Is Structural Engineering Education Creating Barriers to Innovation and Creativity?

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Abstract – **It can also be argued that structural engineering pedagogy and curriculum have not changed significantly in the past 50 years. Traditional structural engineering curricula pay particular focus to prescriptive methods for design focusing on lowest weight designs. Additionally, engineering core courses are focused on lessons in which a "correct" solution to a well-constrained problem should be reached as efficiently as is possible. Consequently, by the time students are engaged in upper level design or graduate studies, any attributes of creativity or innovation have effectively been removed from their skill set. This paper will examine current methods in engineering pedagogy that may be restricting creativity and the current discussion at the national level on revising the structural engineering curriculum.**

1. INTRODUCTION

"If you're not prepared to be wrong, you'll never come up with anything original" Sir Ken Robinson, 2006 TED Talk, ***Do schools kill creativity?***

As we approach 2020, it is useful to look back at the National Academy of Engineering's report on the Engineer of 2020 [1] which states, "**Creativity** (invention, innovation, thinking outside the box, art) is an indispensable quality for engineering, and given the growing scope of the challenges ahead and the complexity and diversity of the technologies of the 21st century, creativity will grow in importance. The creativity requisite for engineering will change only in the sense that the problems to be solved may require synthesis of a broader range of interdisciplinary knowledge and a greater focus on systemic constructs and outcomes." Australia's national engineering body, Engineers Australia, puts the problem in more concrete terms as follows: "Innovation is extremely important to a country as it is closely related to productivity…In the absence of sustained innovation, the rate of growth in labour-constrained economies will ultimately fall to zero…By focusing on innovation in industries relevant to engineering, it is possible to increase productivity and contribute to the economic prosperity of the nation."

Yet despite the call for creativity in engineering, undergraduate engineering training is still highly prescriptive, deductive and focused on well-constrained problems with correct answers. Students in structural engineering are often focused on getting the answer in the back of the book, finding the lowest weight solution, and/or using high level analysis methods to find "exact" solutions to problems with unrealistically "exact" inputs.

The engineering education curriculum on average is not only antithetical to creativity and innovation, but it focuses on what topics students are learning rather than what skills they are developing. In 2016, the National Council of Structual Engineers Association (NCSEA) [2] published the most recent results of a Structural Engineering Curriculum Survey performed every 3 years. The idea behind the survey is positive – develop a list of recommended courses that every structural engineering student should have and determine to what extent those courses are being offered nationally. Per NCSEA, the recommended courses include: Structural Analysis I&II, Matrix Methods, Steel Design I & II, Concrete Design I&II, Timber design, Masonry Design, Dynamic Behavior of Structures, Foundation Design/Soil Mechanics, and Technical Writing. Compare this to the Structural Engineering Institute' s Vision Document [3] which, in discussing a vision for structural engineering education, discusses the "skills and abilities needed to innovate and lead."

External influences on curricula are also not helping to focus on skills or abilities. Despite an emphasis by ABET on student outcomes, the ABET criteria still are grounded in a prescriptive curricular approach focused on the number of credit hours and breadth of material coverage. And none of the ABET outcomes address creativity or innovation. [4]. So the question is, are we developing a basic fact base for structural engineers, a fundamental understanding of engineering concepts or a necessary skill set? Consider something as fundamental as the current Wikipedia [5] definition that:

Structural engineers analyze, design, plan, and research structural comonents and structural systems to achieve design goals and ensure the safety and comfort of users or occupants. Their work takes account mainly of safety, technical, economic and environmental concerns, but they may also consider aesthetic and social factors.

Note that the emphasis is on what structural engineers do (design, analyze, research) rather than on what they know. However, when describing education, the discussion immediately shifts to core subjects. Even in mainstream / general public decriptions, there is a fundamental disconnect in required skills / abilities and the emphasis of education on topics.

2. ENGINEERING CURRICULAR IMPACTS ON CRITICAL THINKING, CREATIVITY AND INTELLECTUAL DIVERSITY

In any discussion of engineering education, whether with academics or professionals, a ubiquitously mentioned desired skill in engineering is critical thinking. Woods et. al [6], in providing research based advice on developing critical thinking skills state in their conclusions, entitled "If you only get one idea from this paper,"

Focusing lectures, assignments, and tests entirely on technical course content and expecting students to develop critical process skills automatically is an ineffective strategy.

And yet, students are still more focused on the "right answer" than they are on the process. Additionally, this paper specifically mentions grading the process rather than simply the product.

Studies suggest that students entering engineering are actually more novel and have no less critical thinking skills than "trained" graduating seniors. Genco et. al [7] examined design generation and compared novely of the design concepts and design features developed by teams of freshman and teams of seniors, and the freshman scored significantly higher than the seniors. They also had lower "design fixation" or conformity with previously established or example design features. This is in line with Guilford's [8] findings on expertise and creativity. While some amount of knowledge is necessary to develop a creative solution, extensive knowledge or expertise tends to limit creativity by constraining thoughts to known solution spaces.

Even more discouraging are the results in a study of creativity and critical thinking skills in freshman and senior engineers by Sola et. al [9]. Using validated metrics to examine creativity, they found, like Genco et al, that freshmen were more creative than their senior counterparts. More alarmingly, freshman engineering students outperformed both the general population of freshman students (57.8 vs. 56.2) and the seniors in engineering (57.8 vs. 53.8). And while the engineering students actually ***decreased*** in critical thinking skills from freshman to senior year, the normative group both increased (from 56.2 to 59.2) and significantly outscored senior engineers (59.2 vs. 53.8). The suggestion that rather than developing critical thinking skills, engineering curricula actually stunts them; this is not currently part of narratives on educational reform.

It may also be that creative students and those that add intellectual diversity to the ranks of engineering are being driven out of the field in an attempt to mold students into a specific vision of highly analytical archetypes. Kellogg [10] uses results from the Hermann Brain Dominance Instrument (HBDI) to show that students with less "typical" analytical thinking preferences (shown in blue) are likely to leave engineering before graduation (see Figure 1).

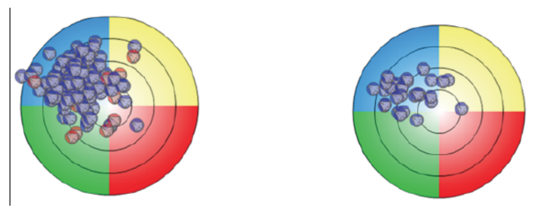

Fig. 1: Differences in first year and fourth year students in a traditional engineering major. Red circles indicate females.

The HBDI is a validated instrument that indicates a cognitive preference; because it measures preference rather than ability, it is not a measure that changes substantively over time without the impact of a traumatic event. It can be argued that intellectual diversity creates the necessary climate for innovation and creativity on teams more so than simple demographic diversity. But a traditional engineering curriculum has the potential to drive out more intellectually diverse students.

Additionally, Atwood and Pretz [11] examined factors that lead to persistence in engineering. They found that not only was creative self-efficacy not a factor in persistance, but students who self-described as highly creative were over 20% less likely to graduate in engineering than those who viewed themselves as "not very creative." This may be due to a consideration of engineering as serious and accurate rather than creative. [12].

In considering creativity, researchers discuss the four P's of creativity: Person, Process, Product and

Press. [13]. Engineering students, at least when entering the field, are not generally less creative than their counterparts in other majors [9]. And freshman engineers are capable of developing creative products. So it may not be necessary to develop creativity in the person, the engineering students, but rather to change the press, that is, the environment in which creativity occurs. Kazerounian and Foley [12] present a strong case for how the environment negatively impacts creativity in engineering students. They suggest that the elements inherent to creativity – use of non-standard approaches, risk, and learning through failures, are not amenable and are actively discouraged in engineering education. In their study, they determined through student surveys that none of the creativity criteria presented were identified by students as being part of their engineering curricula. They also discuss the difference between students that are motivated to achieve and those that wish to avoid failure (promotion vs. prevention). Students driven to achieve merely to avoid failure are far less likely to take the necessary risks that lead to creative or innovative processes and products. Hadgraft [14] suggests business models for encouraging creative environments in engineering and argues that the environment, rather than the individual characteristics of the students, is hampering the development of students' creative potential.

3. A VISION FOR STRUCTURAL ENGINEERING CURRICULUM

In 2013, the Board of Governors of the Structural Engineering Institute (SEI) of the American Society of Civil Engineering (ASCE) published a Vision document [3] outlining, first among other initiatives, the need for a reform of structural engineering education. The executive summary calls explicitly for the adoption of new educational models to equip students with the technical, communications, and critical thinking skills that are necessary for success.

The SEI Vision recognizes that the current (structural) engineering education approach is a result of an incremental evolution that finds its roots in the industrial revolution and that has been refocused in the post-World War II era, and is now weighed down by a vast number of constraints. In the Vision document, engineering education is seen as having become far too parochial, driving students to commit earlier and earlier to a specific branch of engineering, due to the emphatic need of graduating students in four years, thus all but eliminating the breadth that is seen as essential for the future of the profession.

The SEI Vision document also recognizes that the task of re-envisioning the formal education of structural engineers cannot consist of a series of piecemeal actions, but rather it requires the re-imagination of the entire process. SEI proposes to adopt a three-fold approach to this radical paradigm shift in engineering education: (1) the decoupling of undergraduate education from professional training, recognizing that the undergraduate degree is not designed to be the primary source of professional training in engineering; (2) the development of a professional school model with an associated internship model to enable transition into practice; and (3) the creation of a more engaged connection between academia and practice.

The first item in the SEI envisioned approach calls for a radically different undergraduate degree, which could be attained by either creating a general engineering program with the aim of providing foundational preparation and broad education for all engineering majors or by creating a pre-engineering school, akin to the strategy that has been successfully implemented by the law and medicine profession.

The second, concurrent step in the SEI Vision calls for the creation of a professional school to provide a continuation of the education of structural engineering students: whereas the general, or pre-engineering degree would be about foundational knowledge and breadth, the professional degree would be about depth and specific knowledge in structural engineering. Gone would be the worries about adequacy of the few specialty courses provided in undergraduate education, as they would not be entry-level professional requirements. As part of this professional school model, SEI calls for a structured internship model, akin to what several undergraduate programs do with mandatory cooperative education activities (e.g., The University of Cincinnati, Northeastern University, etc.).

The third aspect of SEI vision is best described by furthering the parallel with medical school by envisioning an entity that is not a university nor a structural engineering firm and that performs the same services of a teaching hospital to medical students: a "teaching firm", or a "practice arm of the university", in which engineers-in-training will engage in practice-related activities under the guidance of practitioner-educators with the goal of providing the education that currently is not covered by academic curricula and is not assured in the current workplace environment.

In summary, the SEI Vision states the lofty goal of completely reinventing collegiate engineering education: a potential path for this vision to become reality would be the institution of a pre-engineering degree, which ensures breadth of scientific and technical knowledge (e.g., math, risk and reliability, physics, engineering mechanics, etc.) but also attention to non-technical skills such as creativity, economics, social and political studies, composition and public speaking, paired to the institution of a professional school, which parallels, and possibly is the precursor of, existing graduate schools, with the intent of providing depth in technical knowledge. All the while, the engineering college sprouts a "consulting" branch in which students and faculty engage in the practice of structural engineering.

The challenges faced by this vision are vast. Some stem from the constraints currently placed on the educational system by both external and internal entities: for example, state boards of regents have been applying a steady pressure on universities to reduce the number of credit hours for graduation. Most civil engineering undergraduate programs in the Nation offer an engineering degree with anywhere between 125 and 135 semester credits: many boards would love to reduce those numbers to 120. The Accreditation Board for Engineering and Technology places numerous constraints on engineering curricula, most of which would have to be lifted or completely changed, in order for the SEI Vision to become reality. Furthermore, the proposed Vision will certainly increase the number of years a student would need to spend in school before being able to enter the engineering workforce by at least two or three. Will students (and employers, for that matter) be willing to allow for such a lengthened process? By the same token, will state and private boards of regents stand for an increase in time-to-graduation?

In short, the challenges faced by the envisioned reform come from all sides. States and institutions of higher education will have objections and will be loath to embark in such a radical change. Engineering firms and employers may be hesitant to support such a change when, after all, they are used and all in all satisfied with the engineering workforce that current curricula produce, especially if that is accompanied by a rise in salary and a longer waiting period for new potential employees. In fact, how will engineering firms see the potential competition of the local "practice arm of the university"? One could argue that medical practices are abundant in cities where teaching hospitals operate, and the two seem to coexist without incident, but on the other side of the issue the parallel between medicine and engineering can probably only go so far. Prospective students may be hesitant to embark into a multi-year endeavor when until now a degree and a path to professional registration was guaranteed by a four-year degree.

Of course, there are many advantages to the SEI envisioned reform: engineering degrees, much as law or medical degrees are seen today, will become a true professional degree, with the appropriate aura of knowledge, integrity, and technical prowess that seem to never quite be there in the public opinion eyes with the current engineering degrees. Hopefully, the new structural engineers will also have a better preparation and will not only be capable of designing safe, sustainable, and economical structures, but will also be able to become leaders of society. Academia and the engineering profession will interact more closely on a regular basis, providing a better transfer of research into practice, and concurrently grounding into practicality some of the more exoteric research efforts.

There are other approaches to an engineering education reform that can be considered, and are listed here in no particular order of feasibility or effectiveness. One approach that most likely would require the least change has been advocated by fringes of ASCE for several years now, and it would simply consist into the requirement of 30 semester credit hours beyond the undergraduate degree to be allowed to sit for the Professional Engineer Examination [15]. This would certainly relieve some of the credit hour crunch under which most undergraduate programs currently wither, allowing students to take more courses in their chosen branch of engineering, but at the same time it might somewhat devalue a Masters level degree (which incidentally corresponds to the taking of 30 semester credit hours). Detractors of this approach have indicated that this is just another step down the slope on which the value of degrees has been steadily sliding: a high-school degree in the 60s and 70s prepared an individual just like an associate degree would in the 80s and 90s, and just like an undergraduate degree would in the 90s and 2000s, and now as a Masters degree will in the 2010s. This hyperbole does highlight the main issue of the "plus 30 hours" approach, namely that it is an attempt of an incremental improvement to the current state of education, without challenging the reasons for the need of an improvement, or attempting to cure those reasons at the root.

Another potentially viable approach to provide engineering education with more room for creativity and in general breadth of knowledge without sacrificing the technical knowledge that remains necessary for the transition into engineering practice has been attempted by means of isolated special projects, whereas "pre-engineering" tracks are instituted in a high school curriculum that are meant to prepare students with all the fundamentals necessary to succeed in an undergraduate engineering program, thus freeing credit hours in the undergraduate curriculum for courses other than mathematics, physics, chemistry, and possibly basic engineering mechanics.

There are even more radical possibilities. University degrees have long been tethered to the Carnegie educational unit developed in the late 19th century. Consequently, most educational reform is, by logistical necessity, centered around the question of which 3-credit hour courses can be combined to form a full curriculum. One disadvantage of this approach is the lack of integration of curricular topics – each three (or two or four) credit course is isolated by expert instructor, and integration of topics is limited.. Consider the very traditional case of a technical communications course, taught by an English or Communications professor, in a seprate building from "real" engineering courses. Engineering faculty can relegate the instruction of communication skills to topic experts, and wonder why when the necessity arises that students cannot incorporate these skills into their tehnical courses. Rather than the 3 credit Carnegie unit, the potential exists for studio or workshop courses that include design methods, material behavior, 3D visualization and systems thinking along with integration of non-technical skills. Incorporation of modern pedagogical approaches such as problem based learning and well developed team-teaching approaches could facilitate these approaches, but not without cost. Changes at this level require significant modifications to infrastructure, culture and instructional methods.

Another radical approach was achieved by Alvero College, a women's liberal arts college in Wisconsin. In 1973, Alverno converted to an Ability-Based Curriculum [16]. Regardless of academic program, all students must demonstrate ability-based competency to graduate: Communication, Analysis, Problem Solving, Valuing, Social Interaction, Developing a Global Perspective, Effective Citizenship and Aesthetic Engagement. These are not substantively unlike ABET outcomes for engineering, but they are assessed across classes. Alverno does not give traditional grades; they give substantive qualitative feedback. The core abilities are emphasized across courses rather than isolated in individual classes.

Ultimately, one must be mindful of the challenges that any of these approaches will pose, coming from all sides and levels of the complex system that is engineering education when it interacts with the engineering profession. Support for these changes, whatever they may be, would have to come from states and institutions of higher education, from professional societies, from accreditation boards, from the collective individual firms and employers, and ultimately from society at large, in terms of the recognition of the need for engineers that are indeed engineers and not technologists.

4. CONCLUSION

Traditional lecture based engineering pedagogy, and even cooperative learning approaches that stress development of specific solutions, do not provide the necessary culture to develop students with the ability to fully develop design solutions to real-life, open-ended problems. In addition, a conservative culture in which risk is associated with failure limits the desire of students to even consider creativity as an option. Focusing predominantly on developing analytical skills at the expense of variable solution approaches limits the development of the divergent thinking skills needed for innovation; in addition, it risks intellectual diversity in engineering by deterring those students who may vary from the "typical" analytically dominant mode of thinking. Finally, a focus on coverage of topics rather than development of skills creates students that are limited in critical thinking skills and the skills required for both life-long learning and innovation. New approaches in structural engineering education must be considered to develop new solutions to the grand challenges that face society.

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