2023-10-10

Preparing Structural Engineering Graduates To Increase Their Positive Impact

Louise LYNCH
Technological University Dublin, Ireland;University of Bristol, UK, louise.lynch@tudublin.ie

James NORMAN
University of Bristol, UK, james.norman@bristol.ac.uk

Preparing Structural Engineering Graduates to Increase their Positive Impact

L. Lynch
University of Bristol
United Kingdom
ORCID 0000-0002-9842-3882

J. Norman
University of Bristol
United Kingdom

Conference Key Areas*: Addressing the challenges of Climate Change and Sustainability, Embedding Sustainability and Ethics in the Curriculum.*
Keywords*: Overdesign, Embodied Carbon, Overuse of Materials.*

ABSTRACT

Traditionally the role of a structural engineer was to design structures that were safe for use by society and that enabled society to develop and evolve. However, with the climate emergency structural engineers need to be more conscious of the choices that are made on their projects that lead to overuse of material, and work to reduce the embodied carbon in their structures. This cannot be achieved in isolation, it's a systemic issue, where decisions made throughout a project, from concept to construction, can impact the embodied carbon. The structural engineer needs to be mindful of these decisions to have a greater positive impact on construction projects. It may be due to how the project is specified, how it is designed or how it is constructed but the result is the same, the structure exceeds its functional need, it is overdesigned.

This research investigates, through 14 interviews, why overuse of material occurs on construction projects, specifically buildings, and what the first steps to change could be. This research outlines how some of these first steps include the knowledge and attitudes that are first developed in students within their early years of engineering education. This research aims not only to identify the messages we are giving to students but also to aid educators in recognising the other challenges that young graduates will be faced with. By developing educational programmes to equip individuals with the necessary skillset and knowledge, they can actively challenge traditional attitudes and become vital advocates for change.

1 INTRODUCTION

The construction industry is responsible for nearly 40% of global energy-related CO_2 emissions (Gibbons et al. 2022; J. Orr et al. 2021). As engineering professionals, we have a crucial role to play in reducing our impact on the environment. While efforts have been made over the last few decades to improve the energy efficiency of buildings and reduce operational carbon emissions, the embodied carbon from the structural elements has become a much larger proportion of the overall building carbon than before (J. Orr et al. 2021). To address this issue, all stakeholders in the construction industry must take action to reduce the embodied carbon in buildings.

Meadows (2008) highlights the importance of "leverage points" in the system where a small change can lead to a significant shift in behaviour. The education of professionals in this industry is a leverage point. The education of structural engineers is a significant part of this, not just their technical understanding, but their ability to impact positively on the change that is needed in the sector.

Unfortunately, the overuse of materials is a prevalent practice in structural engineering, as supported by the MEICON report based on a survey conducted in 2018 (Orr 2018). The underlying reasons for this tendency will be explored further in this paper through the analysis of interview responses. While design standards exist to prevent inadequate design, there is often no defined upper limit for the amount of material used. While there may be constraints due to budget or space, things are often built with more material than necessary without any penalties or defined limits.

However, the material used in construction can be refined, and this paper presents research conducted as part of a PhD study on understanding overuse of material in structural engineering projects. Through interviews with industry professionals, this research investigates how they perceive the culture of overuse and how it can be changed.

2 METHODOLOGY

2.1 PhD research

This paper presents a preliminary exploratory phase of a PhD research project that examines the attitudes and perceptions of construction professionals towards the overuse of materials in structural engineering, with a particular focus on new buildings. Rittel and Webber (1973) coined the term "wicked problem" which is related to social issues that cannot be solved with science. Blockley and Godfrey (2017) use the term to describe the challenge of changing the culture within the construction industry due to the number of people involved. They list clients, designers, contractors, customers, governments, regulators, and the general public, but to address the wicked problem of material overuse in construction, educators can also be added to this list. To positively impact the overuse of material in construction, it is essential to understand the complexities of the system, and how the aims and objectives of any one part can influence the design, and ultimately the embodied carbon of the building. By exploring the perspectives of different individuals involved in the construction process, this PhD research aims to highlight the challenges and identify potential strategies to promote sustainable construction practices and address the overuse of material in the industry. This paper particularly focuses on the role of education for structural engineers in addressing these challenges.

2.2 Sample Identification

For this research, a total of 14 individuals were selected for interviews based on the criteria of “personal involvement” and “external cues” (Mauksch, von der Gracht, and Gordon 2020). Specifically, participants were chosen based on their personal involvement with embodied carbon research and/or professional engineering bodies (P1-P8, P12, P13), the length of their career (P9, P10), or for a contrasting perspective to other participants (P14). The final group was chosen as a representative of a more traditional consultancy that has remained active in the industry in recent years, in contrast to the first two groups of forward-thinking individuals or partially/wholly retired engineers with a good perspective of traditional viewpoints but less active in the industry since the declarations of climate emergency (BBC 2019a, 2019b). All participants are qualified engineers based in the UK or Ireland. Although the findings are biased towards the need for change and the viewpoint of the structural engineer, this is not considered problematic, as the goal was to utilise the expertise of these individuals to establish a foundation of viewpoints on causes, challenges, and potential solutions to overuse of material during design and construction.

2.3 Ethical Approval

Ethical approval was obtained from the University of Bristol Faculty of Engineering Research Ethics Committee [Ref: 10703] before conducting the interviews. Participants were fully informed of the study’s purpose, data confidentiality and storage, and their right to withdraw. Written consent was obtained from all participants.

2.4 Interviews

A semi-structured interview approach was used, offering focus and flexibility during the conversation. For example, to capture the diverse perspectives and nuances surrounding the term ‘overdesign’, participants were not provided with a predefined definition, allowing them to express their understanding based on their experiences. This method proved suitable for the exploratory phase of the research, enabling in-depth exploration of the topic's breadth and depth. Interviews were conducted both online and in-person in Summer 2022, lasting 45-60 minutes. Participants shared their backgrounds and discussed their views on ‘overdesign’, the reasons it occurs, and solutions to promote refinement. For confidentiality, participants are labelled P1 to P14.

2.5 Interview Analysis

Interviews were transcribed using AI transcription software and manually verified. Transcriptions were analysed and coded to establish common themes. In the results, quotes may be edited for clarity, while maintaining context, with omissions marked by three dots (…).

2.6 Defining Overdesign

Before analysing the interviews, it is important to define ‘overdesign’ for this study. Orr et al. (2021, xiii) describes it as “overly conservative design of structural elements”, which is subjective. This paper adopts P3’s definition: “using more material than is actually needed to meet the desired outcomes of what the client is asking for”. P2 further contributes to this understanding stating: “Maybe it's not just over design, and over-specifying, and over-demanding from an architect, but it's over building from a contractor, as well”. This shows a distinction between over design by the structural engineer for their own purposes and ‘overdesign’ that results in more material used than needed for the “desired outcomes”, that distinction being that the latter includes the former.

Notably, P3’s definition includes the concept that a new construction project may not be necessary. P5 points out that “if you're designing something that's new, anything that's new, you could argue that you're already in the world of overdesign because the first thing you should do as a designer is try not to build anything at all”. While avoiding a need for new construction offers significant carbon savings, the PhD research focuses on new builds to explore leverage points throughout the construction process for promoting a culture of refinement.

Throughout the interviews, it was evident that the term ‘overdesign’ evoked defensive responses or suggestions for alternative terminology from participants, based on their prior experiences. Considering this, it is important to clarify that this study aimed to explore efforts that can positively influence climate targets by reducing material usage and increasing design efficiency. As a result, future phases of this PhD research will strive to employ more positive language, moving away from the term ‘overdesign’ to allow for a more constructive discussion. Therefore, while the use of the term ‘overdesign’ is limited in this paper, it was employed during the interview process. It is worth noting that using this term with students may have certain benefits, as a negative term can potentially contribute to the development of responsible behaviours.

3 RESULTS

3.1 Overuse in the Construction Industry

To prepare students for their role in reshaping the culture of material overuse in the construction industry, it is crucial to understand the definition and underlying reasons for overuse. The interviews highlighted several themes associated with overuse, including high imposed loads, counterproductive layouts, low utilisation, high rationalisation, rationalisation of geometry, higher concrete grades, and oversized excavations. These concepts can be understood in non-structural engineering terms, such as designing for excessive occupancy, incorporating long spans or inconsistent column positioning, underutilising element capacity, maintaining uniform element sizes regardless of load requirements, employing consistent rectangular cross sections, using excessive cement in concrete mixes, and excavating larger foundations than necessary. While this list provides a contextual snapshot, it does not encompass all aspects of the problem.

To categorise the reasons behind material overuse, this paper adopts a simplified framework based on the construction process’s four key stages to handover: brief, concept, design, and construction. It is important to note that stages beyond handover, i.e. use and end-of-life, were not extensively discussed in this research phase.

During the brief stage, requests may include elements not necessary for achieving the desired outcomes. For example, a higher load may be specified due to client expectations regarding rentability: “They find it easier to rent an office block that has a capacity of 5 kN/m^2 as opposed to 2.5” [P12]. Budget and programme constraints often shape decisions during this stage, with designers expressing the need for more time to refine their designs but that time means their budget needs to be increased: “It's not in our control… if people were given more time to design… and time… equates to fees.” [P14].

In the concept stage, the focus is often on “very long spans…or… complicated transfer structures” resulting in “the structural function coming second to other things” [P3] as opposed to the other way. “If nature was designing these buildings you would end up with form follows function” [P3]. At this stage the structural engineer is often not involved, with the view that “the architects lead designers will generally be there and understand these conversations and take that back to the team” [P12].

The primary reason for overuse in the design stage “is based around reducing risk” [P2], meaning designers are reluctant to push utilisation factors to 100%. There is “a belief that somewhere else in a supply chain, we’re going to have incompetence” [P6]. A preferred utilisation value of 80% was frequently mentioned by participants, as it aligns with findings from the MEICON report (John Orr 2018). Designers often add extra material to future proof against “all the potential for change, which you know, is going to happen down the line” [P6].

The construction stage significantly influences design decisions. Ease of construction becomes a priority for the programme, leading to high levels of rationalisation. This results in an additional reduction in utilisation throughout the structure. This issue was raised by several participants and also supported by research (Moynihan and Allwood 2014). “Trust in the construction quality” [P7] is also a contributing factor. For example, P7 stated: “If you have definitely seen poor construction practice you might want to add a bit more bunce in there”. Bunce is a term used in some parts of the UK to account for an additional safety factor provided by an engineer just to be sure. The extra magnitude is poorly defined but results in a lower utilisation ratio.

On-site decisions also impact material overuse. Contractors may specify higher-strength concrete mixes because “they’re going to pump 50 metres along the way, which means it’s got to be stronger concrete, or they’re wanting flowing concrete or self-compacting concrete, which means you need to have more cement in it” [P8].

3.2 Preparing for Change Through Education

In the past, the mantra of “if in doubt, build it stout” [P10] guided structural engineering design, prioritising robustness. However, to address the carbon impact of new buildings, this approach must be challenged, and a focus on reducing material use needs to become commonplace. Alongside a personal and professional desire to reduce the overuse of material, to eliminate a “sleep at night factor” [P4] it is essential that designers have confidence in the system which includes the accuracy and finality of the information they are provided, the quality of fabrication/construction, and the appropriateness of use. This not only requires an awareness of the problem but a combination of technical expertise to refine designs, and effective time management and communication skills to foster a collective commitment to carbon reduction.

Climate Agenda

The primary reason for the overuse of material in construction is tradition, it’s cultural, it’s systemic, “it’s instilled in lectures in first year… it's absolutely prevalent, right from the first day, first year of an education to be a structural engineer” [P6]. Therefore, the first step to change, within education, is for educators to acknowledge the messages that they embed that contribute to the culture of overuse of material. At a minimum, this means a 'didn't know better' excuse won't continue, and no longer will engineers be able to say that "nothing told me that I needed to dig into this. And maybe because the institutions weren't, my clients weren't, my architects weren't. I let myself go with the flow" [P2].

A personal drive to change can be developed through awareness and exposure during education. A "personal positions on climate emergency are crucial to drive each one of us" [P2]. Educators can "encourage young engineers to find their agenda for every project… if you have no agenda, you just float with other people's agenda and just follow… if you haven't got that agenda, you're having no impact" [P2].

Technical Skills

Imposed loads emerged as the most frequently mentioned form of overdesign in the interviews, highlighting its significance as a starting point for developing the technical skills of structural engineering graduates. Participant P1 emphasised graduates should "have a much better understanding of what a kN/m^2 looks like and how realistic it is".

While design codes serve as a safety baseline, they can be overly conservative, as P5 points out: "The codes are so conservative… if [designers] understand the performance issues better, you can change the serviceability factors, some of which are not mandatory, there are partial factors you can play around with". As a result, structural engineering students must become well-versed in design codes and the origins of these factors, as well as their conservative nature. This knowledge will enable "engineers to design closer to the bone" [P5].

Understanding the code and the partial safety factors can lead to the development of an understanding of how structures fail and the difference between mean strength and characteristic strength. By exposing students to testing in laboratories and observing failure, they can see "when something fails, by definition, it mobilises its mean strength, by definition, it has to because it has to happen over a large surface area for any failure to occur, not the characteristic strength, and there's a gigantic difference between the two" [P6]. If students can be educated to see that designing "to the bone is massively safe" [P6] and "normally when they fail, it's not because of a failure of an individual component, it's usually a failure of a connection or… it's a gross misunderstanding of structural behaviour, neither of which come from code" [P4].

To reduce the risk of changes to designs from site, structural engineers need site experience to develop an awareness of constructability. Sometimes "if you're a young graduate, and you're employed by a firm or consulting engineers … there's not much of an opportunity to get out and do your site experience" [P9], so it is important to include some level of experience within the university curriculum, either through site visit and/or work placements. Thereby ensuring that the refined designs that are created are unlikely to be modified on site for ease of construction. Additionally, knowledge of how things are constructed will guide the use of realistic specification requirements to avoid putting "something in a specification that's impossible" [P2]. For example, unrealistic tolerances can result in elements of work being redone as tolerances weren't met or replaced due to cracking, ultimately an unnecessary waste of material.

While understanding advanced structural behaviour, i.e. vibration, catenary action, secondary effects, tensile skins etc, was discussed by some participants it is not developed further in this paper as it is less likely to be commonplace at the undergraduate level.

Soft Skills

Since material overuse is impacted by numerous decisions throughout the construction process, an individual's technical ability alone won't drive industry-wide change. While it can lessen the individual's impact, softer skills are needed to transform the system. These are skills outside the technical

In the modern digital era, time constraints play a significant role in the design process. With meetings being held online and drawings no longer physically posted, the time available for reflection and idea generation is significantly reduced. "Time spent on allowing people to mull ideas over is a really important aspect of trying to not overdesign" [P7]. Therefore, it is crucial to develop students' time management skills to prepare them for the demanding time requirements of the industry. This includes allocating time for reflection, review, and embracing feedback cycles as valuable components of the design process.

Structural engineers play a crucial role in advocating for sustainable design decisions. They first need to advocate to be included in discussions that affect the brief and the concept. Then they need the tools and confidence to speak up in these meetings and provide valuable input on decisions that affect the design efficiency. As P7 stated: "giving them the tools to feel empowered in speaking up about putting a column there or reducing your grid or maybe don't have that heroic cantilever". This skill will also allow engineers to advocate for design freezes, to tackle the need to future proof for fear of change. By developing their confidence and providing them with diplomatic communication skills, students can become advocates for sustainable and efficient concepts that allow a refined design.

Communication dynamics differ when engaging with different stakeholders in the construction industry. While discussions with stakeholders during the brief and concept stages often involve individuals who share a formal higher education background, interacting with construction operatives requires a different set of communication skills. P9 speaks from personal experience, describing the challenge of conveying information to construction operatives who may not have formal education or strong literacy skills. They emphasised the difficulty of communicating complex ideas, stating, "I do a lovely set of drawings; he's not even looked at them... I've even stood there with him... and he doesn't understand what I'm talking about. ... So, conveying information to the people who are implementing it is very, very difficult."

To overcome these challenges, students need to develop communication skills that encompass clarity, empathy and collaboration, while maintaining assertiveness. They should use straightforward language, avoid technical jargon that others may not understand, and break complex instructions into manageable steps. Additionally, they should demonstrate empathy by appreciating and respecting the skills and expertise of construction operatives. Collaborative communication is crucial, allowing for feedback and a better understanding of what can and cannot be achieved on-site.

However, assertiveness is still required to ensure that the quality control required to design efficiently is maintained on site. This may mean a “bit of tough love… to just get people thinking the right way, and they [the contractor] need to know that they're under scrutiny” [P9].

The dynamics between design and construction make this a complex communication arena where very good verbal, written and graphical communication skills are required. The importance of this skill set is represented by its inclusion in accreditation criteria for engineering programmes (JBM 2021). Ensuring this skillset, already in the curriculum, is adapted to deal with these efficiency conversations would prepare the students for implementing positive change within the industry.

4 DISCUSSION AND CONCLUSIONS

The overuse of material in structural engineering projects is a complex issue, which starts within education and continues throughout careers in industry. There is no single straightforward solution to moving towards a more efficient and sustainable construction process. However, addressing this challenge is essential to reducing the embodied carbon of buildings and achieving global climate targets. From educators to senior structural engineers, the message that is traditionally passed to the next generation of structural engineers is one of wastefulness. This message needs to change, and it needs to change from day one of a structural engineer’s exposure to the industry, for most students this exposure begins in the lecture theatre. For students with previous engineering exposure, day one of university is still an opportunity to reset, an opportunity to reshape their existing mindset at this key transitional stage of their careers.

Education can make a significant impact by developing a structural engineering students’ knowledge of the importance of using less material and where savings can be made. These savings can come from a deeper understanding of the design codes, loading and constructability. By developing their technical ability to design structures with greater efficiency and ensuring that their designs are constructible, structural engineers can play a vital role in shaping a sustainable future within the industry. For a greater impact, students need to have the ability to communicate with other stakeholders on either side of the design phase to have projects where efficiency is a common goal and quality assurance is essential.

By encouraging a new generation of engineers equipped with the knowledge, skills, and confidence to challenge traditional practices, engineering education can contribute to the positive impact these structural engineering graduates can have in reshaping the construction industry towards a more sustainable and efficient future.

This PhD research will advance by focusing on key roles in the construction system and expanding participant selection from the industry. A randomised approach will capture a realistic view of cultural change in new builds, informing strategies to reduce material usage and promote sustainability.

5 ACKNOWLEDGEMENTS

This research is being carried out under an EPSRC Doctoral Training Partnership Studentship.

REFERENCES

BBC. 2019a. "UK Parliament Declares Climate Change Emergency." BBC News. May 1, 2019. https://www.bbc.com/news/uk-politics-48126677.

———. 2019b. "Climate Change: Ireland Declares Climate Emergency," May 9, 2019. https://www.bbc.com/news/world-europe-48221080.

Blockley, David, and Patrick Godfrey. 2017. *Doing It Differently*. Second edi. ICE Publishing. https://doi.org/10.1680/DIDSE.60821.

Gibbons, O.P., J. Orr, C. Archer-Jones, W. Arnold, and D. Green. 2022. *How to Calculate Embodied Carbon*. 2nd ed. The Institute of Structural Engineers. www.istructe.org.

JBM. 2021. "Guidelines for Developing Degree Programmes (AHEP3)." *Joint Board of Moderators*.

Mauksch, Stefanie, Heiko A. von der Gracht, and Theodore J. Gordon. 2020. "Who Is an Expert for Foresight? A Review of Identification Methods." *Technological Forecasting and Social Change* 154 (May): 119982. https://doi.org/10.1016/J.TECHFORE.2020.119982.

Meadows, Donella H. 2008. *Thinking in Systems*. Edited by Diana Wright. London: Chelsea Green. https://www.bookdepository.com/Thinking-in-Systems-Donella-Meadows/9781603580557?redirected=true&utm_medium=Google&utm_campaign=Base1&utm_source=IE&utm_content=Thinking-in-Systems&selectCurrency=EUR&w=AFFPAU96903G8ZA8VTCS&gclid=EAIaIQobChMIvf_MlpbV9wIVzdPtCh2yoAixEAQYAiABEgK0qfD_BwE.

Moynihan, Muiris C., and Julian M. Allwood. 2014. "Utilization of Structural Steel in Buildings." *Proceedings of the Royal Society A* 470 (2168). https://doi.org/10.1098/RSPA.2014.0170.

Orr, J. 2018. "Minimising Energy in Construction (MEICON) - Survey of Structural Engineering Practice." https://www.meicon.net/survey2018.

Orr, J., M Cooke, T.J. Ibell, C Smith, N Watson, W Algaard, Arnold W, et al. 2021. *Design for Zero*. London: The Institute of Structural Engineers. https://doi.org/10.5694/j.1326-5377.1918.tb11464.x.

Rittel, Horst W.J., and Melvin M. Webber. 1973. "Dilemmas in a General Theory of Planning." *Policy Sciences* 4 (2): 155–69. https://doi.org/10.1007/BF01405730/METRICS.