the end of a master's degree in architecture. In Spain, the final master project (FMP) consists of a comprehensive project of architecture of a professional nature where all the competences acquired from different disciplines should be applied to the project of a building at the level of full resolution, in compliance with technical and administrative regulations. Final master projects are real-world projects in the sense that they are designed to be realistic and replicate professional practice.

The architecture FMP is similar to the engineering capstone project, in that its purpose is 'to provide opportunities for students to synthesize and apply prior coursework in an environment that simulates real-world experiences through open-ended projects' (Pembridge and Paretti 2010, 8). Dinehart and Gross (2010) emphasise the integrative and realistic characteristics of the capstone project: 'the objective of Villanova University's structural capstone course is to integrate technical and non-technical issues through a challenging real world project' (p 1). For other authors capstones

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involve the use of active learning strategies for both applying existing knowledge and developing new knowledge (Stanford et al. 2013).

Structural design

The structure is one of the main components of architectural and civil engineering projects. Some authors (e.g. MacLeod 2007; Molyneaux et al. 2007; May 2009) proposed that structures learning should focus on the main tasks that will be undertaken by graduates in their professional practice: (1) designing the structure, (2) modelling the structure for its analysis, (3) calculating the structure, (4) verifying the results of the calculation, (5) interpreting the results, and, (6) improving the design based on the results obtained.

We can group the structural project tasks in two distinct categories: structural design and structural analysis (Figure 1). As it can be deduced from Figure 1, the process of designing a structure includes at least two design products: the initial design (before the analysis) and the final design (after the analysis). As structural design is an iterative process (Simonen 2014; Garavaglia, Basso, and Sgambi 2020; Solnosky et al. 2020), there are usually many intermediate designs.

Arciszewski and Lakmazaheri (2001) divided the structural design process into *conceptual* and *detailed design*. A conceptual design is 'an abstract description of a future structural system in terms of nominal attributes' (p 447). A detailed design is 'a quantitative description of the future structural system in terms of numerical attributes' (p 447). At present, most teaching efforts in architecture and engineering schools are devoted to teaching the detailed design methods and little attention is paid to conceptual design, despite its importance in real-world projects (Arciszewski and Lakmazaheri 2001). This paper deals with the teaching of conceptual design and we will use the term *structural design* to refer to conceptual design. The main tasks in conceptual structural design include defining the main structural system, floor system, lateral stability system, materials, structural pattern, pre-sizing and integration between structure and architecture.

Design problems: difficulties and remedies

Design problems have been considered one of the most difficult type of problems in the problem-solving literature (Jonassen 2000), since they are ill-structured problems. The main reasons argued for the difficulty of design problems are: (a) the problem space is too large, (b) the problem

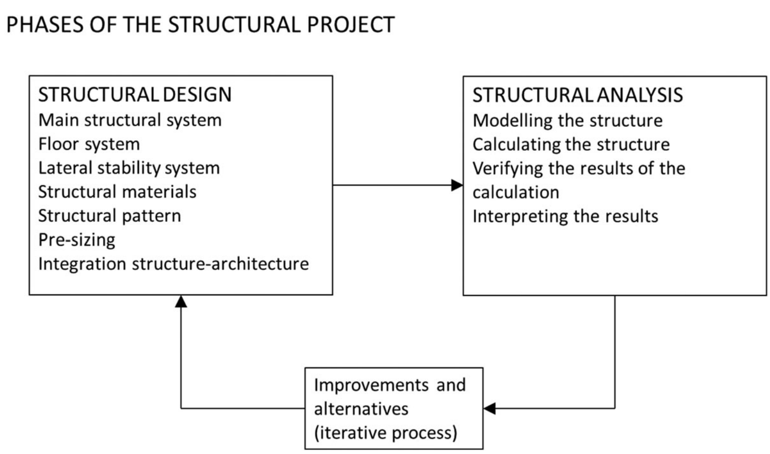

Figure 1. Phases of the structural project.

specifications are ill-defined, (c) the solution requires the integration of knowledge from multiple disciplines and (d) there is not a unique 'correct' solution (Ball et al. 1997; Dorst 2004).

Furthermore, the architecture design process is a non-linear creative and multidisciplinary activity (Sgambi 2021). Architecture students often lack the required autonomous thinking (Wu and Weng 2013) and without a proper guide from the instructors they can feel frustrated and loose motivation after several trial-and-error iterations. Also, architecture students typically have difficulties in transferring the concepts they learn in previous subjects into complex real-world projects (Herr et al. 2012; Wu, Huang, and Weng 2014).

To remedy these difficulties, Wu, Huang, and Weng (2014) succesfully applied an interactive learning model of architectural design based on the analogical thinking and social learning theories. Analogical thinking was introduced through the study of existing works or solutions developed by others. The students can take advantage of the similarities between their problems and previous architecture works, reducing the time spent in trial-and-error iterations, which results in a more efficient learning (Wu and Weng 2013). Social learning was applied through teacher-student and student-student interaction. The social learning theory postulates that learners can learn effectively by observing a model (Schunk and Usher 2012). Models with more status and credibility, such as teachers, have been proved to motivate the students (Schunk and Usher 2012). The perceived similarity between models and observers that occurs when students interact with each other also increases their motivation, since the students are inclined to believe that if the model can learn, they also can (Schunk and Usher 2012).

In the present paper, we discuss the implementation of a learning model that also includes the use of precedent cases and social learning, but while Wu, Huang, and Weng (2014) used their model with simple exercises of abstract design, we applied ours to much more complex structural design tasks in realistic architecture projects.

Structural design education

As with any other type of design, the evolution of the form of a structure is a creative act which involves the making of a whole network of interrelated decisions (MacDonald 1997), and this explains the complexity involved in structural design learning. Despite this, research in structural design education is scarce. Most studies are descriptive in nature or do not explicitly support their conclusions through data collection and analysis.

However, some authors have called for more attention to structural design in architecture education (Wetzel 2012; Herr 2013). Black and Duff (1994) pointed out the need to teach structures in the context of architectural design, and to include design procedures in the core content. Ünay and Özmen (2006, 258) asserted that 'as the main occupation of an architect is to design, then, naturally, the design studio should be at the centre of the curriculum'. And in engineering: 'design should also be included, which requires that the engineering subjects should be taught in the context of design' (May 2009, 188).

Most authors exploring structural design learning models coincided in the advantages of using social learning and/or analogical thinking strategies. Berk and Unay (2010) indicated that architecture students become more familiar with the structural part of their designs if the teaching includes the analysis of examples of built structures they admire. Aparicio and Ruiz-Teran (2007) implemented a method for teaching structural design based on the project-based learning method and teamwork and reported good results in terms of students and teachers' satisfaction. Stanford et al. (2013) described the benefits of using real-world projects and teamwork in a civil engineering capstone course. Herr et al. (2012) proposed an approach to structural design education for architecture students focused on the integration between structure and architecture and the development of 'structural common sense' using hands-on projects, teamwork, model building and the study of precedent case studies.

Although none of the existing studies about structural design education are focused on students' learning difficulties, some authors have pointed out the weaknesses or disadvantages of their teaching models. In most cases (Aparicio and Ruiz-Teran 2007; Herr et al. 2012; Stanford et al. 2013) the authors reported an increased workload for the students and teaching staff, which is a typical issue of project-based learning models (Helle, Tynjälä, and Olkinuora 2006). In fact, most research on learning difficulties has been focused on basic structural analysis concepts and procedures (Tsechelidou 2013). Common conceptual difficulties reported are: the meaning of stress and strain and the relationships between them, moment equilibrium, the effect of compatibility conditions on deformation, applying boundary conditions, the concept and function of moment and shear force, understanding load paths and the concept of determinate/indeterminate structures (May et al. 2003; Male and Baillie 2011; Saidani 2014).

In a recent contribution, Sgambi (2021) defined and tested three strategies to carry out the structural design of students' architectural projects: top-down, bottom-up, and collaborative. The top-down approach is the one most often used in academic multidisciplinary design studios. In the top-down strategy the technical disciplines (e.g. structures) intervene only when the architectural design has been completed to a great extent. One drawback of this method is that the requirements of structural design can lead to the failure of the original architectural concept (Sgambi 2021). The bottom-up approach is one in which the architectural design develops from a previous structural concept, often based on a regular geometric grid. One major disadvantage of this strategy is the loss of design freedom. Finally, in the collaborative approach a number of design ideas are examined in depth at the same time, following a multidisciplinary and brainstorming approach, until the most appropriate solution emerges. Based on the analysis of the students' design process, the author concluded that the collaborative approach reduced the learning cycle.

The present study

The aim of the present study was to investigate the implementation of a method for learning structural design based on project work, case studies and interaction with the teacher and peers. Our research is specifically focused on the difficulties faced by the students and the remedies they used to overcome them.

The research questions guiding the study are:

(1) What difficulties do architecture students encounter in the structural design for their final master project?
(2) What strategies do they use to address these difficulties?

To answer these questions, we asked the protagonists of learning, the students, through open-ended surveys. This study can help instructors to understand the difficulties faced by the students and provide remedies, in order to improve the processes that they use when they design the building structure for their projects.

Method

Research design

The study follows a qualitative approach. As the course is delivered with a student-centred approach, we applied interpretative research methods, based on the students' perspective. We collected data from FMP architecture students through open-ended surveys. We used thematic analysis to identify categories and themes, following an inductive approach, which means that the codes and themes derived from the content of the data and were not influenced by a priori hypotheses brought by the researchers (Braun and Clarke 2006). The thematic analysis was experiential in its orientation, as we give voice to the participants to collect their experiences and meanings. Due to the scarcity of previous research, the present study is exploratory in scope. Thus, we are interested in understanding, not in testing hypotheses. For that reason, a qualitative approach is appropriate in the present case.

Context

The architecture curriculum in the University of Seville (Spain) has a five-year degree and a one-year master's degree, which grants the professional capacity. In the five-year degree there are three structure subjects of six European credits each. In this university each credit consists of 10 contact hours and 15 non-contact hours. In these subjects the students learn structural design and analysis. The contents include fundamental structural concepts, steel structures and reinforced concrete structures. There are also seven multidisciplinary subjects named 'architecture workshop', also of six credits each, in which the students undertake the structural design of architectural projects. Each semester workshop is focused on a particular architectural theme (e.g. house, residential building, infrastructure, etc …).

The master's degree has 60 credits distributed in 30 credits in the final master project (FMP) and another 30 in four complementary courses: Design Studio, Structures and Foundations, Urban Planning, and Building Technology. The FMP is a real-world architectural project that requires activating prior knowledge, learning new practice knowledge, and integrating and applying it. The Structures and Foundations course is focused on the structural design of the students' final master project. The course has a student-centred approach, with a large proportion of student work in the classroom, both individual and teamwork, with tutor guidance. There are few lecture presentations. There are also critical sessions, in which students publicly present the state of their work and receive feedback from tutors and students. Finally, there is a public presentation and defence of the project before a panel composed of the eight course tutors, one per discipline, and an external architect of renowned prestige. The FMP is an individual work, but the course is delivered to provide the students with opportunities to interact with their classmates. The students started working on their FMP at the beginning of the first semester, but the Structures and Foundations course began in the second semester, which allowed the students to develop their structural design once the basic architectural project was defined (top-down approach). The teaching staff fostered the use of alternative solutions in the first stages of the design process (collaborative approach), so that at least one design alternative had to be drafted by all the students before embarking on the final solution. The bottom-up approach was also applied by some students, who based the architectural designs of their buildings on regular structural grids to ensure a smooth, unproblematic integration between structure and architecture.

Participants

Four students' groups of the architecture master's degree participated in the experiment. Each group had 32 students (128 students in total). The mean age of the students was 24.5 years. The gender proportion was 55% men and 45% women. The initial survey was answered by 117 students (91% of the population), and the final survey by 47 students (37% of the population).

Instrument

We passed out two surveys with two questions.

Survey 1 (initial survey) took place in February, right at the beginning of the Structures and Foundations course, with the FMP already started. Question 1A: What difficulties do you have, or will you have, in designing the structure of your project? Question 1B: How do you plan to address these difficulties?

Survey 2 (final survey) was carried out in June, after finishing the Structures and Foundation course and the FMP. Question 2A: What difficulties did you have in designing the structure of your project? Question 2B: How did you address these difficulties?

Data analysis

We conducted the thematic analysis on two levels. At the first level we detected emerging categories through a reflective reading of the responses, coded the data and attributed meanings to the categories. Codes provide a label for the categories, which identify features of the data that can be relevant to the research questions (Braun and Clarke 2006). The data were independently coded by two members of the research team.

At the second level we grouped categories into families or themes, counted frequencies, examined relationships between categories and generated hypotheses and explanations. As is common in thematic analysis (Joffe 2012) we have combined analysis of the frequency of codes with analysis of their meanings. The analysis of frequencies had the purpose of examining the prevalence of themes and revealing possible trends in the data, rather than testing hypotheses.

The qualitative data were analysed with the help of Atlas.ti software. The survey was originally conducted in Spanish and the students' responses were translated into English by the authors.

Validity and reliability

Interrater reliability was assessed using the Kappa coefficient method (Cohen 1960). Two researchers (the first and third authors) carried out the data analysis independently, identified categories, agreed a category system, coded and obtained the frequency of each category of responses. The Kappa assessment allowed the mitigation of interpretative bias (Walther, Sochacka, and Kellam 2013). Table 1 presents the results of the Kappa analysis, showing a very good agreement (Kappa > .80) between the two raters (McHugh 2012). The resulting category system was then reviewed by the second author, who carefully read the students' responses but did not take part in the data gathering process. The category system was refined until agreement was reached among the three researchers.

In qualitative research, validation is concerned with 'whether the interpretations appropriately reflect the reality observed' (Walther, Sochacka, and Kellam 2013, 639). Walther, Sochacka, and Kellam (2013) identified a number of strategies in the research process that can contribute to overall validation. Some of them are relevant to the present study. First, the fact that the experiment was conducted in a natural setting allowed the data to include multiple perspectives, and thus contributed to theoretical validation. Second, the strategies used for cross-checking the coding categories increased procedural validation. Third, pragmatic validation is reinforced when 'the findings are re-contextualized into the practice investigated' (Walther, Sochacka, and Kellam 2013, 648). In this case, the main knowledge gained from the study has been applied in practice to improve the course the following year, with positive results (see the recommendations section).

Table 1. Interrater reliability.

Moment	Question	Kappa coefficient
Initial	1A-DIFFICULTIES What difficulties do you have, or will you have, in designing the structure of your project?	0.977
Initial	1B-SOLUTIONS How do you plan to address these difficulties?	0.865
Final	2A-DIFFICULTIES What difficulties have you had in designing the structure of your project?	0.918
Final	2B-SOLUTIONS How have you addressed these difficulties?	0.859

Findings and discussion

Difficulties experienced by the students in the structural design

Table 2 lists the main difficulties found by the students in the structural design of their buildings, derived from their answers to questions 1A and 2A. Categories with frequencies lower than 5% in the initial and final survey were excluded from the analysis.

Between 30 and 35% of the students found it difficult to integrate the structure with the architecture. This is a broad category, which encompasses a wide range of difficulties, mainly related to the interaction of structural and architectural requirements that often conflict (MacDonald 1997): floor plan requirements (e.g. open-plan designs), the continuity of supports (columns, walls) among different building floors, the height of beams and floor slabs, the interaction between structural elements and exterior wall openings. One student, for example, commented: 'the limitations imposed by the context of the project (the Roman thermal baths of Itálica) forced the use of a light and demountable structural system. So, finding a system with minimal sections and an unobtrusive appearance has been the most complex task'. Another indicated: 'the columns must be located in proper places both on the basement floor (parking) and on the ground floor (common areas) and on the upper floors (housing)'.

The students faced different problems for the integration of structure and architecture depending on the particular strategy used in the structural design process, according to Sgambi's classification (Sgambi 2021). Some of the students using a top-down approach reported that designing the building without the structure led to unexpected changes in the architectural space, which partially or wholly ruined the original idea. For example, one student commented: 'the main difficulty is one serious shortcoming on my part, designing without thinking of the structure, I didn't think that those open-plan spaces that I imagined had a cost in terms of deep beams, columns in unexpected locations … '. On the other hand, students following a bottom-down approach found difficulties in matching the architectural design with a fixed structural grid. For example: 'in my case, I thought of a 6 × 6 grid for space design that could later function as a structural pattern, but as I advanced in the project this idea slowly lost ground'. The difficulties associated with each design strategy are aligned with those described by Sgambi (2021).

Table 2. Students' difficulties in designing their structures: categories, meanings and frequencies.

Categories	Meanings	Frequencies in the initial survey	Frequencies in the final survey
INTEGRATION OF STRUCTURE AND ARCHITECTURE	Integration of structure and architecture: in the formal, spatial and geometric configuration of the building; the structure as organizer of the spaces	32.5%	31.9%
LONG SPANS	Long spans structures, long cantilevers, open floor spaces	30.8%	27.7%
STRUCTURAL PATTERN	Making a structural pattern; situation of structural elements; singular point solution	17.9%	12.8%
PRE-SIZING	Making pre-sizing; pre-sizing of trusses, columns, long spans structures …	13.7%	31.9%
COMPLEX GEOMETRIES	Non-orthogonal grids, inclined lines, irregular forms, organic forms, building on slopes …	12.8%	17.0%
STRUCTURAL MATERIAL	Choice of structural material; difficulties of material (fire, corrosion…)	9.4%	14.9%
BIG STRUCTURAL ELEMENTS	Big structural elements (beams, columns, floors and roofs); interference with architectural spaces	9.4%	8.5%
LATERAL STABILITY SYSTEM	Choice of lateral stability system (horizontal loads); design and situation of elements	6.8%	10.6%
MAIN STRUCTURAL SYSTEM	Choice of main structural system	6.0%	12.8%
JOINTS	Choice of joint types; design of joints	6.0%	2.1%
FLOOR SYSTEM	Choice of floor and roof slab types; design of floors and roofs	1.7%	17.0%

Long spans presented a major difficulty for 30% of the students (see, for example, Figure 4). Long spans (10 m. or greater) constituted a challenge for the students due to three reasons: (a) long spans require using special and non-standard systems, in which architecture students are insufficiently trained (b), they require large-section members and take a lot of space, and thus interfere with the architectural space and (c) designing and drawing long span systems is more complex than standard span ones (e.g. they may involve stability issues). One illustrative comment is: 'I'm designing a building with large cantilevers and choosing a structural system was difficult since a steel truss would interfere with the spatial functioning of the building'. Another student indicated: 'the main problem will be working with a long span structure with bidirectional triangulated trusses, due to its complexity and also because I have never worked with something similar'.

The structural pattern was also one of the most frequently mentioned difficulties. A structural pattern is defined as 'the two-dimensional layout of supports and spans, as well as three-dimensional arrangements having formal and spatial implications for an architectural design' (Ching, Onouye, and Zuberbuhler 2013, 40). Therefore, the structural pattern is perhaps the most relevant component of structural design and constitutes the basis for the integration of structure and architecture. In this category, the difficulties were often associated with projects in which variations in geometry and function between different areas of the building required the use of multiple structural patterns and spans. For example: 'the geometry of the structure, including the proper placement of the main structural elements (columns, beams, frames …), is difficult to define. The geometry of the library and common areas presents variations with respect to the rest of the project (housing, workshop or administrative area), thus the spans vary and this has to be solved'.

Some students found difficulties in the pre-size process. Others had problems with the pre-sizing of specific structural members. One major cause of difficulties in this category was the activation of prior knowledge on pre-sizing methods. For example: 'I guess that the greatest problem has been to remember the methods for pre-size calculation'. Transfer of knowledge from previous subjects into real-world design problems is a known difficulty for architecture students, as reported by previous authors (e.g. Wu, Huang, and Weng 2014).

Regarding the floor system, the most frequent difficulty was the choice of the type of slab and, to a lesser extent, the design of the selected slab. It is worthy to note that many of the students signalling this difficulty in the final survey were dealing with long span systems, which they found unfamiliar. For example, one student explained: 'the most complicated task has been the choice of floor slab type for the large spans that I have in the project, and how to carry out its dimensioning and checking, since we have not dealt with this type of slabs previously in the degree'.

Other less relevant difficulties were complex geometries (see Figure 2 for an example), big structural elements (that interfere with architectural spaces), the choice of structural materials, the lateral stability system (e.g. Figure 3) and the choice of the main structural system. It is noteworthy that all components of the structural design (Figure 1) presented some kind of difficulty.

Figures 2–4 show structural design examples by some of the students participating in the experience. The specific difficulties associated with each example are indicated.

Comparison of difficulties in initial and final surveys

Figure 5 is a bar chart showing the frequency of the difficulties reported by the students in the initial and final surveys (items 1A and 2A). It is noteworthy that the frequency of most categories in the initial survey is similar to that of the final survey, which means that the students were able to detect in advance which structural aspects were going to present significant difficulties. However, there are two categories where the frequency increased considerably: pre-sizing (from 14% to 32%) and floor system (from 2% to 17%). This means that the students initially underestimated the difficulties encountered in these two categories. In the pre-sizing case, one cause of the difficulties experienced was that the students were not able to transfer the knowledge for pre-size calculations to their projects. Thus, their inability to predict this difficulty in advance could be

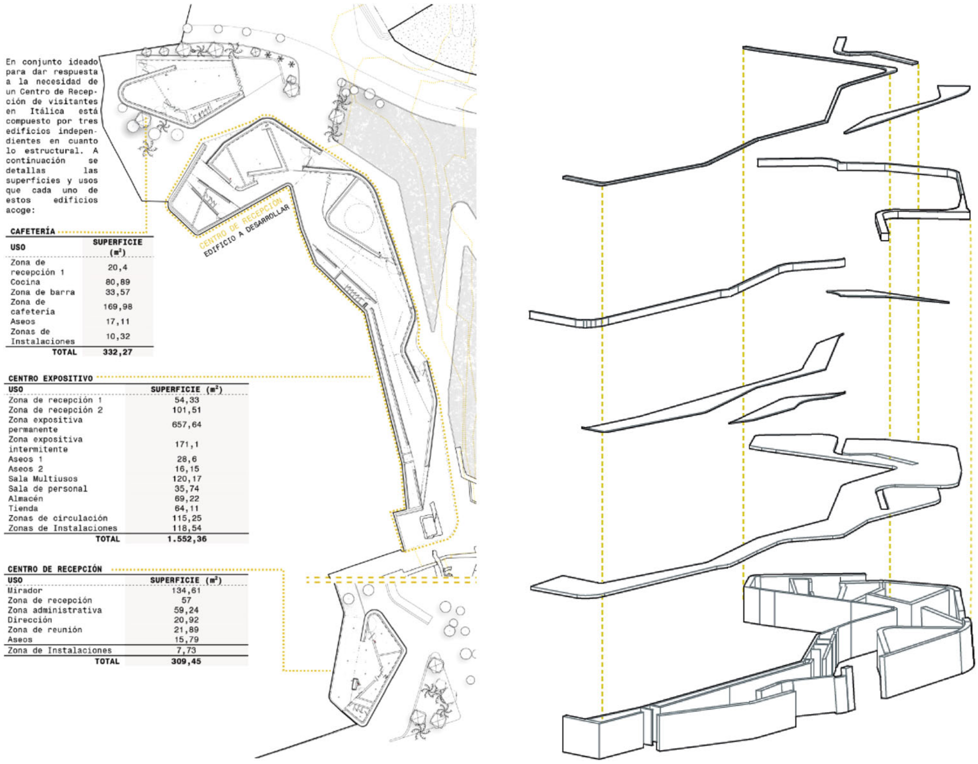

Figure 2. Structural design by the student María de la Luz Frías. Difficulties addressed during the process: integration of structure and architecture, complex geometries, structural pattern.

explained by their confidence in having acquired the required knowledge in previous subjects. In the floor system category, the difficulties were associated in many cases with large spans. It is possible that the students were not able to predict the impact of using large spans in terms of the additional complexity of the floor slab system.

Finally, in the joints category, the students seemed to overestimate the difficulties. This is maybe due to the fact that the students are usually not required to do complicated joint design calculations in the context of an FMP.

To correct the possible bias introduced by the decrease in response rate between the initial and final surveys, we have plotted an additional bar chart including only the students who responded to both surveys (Figure 6). Comparing Figures 5 and 6 we can see that, in most categories, the evolution of frequencies from the initial to the final survey is similar. There are two exceptions: the long spans category showed a more substantial decrease between the initial and final surveys in Figure 6, and the complex geometries category showed a more substantial increase in Figure 6. Nevertheless, the tendency in all categories is similar, and the differences in the initial survey if we consider only the students that responded also to the final survey are not qualitatively important (from 30.8 to 38.1% in long spans and from 12.8 to 7.1% in complex geometries).

Students' remedies to their difficulties

Table 3 shows the remedies used by the students to address the difficulties, according to their answers to questions 1B and 2B. As we did with the difficulties, categories with initial and final frequencies below 5% were discarded in the analysis.

The remedies used by that the students to address difficulties were of three types:

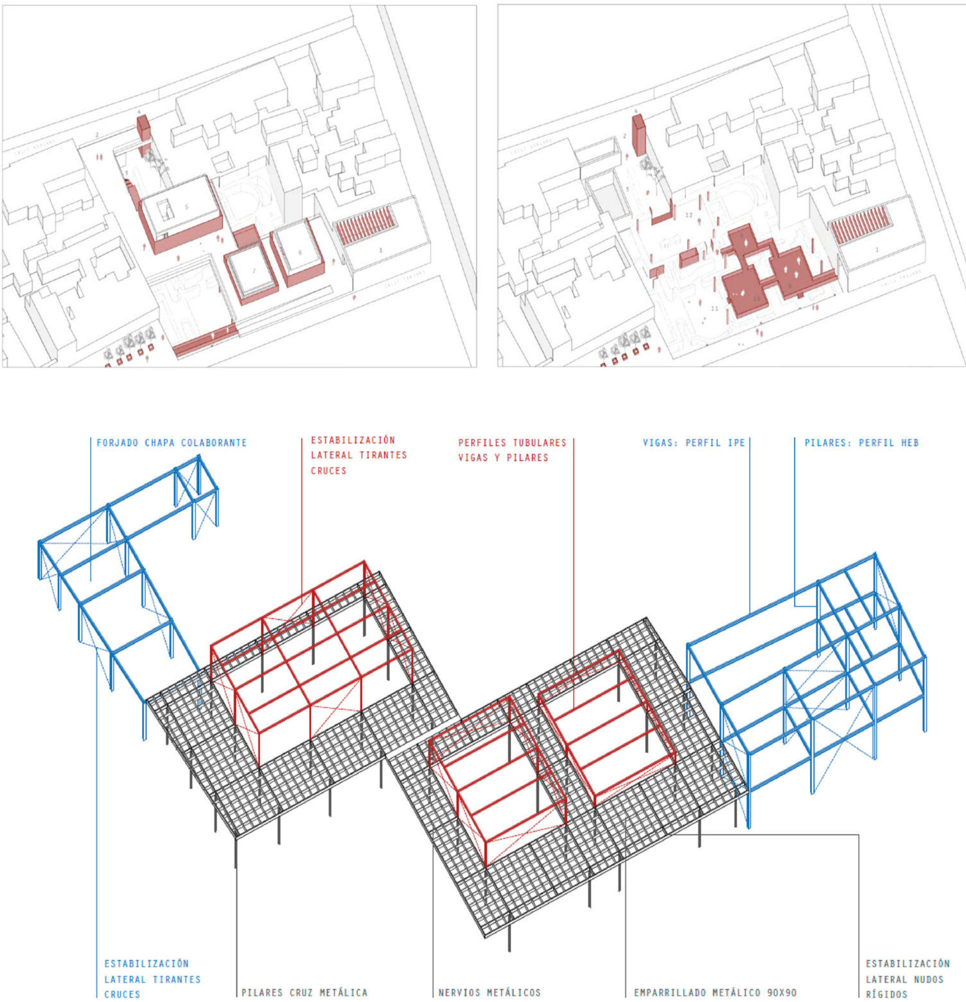

Figure 3. Structural design by the student Cristina Vicente. Difficulties addressed during the process: integration of structure and architecture, main structural system, lateral stability system, floor system, structural pattern, pre-sizing.

Documentary component

Nearly 50% of the students commented on the use of **sources of information**: books and other documents, searched for by the student (library, internet) or provided by the teacher. When referring to sources of information, the students used the words research, search, consult, analyse and study: 'searching information in reliable sources', 'looking in library books', 'looking for information on the Internet'. Many students mentioned that they referred to their notes and material from previous subjects, which is a way of activating previous knowledge.

Around 36% indicated that they used **case studies**, which involves studying architectural projects and works with some similar characteristics to their projects. The students made frequent use of the word 'similar' when referring to other cases that can help them: 'I'm thinking of resorting to researching other projects that may have similar situations to mine in order to clarify doubts'. Many students investigated how similar problems have been addressed in the past by experienced architects: 'by looking for similar cases that solved the same problems found'. In this sense, another student indicated: 'the search for precedents that have similar problems proved to be fundamental for learning how to address such difficulties since we never stop learning from those who have more experience'.

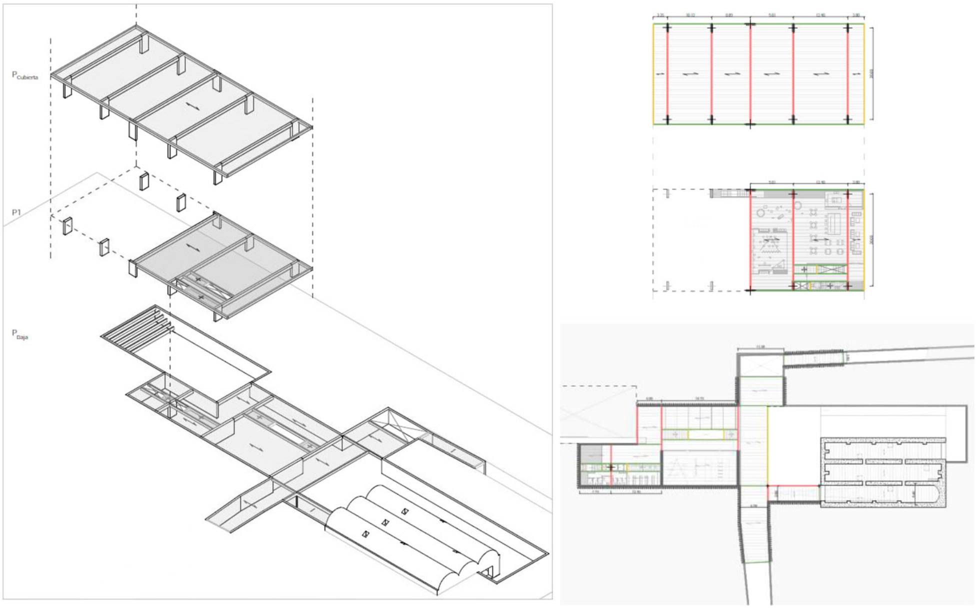

Figure 4. Structural design by student Marta Berral. Difficulties addressed during the process: integration of structure and architecture, main structural system, long spans, complex geometries, floor system, structural pattern, pre-sizing.

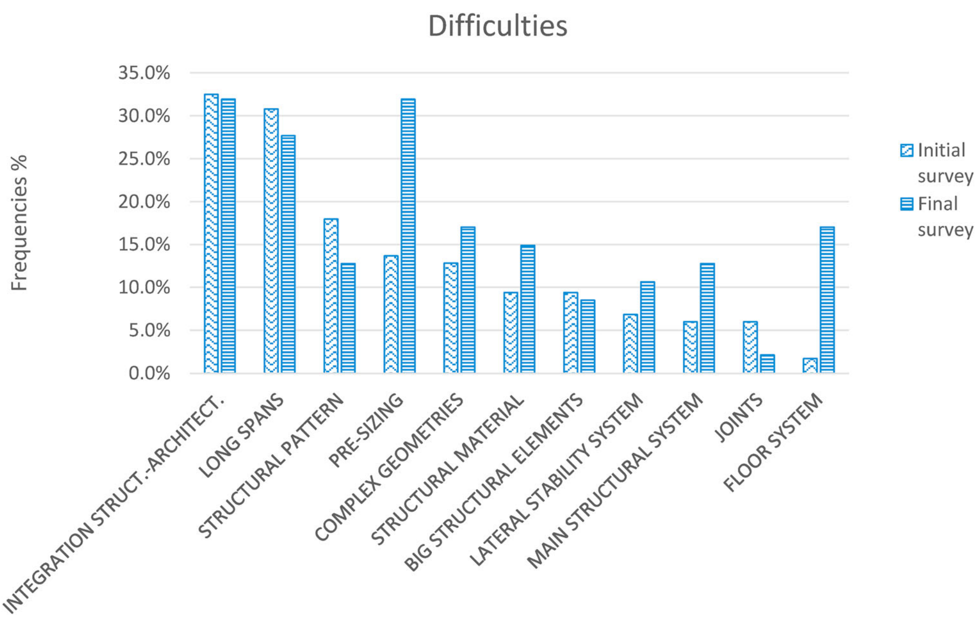

Figure 5. Difficulties detected by the students in their structural designs: comparison between answers to the initial and final surveys including all the students. N (initial) = 117; N (final) = 47.

The didactic use of existing solutions developed by others is the basis of the analogical thinking theory, which was previously applied with good results by Wu, Huang, and Weng (2014) to architecture design problems. According to Wu, Huang, and Weng (2014), analogical learning can help the students to develop principles and build their design concepts.

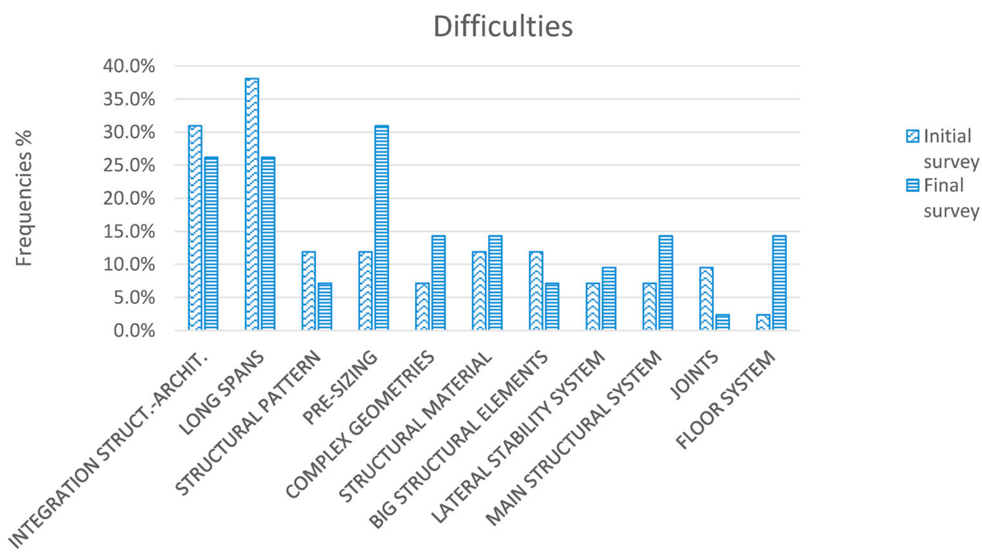

Figure 6. Difficulties detected by the students in their structural designs: comparison between answers to the initial and final surveys including only the students who responded to both surveys. N (initial) = N (final) = 42.

Table 3. Remedies used by students for their difficulties: components, categories, meanings and frequencies.

Components	Categories	Meanings	Frequencies in the initial survey	Frequencies in the final survey	
Documentary component	INFORMATION SOURCES	Activating previous knowledge: documentation of previous subjects. New knowledge: research in books and other documents (library, internet, provided by the teacher …)	39.3%	44.7%	
	CASE STUDIES	Projects, works, examples, real buildings, capstone projects	35.9%	34.0%	
	Social component	TEACHERS	With the help of the teacher (in class, in tutorials, by email): raising and resolving doubts, revision of the work, guidance, advice, indications, etc.	48.7%	66.0%
CLASSMATES		With the help of colleagues: raising and resolving doubts, revision of work, consultation and comparison of colleagues' work, debates, discussion, joint work	6.8%	36.2%	
Experimental component	VARIATIONS	Working with different solutions, tests, iterations, modifications, changes, options, provisions	17.9%	27.7%	
	INTEGRATION STRUC-ARCHIT	Working coherently with the architectural proposal, maintaining the original idea, integrating the structure and architectural project	14.5%	19.1%	
	CONTINUOUS WORK	With dedication, with constant work, with effort, with time	12.0%	14.9%	

Social component

A major part of the students (66%) stated that they had turned to the **teachers** to address difficulties. The students explained that the teacher 'solved' their doubts: 'the tutorials have also been a great help, where I've been able to raise all the doubts I had', 'other problems arose from misconceptions that were identified in the tutorials, thanks to which all the doubts were clarified'. The teacher also reviewed the student's work: 'through corrections with the teacher'. At other times, the teacher guided the student by providing sources of information: 'I've used the bibliography recommended by the teacher', 'I've mainly worked by consulting my own references or those provided by the teacher'. These comments reveal that the teacher has played that role of facilitator, rather than simply transmitting knowledge. In project work, Kokotsaki, Menzies, and Wiggins (2016) stressed the importance of the teacher's ability to effectively scaffold, motivate, support and guide students in their learning.

Another portion of the students (36%) indicated that they had turned to their **classmates** for help. Not only asking questions, but also debating and interacting with their peers: 'comparing and discussing the structure with other classmates', 'talking with classmates to better understand certain concepts'. These quotes suggest that active discussion is taking place, which increases the ability to test ideas, synthesise knowledge and achieve deeper understanding (Kizkapan and Bektas 2017). This cooperation among peers is very striking and interesting, considering that the FMP is an individual work.

The students' comments about remedies in the social component confirm the benefits of applying social learning strategies to architectural design problems (Wu, Huang, and Weng 2014). In particular, the type of student-student interaction described in the previous paragraph coincide with claims by Wu, Huang, and Weng (2014), who asserted that the students 'can learn from each other through mutual observation and mutual critiques' (2). In explanations of the theory of social constructivism, Vygotsky (1978) argued that language is a key tool for promoting thought and constructing reasoning, thus discussion is an important and beneficial strategy in the learning process.

The comments in this category also reveal that the students worked with autonomy and carried out constructive research. For example: 'during the first two weeks, my first reaction was to go to the teacher to learn how to address the difficulties. Afterwards, I decided to look for things by myself. When I didn't know or I didn't find a convincing solution I asked a classmate with the same structural system as me, and if that person was also in doubt or had a different case than me, I consulted the teacher'. Some authors agree that one major benefit of project work is that the students organize and control the process (Helle, Tynjälä, and Olkinuora 2006; Kolmos 2009) in a self-directed learning environment (Chen, Kolmos, and Du 2021).

Finally, the experience narrated by the students in terms of cooperation and active discussion fits well with the characteristics of a *community of practice* (Wenger-Trayner and Wenger-Trayner 2015), which is based upon the principle that learning is a social process. According to Wenger-Trayner and Wenger-Trayner there are three crucial principles that define a community of practice: (1) people share a domain of interest, (2) members engage in joint activities and discussions, help each other, and share information, and it is through interaction that they constitute a community and (3) they develop a shared repertoire of resources.

Experimental component

Nearly 30% of the students indicated that they have used **variations** to improve the structural design: alternatives, tests, iterations, etc.: 'it'll be necessary to investigate other options in case my first choice does not quite fit the geometry of the building'. Another student emphasised the continuous work on variations: 'constantly making changes to the original draft, as well as adaptations and modifications of certain parts'. Some authors have stressed the importance of variations in structural design. Garavaglia, Basso, and Sgambi (2020), for example, concluded that 'the development of the design always requires continuous tests and subsequent changes just as the structural choices require continuous checks and modifications (p 474)'. Harmer and Stokes (2014) claimed that a project offers the opportunity for students to learn by revision. The effective use of variations is an important skill in problem-solving: 'keeping options open, seeing the situation from many different perspectives and points-of-view' (Woods et al. 1997, 76). Wurdinger (2018) said that acquiring problem-solving skills requires students to undergo multiple trial and error episodes in which failure is part of the process. The comments on the use of various design alternatives suggest that some students are using strategies falling into the collaborative approach proposed by Sgambi (2021).

Another 19% stated that they had focused on the **integration between structure and architecture** to improve the structural design of their projects. The word 'coherence' is frequently used: 'proposing solutions that are coherent with the idea of the project'. Another student indicated 'trying at all times to be coherent with the idea, looking for alternatives in constructive and structural models that fit the proposal and its needs'. The relevance of the integration between structure and architecture stresses the importance of learning in a situated learning environment. Learning is most effective when it is situated in an authentic, real-world context. When students acquire information through experience in a meaningful context (Blumenfeld et al. 1991), they can form connections between the new information and their prior knowledge to develop a deeper conceptual understanding.

Finally, 15% of students indicated that **continuous work** (understood as constant work, dedication, effort, time investment) has helped them to address difficulties. One student, for example, described: 'working little by little every day until I got the best result'. Another student pointed to a self-directed learning approach: 'the most effective way has been to try to solve it on my own'. These quotes emphasise active construction, according to the constructivist theory. John Dewey (1938) established the basis of this theory around the idea of 'learning by doing'. Students activate relevant prior knowledge and build new knowledge through their experiences and interactions. The development of deep understanding is a continuous process that requires students to construct and reconstruct their knowledge.

Use of combined strategies

Many students that used variations in the project explained that the integration between structure and architecture was the main factor guiding their iterations. For example, one student commented: 'the structural design was, in this case, capable of making the project idea a reality, but also of ruining it. That's why I came up with numerous possibilities, which gave rise to very different architectures'. And another: 'I plan to address the difficulties through an iterative process between the architectural project and the structural project, integrating solutions that improve all aspects of the design'. And a third: 'I carried out a study of which structural systems would satisfy the constraints associated with the project and, after analysing the different systems … I understood which one was the most appropriate for my project'. These quotes stress the relevance of situated learning and project realism. For Helle, Tynjälä, and Olkinuora (2006) 'work-based projects can be considered learning environments in which students can participate in authentic practices and practice skills needed in real life projects' (p 293).

In fact, most students combined strategies from various types (social, documentary, experimental). One student, for example, described: 'with the help of tutorials, reference books and articles and the work done in class, relying on the experience of other classmates and public corrections in the classroom'. And another: 'collaborating with the teaching staff, consulting with classmates and through bibliography'.

Many students prioritised autonomy in their work and only turned to their classmates or the teacher when needed: 'most of the time I always try to address it on my own, either through the internet, books, regulations or subjects from other courses, but if I wasn't able to solve the complication, I would turn to my classmates with similar cases or to the teacher'.

This use of various strategies, prioritising autonomy, emphasised the students' abilities for self-directed learning and learning by doing. In this sense, Akinci-Ceylan et al. (2022) showed that there is not a standard method for solving an ill-structured problem, and that problem solving processes are variable and usually require more than one strategy.

Comparison of remedies in the initial and final surveys

Figure 7 is a bar chart showing the remedies used by the students to address the difficulties in the initial and final surveys. As in the case of the difficulties, we have also plotted (Figure 8) another chart using only the responses of the students who were present in both surveys. Comparing both charts we can conclude that there are no substantial differences, except maybe in the interaction between structure and architecture category, which shows a much more substantial increase in Figure 8 (using only students responding twice).

In Figure 7 we can observe that the students anticipated from the beginning the importance of the remedies in the documentary component (case studies and information sources), while not so of those in the social component (teacher and classmates help). The teacher help increased by 15 points from the initial to the final survey. Students trusted the teacher's guidance and were more aware of this after completing the process. More significant is the 30-point increase in peer help (from 6% to 36%), showing that the development of the course encouraged cooperation to a large extent. It seems that the students were a priori more familiar with the value of teacher help but underestimated the benefits of interacting with their peers. Schunk and Usher (2012) showed that the similarity between models and learners increased motivation and learning. Finally, in the experimental component, the use of variations and the integration between structure and architecture were mentioned more frequently in the final survey. This trend is more marked in Figure 8, using only the students responding to both surveys. One possible explanation for the increase in frequencies is that the

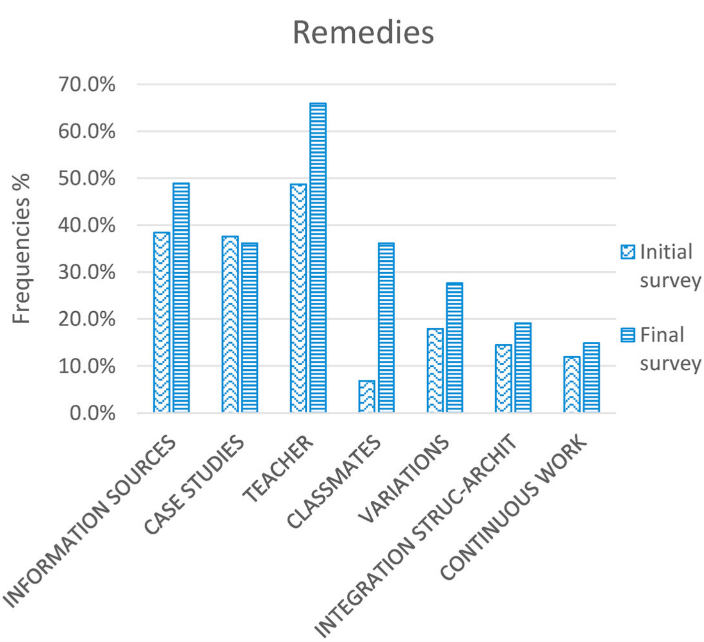

Figure 7. Remedies used by the students to address difficulties: comparison between responses to the initial and final surveys including all the students. N (initial) = 117; N (final) = 47.

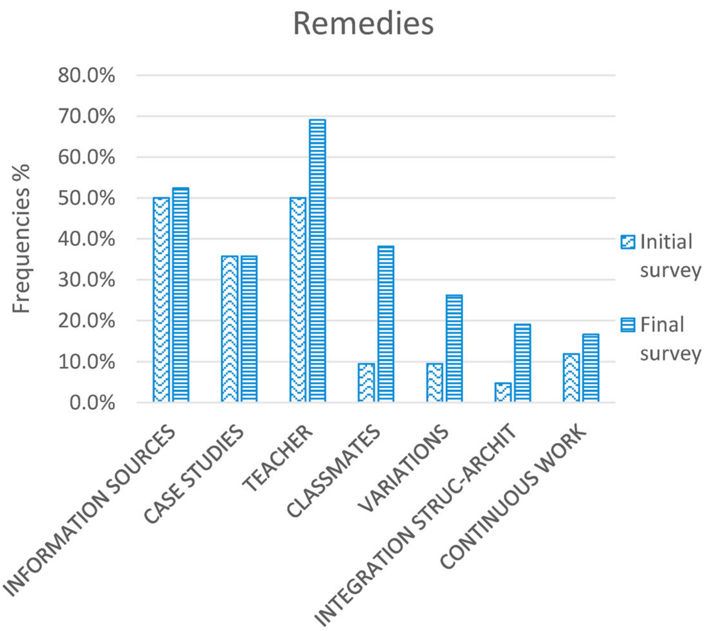

Figure 8. Remedies used by the students to address difficulties: comparison between responses to the initial and final surveys including only the students who responded to both surveys. N (initial) = N (final) = 42.

students became aware of the strategies that they can employ as they advanced in the projects, since reflection is a process based on personal experience (Grossman 2009).

The increase in strategies used in the development of the work, together with the simultaneous or sequential use of several strategies, and the meanings of the students' quotations showed that the participating students possessed and practiced the following skills:

(1) Self-directed learning. The students reported learning and working with autonomy. According to Sumarni (2015), project work facilitates the development of students' skills for design, problem-solving, decision making and autonomous work.
(2) Constructive investigation with problem-solving skills. An investigation is a goal-directed process that involves inquiry, knowledge building, and resolution (Thomas 2000). Students participate in authentic processes of problem solving, that are central to expert performance in the discipline (Krajcik and Blumenfeld 2006).
(3) Positive social interaction. The participants in the experience reported using teacher-student and student-student interaction. Both strategies proved useful for structural design learning, in coherence with the principles of the social learning theory. Social interaction has been shown to lead to a deeper understanding of concepts and principles through sharing, using and debating ideas with others (Blumenfeld et al. 1996).

Implications and recommendations

The findings of the present study have several implications for engineering and architecture educators teaching structural design with real-world projects, mainly related to the benefits of using analogical thinking, social learning and design alternatives.

Some recommendations follow from the findings of this study. First, peer learning has shown to be an important source of learning in the context of our experience. Therefore, cooperation among students should be promoted, even if the final product is an individual project. Second, the instructor should not only act as a provider of knowledge but also as a facilitator. Thus, interaction between instructor and students should be fostered. Third, we found evidence that case studies can be a valuable tool for addressing difficulties. The study of precedents with similarities to the students' projects should be included as a course activity. One strategy combining both benefits, which has been successfully used by the authors in the subsequent year, consists of involving the students in the analysis of case studies in teams of three or four, before they individually undertake their own projects. Fourth, experimenting with variations proved to be useful for learning. Project alternatives should be explored before arriving at the final solution, with an emphasis on the iterative nature of structural design. Finally, it is highly recommended to elaborate learning units for the aspects of structural design that have caused the main difficulties to the students: large spans, integration between structure and architecture, structural patterns, pre-sizing and dealing with complex geometries.

Limitations and future work

Some limitations of the present study should be acknowledged. First, being a qualitative study with a limited sample, our findings are valid for the particular context of the experiment, and transferring this to other contexts is not straightforward. Second, we based our findings on the students' perception, gathered through open-ended surveys. That may leave undetected some difficulties of which the students may not be aware. In this respect, further research is being prepared in which we will also examine the students' difficulties by systematically revising their projects to analyse common errors. Also, a more detailed account of the students' experience through semi-structured interviews and/or focus groups would allow exploring in more depth the complexities of the process of structural design. Finally, future research with a more quantitative approach should be undertaken to confirm the findings of this study, in terms of students' difficulties and their remedies.

Conclusions

We have examined the difficulties that FMP students had to face when designing the structure of their projects. According to the surveys, these difficulties were (in order of frequency): integration of structure and architecture, pre-sizing, long spans, complex geometries, floor system, structural material, structural pattern, main structural system, lateral stability system, big structural elements, integration of different floors, joints. It is noteworthy that all the components of structural design (Figure 1) present some kind of difficulty.

The results showed that the students used seven strategies to address their difficulties, which we have grouped into three category systems: (1) documentary component, via information sources and case studies, (2) social component, via interactions with teachers and classmates, and (3) experimental component, via variations, integration of structure and architecture and continuous work. Most students used at least two components. The comparison between the initial and final surveys indicated that the frequencies increased considerably in the social and experimental components. The largest increase is 30 points in the interaction with peers, perhaps showing that the course development encourages cooperation to a large extent, despite the fact that the FMP is an individual work.

Finally, the increase in strategies used in the development of the work, together with the simultaneous or sequential use of several strategies, and the meanings of the students' quotations showed that the FMP project students that participated in our study possessed and practiced the following skills: (1) self-directed learning, (2) constructive investigation with problem-solving skills and (3) positive social interaction.

Our findings can help instructors to better understand the difficulties faced by the students when designing the structure of their FMP. In terms of remedies, this study confirms and extends the findings of previous research regarding the benefits of social learning, analogical thinking and design alternatives for teaching design problems, and verifies their value in the specific field of structural design education.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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