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► To cite this version:

Alejandro Gonzalez-Martin, Gisela Hernandez-Gomes. Analysing mathematical and didactic praxeologies in an engineering course: the case of Strength of Materials.. INDRUM 2020, Université de Carthage, Université de Montpellier, Sep 2020, Cyberspace (virtually from Bizerte), Tunisia. hal-03113893

HAL Id: hal-03113893

<https://hal.science/hal-03113893>

Submitted on 18 Jan 2021

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Analysing mathematical and didactic praxeologies in an engineering course: the case of Strength of Materials

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This paper provides an overview of the various stages of our research, which seeks to better understand the use of calculus in university engineering courses. We first illustrate the use of integrals in a classic task (sketching a bending moment diagram) in a Strength of Materials course, showing that although integrals appear in the theoretical block, they are not explicitly used in the practical block. Our analysis of the course's reference book shows that this situation is replicated for all notions defined as integrals. This leads us to seek further information by examining teaching practices and by considering mathematical and didactic praxeologies. Our preliminary results indicate that, although integrals are present in the knowledge block of the course, their presence in the practical block and in the evaluation is significantly weaker.

Keywords: Teaching and learning of mathematics for engineers, teachers' and students' practices at university level, textbooks, Anthropological Theory of the Didactic, integrals.

INTRODUCTION

Recent research in mathematics education and in engineering education has shown that university engineering students encounter a number of difficulties in mathematics courses in their early years of study, resulting in high failure rates and dropouts (Ellis, Kelton, & Rasmussen, 2014; Rooch, Junker, Härterich, & Hackl, 2016). Neubert, Khavanin, Worley, and Kaabouch (2014) state that efforts should be made to increase student retention in engineering courses in the first years of a programme (particularly in first-year non-engineering courses), as this is when most dropouts happen. It is important to note that, in many engineering programmes around the world, mathematics and physics courses are generally taught in the first years, with specific engineering courses appearing in later semesters. This classic structure separates 'basic' and professional disciplines, and can aggravate students' difficulties, reducing their ability to make links between concepts and negatively affecting the teaching-learning process (Perdigones, Gallego, Garcia, Fernandez, Pérez-Martín, & Cerro, 2014). For instance, Loch and Lamborn (2016) report that in engineering programmes, first-year mathematics courses often focus "on mathematical concepts and understanding rather than applications" (p. 30). Authors such as Flegg, Mallet, and Lupton (2011) highlight this lack of connection between mathematics content and engineering content among engineering students, which can lead the latter to view their mathematical courses as irrelevant. We believe this situation may contribute to students' lack of interest and motivation in their mathematics courses. Faced with these problems, the mathematics and engineering education communities have been engaged

in research and discussion, not only on which topics engineering students should study, but also on what kind of mathematical knowledge and skills are needed by engineers, with an eye towards improving engineering students' mathematics training (Bingolbali, Monaghan, & Roper, 2007).

Among the pioneering works on this topic, Noss (2002) identified that structural engineers do not “‘use mathematics’ of any sophistication in their professional careers” (p. 54). Providing testimonies from engineers to support his findings (“an awful lot of the mathematics they were taught, I won’t say learnt, doesn’t surface again,” p. 54), Noss suggests that university mathematics content often goes undetected in real-world engineering practices, although it underlies basic, frequently used operations. For instance, with respect to civil engineers, Kent and Noss (2003) conclude that in “95% of the work [they] do, the mathematics is basic” (p. 18) and that many of them do not even use calculus. In particular, the authors suggest that although calculus can play an important role in engineers’ education by helping them grasp basic engineering principles, it may rarely be used explicitly in the workplace. Kent and Noss call for further research on engineers’ use of mathematics (calculus in particular) — a pressing concern given the high failure rates in university calculus courses.

In line with the previous, and in order to identify mathematical skills used in engineering, in recent years we have investigated how single-valued integrals are used in engineering courses. We seek to reveal potential ruptures between how notions are first introduced and used in calculus, and how they are later applied in introductory engineering courses. Initially, we analysed how these notions are presented in engineering textbooks, working under the assumption that many university teachers plan their teaching using textbooks as an important resource (e.g., Mesa & Griffiths, 2012). At previous conferences, we presented our results regarding the use of integrals to define first moments of an area (Q), moments of inertia (I), polar moments of inertia (J), bending moments (M), and centroids (C) in a Strength of Materials course for Civil Engineering (González-Martín & Hernandez-Gomes, 2017, 2018, 2019). Our analyses show that, although these notions are defined using integrals, the practices employed either use very basic calculus techniques or eschew them completely (more details are provided in the Data Analysis section below). This echoes Noss’ (2002) and Kent’s and Noss’ (2003) results. Having analysed the entire reference textbook used for this particular Strength of Materials course, in this paper we present a summary of our results, as well as some initial results concerning the teaching of this course and the effective use of integrals, based on interviews with an engineering teacher.

We note that the preliminary results from our analyses of how integrals are used in relation to bending moments, first moments of inertia, and centroids are consistent with Faulkner’s (2018) results. Faulkner analysed the entire coursework of a first-year engineering course (Statics), showing that only seven out of the 84 exercises ($\approx 8\%$) required some explicit knowledge of calculus, with five of these seven exercises appearing in the same chapter. This means that a student with no knowledge of calculus content could still achieve a grade of A- in this course. We are not aware of other

research investigating engineering courses in their entirety, and our work aims to fill this gap. Moreover, although some existing research does involve analysis of course material or interviews with engineers, we are not aware of any work of this nature that also examines the classroom practices of engineering teachers or the latter's use of calculus content in their courses. The existing research generally focuses either on the calculus courses that serve as prerequisites for engineering courses or on workplace practices; however, what happens in the middle (the teaching of professional courses) is usually overlooked. Therefore, our research programme seeks to answer the question: how is calculus content used in engineering courses, both in course materials and in teachers' practices?

THEORETICAL FRAMEWORK

As we are interested in variations in practices between mathematics activity and engineering activity, our research uses tools from the anthropological theory of the didactic (ATD – Chevallard, 1999), which considers human activities to be institutionally situated. A key element of ATD is the notion of praxeology, which allows for the modelling of human activity. A praxeology is formed by a quadruplet $[T/\tau/\theta/\Theta]$ consisting of a type of task T to perform, a technique τ which allows the task to be completed, a rationale (technology) θ that explains and justifies the technique, and a theory Θ that includes the discourse. The first two elements $[T/\tau]$ are the practical block (or know-how), whereas the second two $[\theta/\Theta]$ form the knowledge block that describes, explains, and justifies what is done. Although ATD distinguishes between different types of praxeology, due to space limitations we only present our analyses in terms of tasks.

Moreover, teaching practices can also be modelled using praxeologies. In the case of didactic praxeologies, Chevallard (1999) identifies six moments: 1) the first encounter with the content to learn; 2) the exploration of the type of tasks and the elaboration of a technique relative to these tasks; 3) the constitution of the technological/theoretical environment relative to these tasks; 4) the technical work, which at the same time aims to improve the technique making it more powerful and reliable, and to develop the mastery of its use; 5) the institutionalisation; 6) the evaluation of what was learned. We use these moments in our analysis of the interview with the teacher.

METHODOLOGY

Our research project involved the collaboration of an engineering teacher who holds bachelor's and master's degrees in Civil Engineering and who has extensive experience in structural systems and reinforced concrete. This teacher works in a Brazilian university, where Strength of Materials (SM) for Civil Engineering is taught as a second-year course in the engineering programme (part I, SM-I, in the third semester, and part II, SM-II, in the fourth semester). This course is taken once students have completed differential and integral calculus courses in their first year. In Brazilian universities, SM is mandatory in engineering: it is part of basic engineering training

and serves as a prerequisite for advanced engineering courses such as Stability of Construction, Concrete Structures and Prestressed concrete. For the data presented in this paper, the methodology was applied in three phases:

- First, we analysed the general structure of the content related to integrals in first-year calculus courses at the engineering teacher's university, using a hard copy and an electronic version of the course reference book (Stewart, 2012). We identified the main tasks concerning integrals proposed to students, the techniques used to solve them and the rationales (technology) employed (see González-Martín & Hernandez-Gomes, 2017, 2018).
- Second, we analysed a classic international SM textbook used at the same university (Beer, Johnston, DeWolf, & Mazurek, 2012), also examining the electronic and hard copy versions. For this book, we identified all notions that are defined as an integral, using keyword searches in the electronic version, and pinpointed all appearances of the symbol “ \int ” in the hard copy version. For all content defined using a single-valued integral, we identified the tasks involving the latter, as well as the techniques and explanations present. For examples about bending moments and first moments of an area, see González-Martín & Hernandez-Gomes (2017, 2018, 2019).
- Third, we interviewed the engineering teacher on four occasions (I1: March 2016, I2: November 2016, I3: August 2019, I4: September 2019), and had access to his lecture notes. Interviews were conducted in Portuguese; they were audio-recorded and transcribed, with excerpts translated into English. During these interviews, we discussed the specific case of bending moments and how it is presented to students, as well as the tasks and techniques explained. We also discussed the course overall and the use of integrals and calculus content: how frequently this content is used to complete the various tasks presented in the course, and how much this content factors into the students' evaluation.

Due to space constraints, this paper provides a summary of the main results from our textbook analyses on bending moments, followed by an overview of the use of integrals throughout the entire book. We end by providing data from the interviews concerning the use of integrals throughout the entire course.

DATA ANALYSIS AND DISCUSSION

Phases 1 and 2: Calculus and bending moments

At this university, single-variable courses follow the structure of Stewart (2012). The content concerning integrals is organised into two blocks (see González-Martín & Hernandez-Gomes, 2017, 2018). The first block introduces a repertoire of techniques for calculating indefinite integrals (from immediate integration to more complex cases), with theoretical elements mostly absent. The second block introduces Riemann sums to formally define integrals and interpret them as areas, and leads to the Fundamental Theorem of Calculus and the calculation of definite integrals using

Barrow's rule; this leads to some applications of the integral (area, volume...). Many of the techniques used here are derived from the first block.

Regarding bending moments (introduced in SM-I), generally, loads are perpendicular to the axis of a beam (*transverse loading*). These transverse loads can be concentrated, distributed, or both. When beams are subjected to transverse loads, any given section of the beam experiences two internal forces: a shear force (V) and a bending couple (M). In the case of distributed forces, V is defined as the integral of the load (w) and M is defined as the integral of V . The latter creates normal stresses in the cross section, whereas V creates shearing stresses. Therefore, one of the main factors to consider in designing a beam for a given loading condition is the location and maximum value of the normal stress (M) in the beam. For students to determine this location, techniques for sketching bending-moment diagrams are introduced. These techniques produce diagrams such as the one in Figure 1.

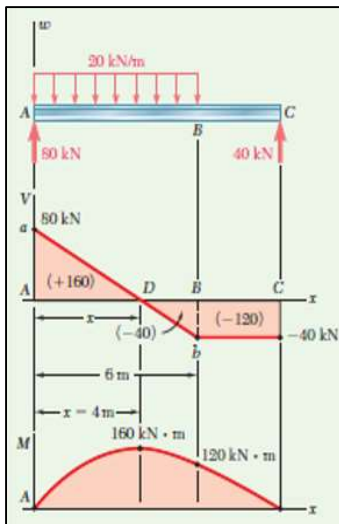


Figure 1: Task concerning bending moment diagrams in Beer et al. (2012, p. 364)

It is important to note that although these notions are defined as integrals, the actual technique does not rely on content or techniques derived from the calculus course (the graph of M in the lower portion of Figure 1 is the graph of the antiderivative of V , which itself is shown in the middle portion). The technique consists of obtaining values for specific points using basic formulae and calculations and then connecting them with a free-hand sketch (see points A , B , C at the top of Figure 1—distribution of the load—and how these points determine other points in the two graphs below them). After an initial example, the rationale (technology) for this technique is given: “Note that the load curve is a horizontal straight line, the shear curve an oblique straight line, and the bending-moment curve a parabola. If the load curve had been an oblique straight line (first degree), the shear curve would have been a parabola (second degree), and the bending-moment curve a cubic (third degree). The shear and bending-moment curves are always one and two degrees higher than the load curve, respectively. With this in mind, the shear and bending-moment diagrams can be drawn

without actually determining the functions $V(x)$ and $M(x)$ ” (Beer et al., 2012, p. 362). Although this rationale is based on content from calculus, we note that, as given, this rationale can be used to apply the technique without referring to integrals.

Our results concerning the introduction of bending moments (for more details, see González-Martín & Hernández-Gomes, 2017) seem to confirm Noss' (2002) and Kent's and Noss' (2003) findings: although calculus underlies the technique used to sketch the above diagrams, the technique itself consists of basic calculations and free-hand sketches. To investigate this phenomenon further, we analysed the entire reference book.

Phases 1 and 2: Calculus and SM

According to the university's curricular guidelines, the content of SM-I, focuses mainly on analysing internal forces, sketching and interpreting their diagrams and studying pieces subjected to flexion and stresses. In SM-II, the content focuses mainly on deepening the study of pieces subjected to flexion (studying different types of flexion), determining tensions and sketching their diagrams and studying torsion, deflexion, and rotation in beams. Both courses follow the structure of Beer et al. (2012), in which each chapter is divided into different sections: theory, concept applications (CA), sample problems (SP), and several homework assignments. Both CAs and SPs appear in the theory sections, focusing on specific topics and helping to illustrate the application of specific content. In our first analyses, we focused on the topics of first moment of an area (Q), moment of inertia (I), polar moment of inertia (J), bending moment (M) and centroid (C). Our results showed that integrals are mostly used in the theoretical sections, to introduce and define these notions, as well as to deduce certain properties (see González-Martín & Hernandez-Gomes, 2019). Figure 2 shows that although these notions are defined as integrals, they are involved in praxeologies where, for the most part, students can use the tables and formulae provided to find the values needed to solve tasks. The actual technique does not rely on using integrals, and it is only if we seek to find the rationale for the technique (technology) that integrals make an appearance. However, as illustrated above with bending moments, explicit justifications of these techniques, when they occur, rely on a professional discourse and are not (at least for the student) explicitly related to explanations and properties as they are taught in calculus courses.

	Theory			Concept Application (CA)			Sample Problem (SP)		
	<i>A</i>	<i>B</i>	<i>C</i>	<i>A</i>	<i>B</i>	<i>C</i>	<i>A</i>	<i>B</i>	<i>C</i>
First Moment	12	7	0	10	0	1	7	0	0
Moment of Inertia	12	5	0	6	0	3	9	0	1
Polar Moment of Inertia	5	2	1	3	0	1	1	0	0
Bending Moment	33	15	6	15	0	13	24	0	11
Centroid	21	2	0	11	0	0	12	0	0

* Column A: the notion appears without any explicit connection to integrals.

Column B: the notion appears connected to the integral symbol, with no calculation.

Column C: the notion appears and an antiderivative is calculated.

Figure 2: Frequency of integrals in theory, CA and SP.

The scenario is replicated throughout the book with all notions defined as integrals. Moreover, in the few cases where an integral needs to be calculated in a CA or an SP, the functions involved are constants, x^n , $(x - a)^n$, $1/x$, $\sin(ax)$, or $\cos(ax)$. These results, which are coherent with Faulkner's (2018) concerning a Statics course, prompted us to interview our teacher about the actual use of integrals in his course and to study the level of similarity between the mathematical praxeologies in his teaching practices and those in the reference book.

Phase 3: Interview and lecture notes of the engineering teacher

In this section we provide some details about the mathematical and didactic praxeologies that are present in the teaching of SM, based on our interviews with the

engineering teacher. The latter agrees that the course employs a number of basic mathematical tools:

T-I1: Thinking about Strength of Materials, we use, for example, proportionality, the Pythagorean Theorem, and basic trigonometry.

Newton's binomial is also used in the course. Although these notions sometimes appear in praxeologies where deductions are necessary to arrive at a needed formula, and while some complexifications are used to study certain phenomena, the teacher adds that "we do not ask these deductions in the exams." Regarding the use of calculus in the course, he confirmed that it appears in the introduction of topics. For instance:

T-I1 At the beginning of Strength of Materials [I], we start studying distributed loads. To deduce the resultant, which we call *mechanically equivalent force*, I will use a concept of Calculus: the infinitesimal. Then you calculate the value in infinitesimal chunks, and the resultant of all this is the integral of $[w(x)dx]$. [...] So, I'm using this and all... And again, it's a little bit of Calculus.

The teacher confirms that integrals appear in the course when covering the topic of internal forces in a beam, and when studying the relationships between load (w), shear force (V), and bending moment (M), which are used to sketch bending-moment diagrams. He says he highlights the use of integrals in the theoretical part, as in the textbook. However, he confirms that integrals are set aside during the practical part:

T-I4: This way of doing things [deducing forces using integrals] is set aside when we start sketching. At each point where loads change, we can determine the values of the [shear force and bending moment]. And if we know these values in the extremities of each section [we can perform the task] [...] On this beam, you have a uniformly distributed load; if I know the shear force on the left and right [end] of the section, then we know that $dV/dx = [w]$ constant. What thing, when derived, gives a constant? A linear function. Then, if I know that in the extremities [the values] are 40 and -60, how does it vary? Linearly, I know it is linear. So, these two points define a straight line. Then, I can start sketching the diagram directly. I don't need to find the equation [of the straight line]. [...] From here, for the [bending] moment, I know its value in extremities and I know the load is constant, the shear [force] is linear, [then] the [bending] moment is parabolic, a quadratic function. [...] So, we get to sketch that directly, too.

The teacher confirmed that the calculation of integrals is not necessary throughout this entire section of the course. Moreover, although he makes a connection to derivatives in explaining the technique, the teacher provides students with the rationale from the book (which offers no explicit connection to integrals or derivatives), explaining that this rationale is the one they need to use. Nevertheless, he states that knowledge of integrals is useful "as training, but for many things I don't need to use the integral, although I need to understand it" (I4). We see that, regarding this content, the explicit use of integrals seems to appear in the moments, *exploration of the type of tasks* and *constitution of the technological/theoretical environment*; however, integrals disappear

during the *technical work* and its *institutionalisation*. This led us to question the extent to which integrals are used explicitly in the *evaluation* moment.

As taught by this teacher, the SM-I course has two midterm exams (M1 and M2) and one final exam (FE), totalling 10 points each. To pass the course, the condition $((M1+M2)/2 + FE)/2 \geq 7.5$ is necessary, which means that $(M1+M2+2FE) \geq 30$. M1 contains a question (two out of 10 points) about bending moments and shear forces, in which students must provide a solution recalling the theoretical explanation using integrals. M2 contains a question (worth approximately six points) on the sketching of bending moment diagrams, which can be solved using the given technique without resorting to integrals. Integrals are not explicitly used in the FE. Therefore, in this case, only 5% of the final mark relates to the explicit use of integrals, which is coherent with Faulkner's (2018) results concerning a Statics course. We therefore see that although integrals are present in some moments of the teacher's didactic praxeologies, their presence in the *technical work* and *evaluation* moments is weak. It seems that this teacher's praxeologies are similar to those present in the book.

FINAL CONSIDERATIONS

As stated in the Introduction, more research is needed to determine the actual mathematical knowledge and skills that are applied in a typical engineering workplace. Pioneering researchers (Kent & Noss, 2003; Noss, 2002) have already suggested that most engineers just need 'basic' mathematics, and that university mathematics content is "transformed into something else" (Noss, 2002, p. 54). Recent research analysing the content of engineering courses seems to confirm this. Faulkner's (2018) analysis of a Statics course revealed that explicit use of calculus is only necessary in 8% of the course. There is a paucity of works analysing and assessing actual (classroom and professional) engineering practices, which would help to clarify how much (advanced) mathematical content should actually be necessary to pass courses.

Using tools from ATD (Chevallard, 1999), we took a holistic approach to analysing an engineering course, Strength of Materials: first, we examined the way the course is organised around specific topics; second, we examined the course reference book in a global way; third, we looked at the teaching practices and mathematical and didactic praxeologies activated during teaching. Due to space limitations, we only provide some data on the general aspects of the course, concerning integrals; however, the results of our three stages of analysis seem consistent. Although integrals are used in the course, primarily in the knowledge block, their explicit use is less necessary in the practical block: most techniques (although implicitly based on the use of integrals) rely on basic calculations, the use of tables or given formulae, and geometric considerations. In addition, knowledge of integrals does not factor much at all in the students' final assessment. We believe that this disconnection between practices in calculus courses and in professional courses may reinforce students' views of their mathematical courses as being irrelevant to their training (Flegg et al., 2011).

We highlight the fact that our teacher states integrals are needed “for anything that goes beyond the trivial”, but in the workplace, practices usually follow standardised rules. This seems consistent with the results of Kent and Noss (2003), who suggest that employers look for balanced teams and that “it may be more cost-effective to contract out unusually complex analysis to a specialist design consultancy [...] whereas civil engineering consultancies need more, but still only perhaps 10-20% need to have specialist skills in analysis” (p. 18). This is also coherent with recent results from Quéré (2019), who, in a survey of 261 French engineers, found that only 129 (49.9%) used (university) mathematics in their workplace. Of these 129 respondents, only 43% (21.24% of the overall sample) said they used calculus content in their daily practice.

Finally, our results suggest that, regarding the SM course, although content concerning integrals is necessary, it is rather the knowledge block aspects that seem essential for gaining a better understanding of engineering techniques. We intend to deepen our analyses of the interviews with the teacher to gain further insight into this phenomenon. We also intend to pursue analysis of other engineering courses. Both avenues of research will be the source of future publications.

ACKNOWLEDGEMENTS

We wish to thank the participant teacher for sharing his knowledge and experience. The research presented here was funded by grant 435-2016-0526 through the Insight Program of the Social Sciences and Humanities Research Council (SSHRC) of Canada.

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