Title: Engineering judgement in undergraduate structural design education: Enhancing learning with failure case studies

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Abstract

Universities face the challenge of developing undergraduate structural engineering students' design judgement. This study evaluates whether introducing 'learning from failure', centralised around 'real-world' case studies, will serve to facilitate the development of engineering judgement in structural design. The study identifies the usage of three characteristics of engineering judgement: diagnostic, inductive, and interpretive in the work of first-year undergraduate structural design students. A thematic data analysis approach, combined with a constant comparison method and the rigour of inter-researcher reliability was used to develop coding and mapping to evaluate students' work. The majority of students correctly applied diagnostic engineering judgement to the definition of a problem for a failure case study; and also displayed the inductive aspect of judgement. Students' interpretive understanding embraced multifaceted considerations, with engineering practice, complexity in causality, with learning from history being dominant. Introducing case studies deepened students' enquiry, acting to stimulate development of more nuanced understanding of structural engineering judgement.

Keywords: Engineering Judgement, Learning from Failure, Undergraduate Civil Engineering, Case Study, Structural Design Practice, Engineering Profession.

1.0 Introduction

Addis (1990), postulates that nature of structural design arises from a marriage of structural theory and practice. Theory embraces technical engineering knowledge which must be harnessed by judgement, through appropriate practice, to achieve satisfactory design outcomes. For some years, universities have sought to simulate this process intrinsic to professional practice in the structural design education delivered on undergraduate civil engineering programmes, with a view to shaping young engineers for anticipated industry challenges.

Zhou (2012) argues that 'engineering in practice' is difficult to define; it certainly embraces complex systems of uncertain heterogeneous interacting components including 'science, technology, economic, human and sociology'. To deal with such complex systems the ability to make creative judgements, despite uncertainty, is accepted more-or-less as an axiom in the engineering profession, as an attribute of the practicing engineer (Gunaratne, 1995; Jonassen *et al,* 2006; Kazerounan and Foley, 2007; Cowen, 2010). The tenants of uncertainty, complexity and constraint are never truer than in the discipline of structural engineering where design often has a bias towards bespoke solutions.

Within civil engineering undergraduate programmes, approaches to simulate design practice have generally focused on problem solving (Donald, 2011; Murray *et al, 2019;* Sheppard *et al,* 2008) and encouraging creativity (Lui and Schöwetter, 2004; Daly *et al,* 2014). McNeill *et al* (2016), researched students' beliefs around problem solving in the classroom. That study found that the expectation that known concepts relating to the curriculum of a module would be tested, combined with the presentation of problems in a written form, led to classroom based problems being viewed as simple and less constrained than workplace problems from the perspectives of the nine students interviewed. Arguably the framing of classroom design problems can lead to the narrowing of opportunity for students to make judgements autonomously. Daly *et al* (2014), studying seven engineering courses developed to foster cognitive creative skills to solve design problems, found a lack of evidence of the development of skills revealing relationships, or processes of elaboration and metaphorical thinking. Daly *et al*'s (2014) results suggest that those encouraging creative thinking in undergraduate civil engineering programmes must find new approaches to prompt deeper student enquiry, to synergise ideas and prompt innovative judgment.

Recently, professional papers prepared by authors stemming from industry have advocated that the education of civil engineering students should embrace learning from failure, centralised around 'real–world' case studies (Mottram, 2013; Love *et al*, 2013; Lewis, 2012). Petroski (2006) argues that successful design and failure are inherently intertwined. The former springing from the necessity to improve on the limitations/failures of former design attempts. Within professional engineering practice designs are refined; a process that occurs progressively through a process of 'conceptual growth' (Bornasal *et al,* 2018) as a design develops through key stages from concept to detailed design, fabrication, construction and finally operation. At each stage, practicing structural engineers will encounter design failures and setbacks which must be overcome.

A key requirement of engineering practice is therefore the acquisition of the cognitive ability to make appropriate and effective judgements in this environment. This research aims to explore whether judgement skills, here specifically in structural design, can be facilitated by the introduction of 'learning from failure' case studies into the structural design modules of the first year of an undergraduate civil engineering degree programme, through the thematic analysis of student coursework submissions.

2.0 Context

Defining Judgement

Structural design practice, was defined as early as 1956 by Nervi (1956 p 24), who stated that '*the mastering of structural knowledge is not synonymous with a knowledge of those mathematical development which today constitute the so-called theory of structures. It is a result of a physical understanding of the complex behaviour of a building, coupled with an intuitive interpretation of theoretical calculations*'. Theory and analysis as taught in universities become 'first principles' within the workplace, executed by engineering judgement to produce successful designs. Structural engineers employ these scientific approaches to make judgements about the future performance and behaviour of a structure: will the structure maintain its stability in the temporary or permanent case? Neither structural theory or analysis, or the results derived from their application, can be taken to be uniquely or objectively true. Interpretive judgement is required to make sense of the outcomes of both; one method of analysis might yield an acceptable factor of safety, but not the location of the 'critical members' which have fundamental importance in maintaining stability. Therefore, choices must be made concerning what type of accuracy is important and which analytical methods should be applied.

Judgement has been defined as having '*three fundamental attributes – it has a diagnostic character in problem definition, and inductive character in combination of evidence, and interpretative character in providing meaning and context to predictive conclusion'* (Vick, 2002:100). Examining this definition, it is furthermore apparent that judgement is a process, which occurs at key stages of structural engineers' practice of design. Judgement serves in the diagnostic forming of a hypothesis of how a structure will be behave. Inductive reasoning gathers data and selects theories and analytical methods that are applicable to the problem. These could be characteristics of the form of the structure, the loading conditions, the applicability of elastic or plastic analysis, or the properties of the ground. Finally, interpretive judgement contextualises the results with wider understandings and the intuition of experience.

The Case for Case-Histories

Khun (2012:43) sheds some light on how judgement is developed, stating that a conceptual framework or paradigm develops within a professional community centred on the problem-solving achievement of its theories. '*Close historic inspection of a given speciality at a given time discloses a set of recurrent and quasi-standard illustrations of various theories in their conceptual, observational and instrumental applications. These are the community's paradigms…'* The community's paradigm adds value to engineering practice, for example reducing technical uncertainties and leading to efficiencies in the use of human effort, materials energy and environmental disturbance (Trevelyan and Williams, 2019). Structural engineering practice has its own literature, chiefly case history publications encapsulated in accident reviews, consulting or contracting organisation ‘watch-it’ notes, and articles appearing in the magazines of professional bodies. These documents are subject to the peer-review scrutiny of the professional community, they serve to inform judgement in practice.

The case for considering failure case history in engineering education has been made by others (Love *et al*, 2013; Petroski, 1999; Alexander 1964). Petroski (1991:83) argues that the interpretive analysis of a design structure that has failed, by collapse, is accessible to all. Whether this be a full collapse of a building, a partial collapse of an element of a building for example an atrium, with accessibility is arguably made more synonymous and poignant where such collapse has led to human injury or loss of life. The judgement of structural error involves an intuitive and simple recognition of the ‘misfit’ between structural context and form, and as such offers a potential ‘stepping stone’ to understanding the fitness of a design to meet stated requirements: ‘*Engineering advances by proactive and reactive failure analysis, and thus at the heart of engineering method, is an understanding of failure in all its real and imagined manifestations’*. Whilst Alexander (1964:102) proposes that *‘we are never capable of stating a design problem except in terms of the errors we have observed.’*

The concept of case based learning is also not itself new, and it has been explored as an alternative to informative didactic delivery, with results confirming the relevance of the approach as a mechanism for increasing student engagement, attendance and fostering the relevance of real world problems (Yadav *et al,* 2010; Scherer and Landel, 1995; Fuchs, 1970; Hoag *et al,* 2005; Vesper and Adams, 1969; Raju and Sanker, 1999; Thurston, 1994). Case based instruction has also been recognised to support the development of problem-solving skills (Chinowsky and Robinson, 1997; Henderson *et al*, 1938). However, further work is still required to better understand the effectiveness of approaches that specifically mobilise case studies of failure, and the outcomes of their adoption on the manifestation of engineering judgement within educational contexts.

3.0 Research Design and Method

Theoretical Framework

Fundamentally, this work is grounded in a constructivist approach to learning, accepting that students construct new knowledge and understanding as they participate in lectures, seminars and assessments. More significant here is the positioning of engineering judgment as a critical aspect in the development of engineering design skills. It is suggested that developing students' understandings of engineering failure will in turn reinforce the foundations of their knowledge, and the position from which they can consequently apply engineering judgement to future practice.

The aim of this study to understand whether introducing 'learning from failure', centralised around 'real-world' case studies, serves to facilitate the use of engineering judgement in structural design among undergraduate students. We therefore ask the research question 'does the introduction of learning from failure real life case studies facilitate students' use of engineering judgement?' To answer this question, we look to the empirical space of a specific module on a UK undergraduate degree course, and its assessed coursework for our data. Analysis of this data will enable the identification and exploration of demonstrable uses of engineering judgement, independently and in combination, as part of these coursework submissions. This enables us to answer our research question both bluntly, in terms of yes or no, but also with nuance, as *how* this use manifests within the data is explored.

Due to the exploratory nature and methodological underpinning of the study, no claim is made to generalization, and we duly acknowledge the inherent limitations in our small sample size. However, we suggest there is both novelty and contribution in the way in which we have explored the different types of engineering judgement within student practice, and added a further facet to the conversation ongoing around learning from failure and how it can best inform and shape engineering education going forwards.

Empirical Context

Here, case-based learning is examined as introduced to a first year structural design module for civil engineering students, and which ultimately formed part of their module assessment. The students were enrolled on an undergraduate bachelor degree in civil engineering at a UK university. One of six first year engineering modules, 'Introduction to Structural Design' was undertaken over a full academic year. Students had three hours of direct instructional contact a week with the same academic tutor who had gained structural engineering experience in professional practice. Sessions were delivered in the format of a two-hour lecture and one-hour seminar, with an allocation of a further five hours and twenty minutes for self-study weekly. The learning aim of the module was to disseminate the foundational principles of structural design and the communication of design work. The cohort consisted primarily of direct school entrants aged eighteen, with a predominantly 90% to 10% male to female gender split. Within the first two weeks of their studies as an inaugural activity students were asked to autonomously research case histories of previous engineering failure within a peer group setting. At this stage in the academic year students had no experience of structural design. The cohort (n=60) formed into groups (n=15), and each group was provided with two case study project titles and the dates of the failures that had occurred by the lecturer. One project title was selected from a recent failure occurring in the last twenty years and the other an older project. Students were then asked to define the principal structural form and behaviour of the structure involved in the failure, thus mirroring the diagnostic element of engineering judgement. Furthermore, they evaluated the project against various themes of failure as given in Table 1 (a topic on which lectures were also provided), thereby requiring the students to use inductive reasoning, considered the second aspect of engineering judgement, to assess the engineering parameters of the case history project. Finally, the students were asked to interpret the outcomes of the evaluated themes and to determine the key lessons to be learned from the failure, and whether the project could be considered ‘good design’.

Uncertainty in Loading	Failure to Understand Materials	Errors in Design or Detailing	Human Factors	System Failures	Safety Culture
Extension of Technology to an Invalid Extent	Failure to Identify the Hazard	Deterioration and Lack of Maintenance	Design Change	Robustness	Competence and Quality
Fatigue Loading	Errors in Dynamics	Identifying Significant Risks	Temporary Works and Construction Failure	Mobile Structures	Novel Design
Uncertainty in Extreme Loading	Errors in Stability	Demolition	Inadequate Procedures	Failure to Learn From Previous	Failure to Understand the Structure.

				Incidents	

Table 1: Matrix of possible types of structural project failure (after the Institution of Structural Engineers 2013)

Data Collection

The data used for the study were the student's group assessment submissions (n=15 groups) for the module. These were in the form of a poster presentation in which each group set out their analysis of two distinct failure case studies. This resulted in n=28 case studies for analysis as one group combined their two case studies into one, and one group only provided one case study within their submission.

Analytical Framework

Evaluation of the students' knowledge and understanding has here been explored through the three aspects of engineering judgement found within their assessment submissions, revealed by the ways in which they presented their research of specific case-history failure. This approach is summarized in Table 2.

Aspect of Engineering Judgement	**As evidenced by**	**Examined by**
Diagnostic	Problem definition	Content and thematic analysis
Inductive	Themes of failure. Combinations of evidence for failure	Content and thematic analysis
Interpretive	Context and Influences on the design failure	Thematic analysis of the assessments as a whole

	Lessons Learnt	

Table 2: Approach to the analysis of the three aspects of engineering judgement (after Vick 2002)

As noted in the final column of Table 2, this study adopts both content and thematic analysis in its approach to the data, informed by a wider constructivist methodology. For the first aspect of engineering judgement, content analysis was applied to reveal how the students defined the problem itself (the diagnostic aspect). More nuanced thematic analysis was then used to reveal how they brought together different evidence in the forms of the 'themes of failure' to support this positioning (the inductive aspect). Patterns were revealed by this analysis through an inclusive coding process, which was also able to reveal their relative prominence and relationships within the data as a whole. The final aspect of engineering judgement, the interpretive aspect, was explored through a thematic approach that looked to the data as a whole, able to illuminate and present the *ways* (as distinct from the content) in which the students positioned and understood failure within wider engineering contexts. In mobilizing these different approaches to qualitative data analysis in these complementary ways, we can determine the use of engineering judgement in practice whilst also revealing how it has been used by the students.

Data Analysis

Content and thematic analysis was used to explore the text and images found within the students' group poster presentations. A data-driven coding process was used to ensure the approach was as inclusive as possible, to allow major themes and interpretations as associated with engineering failure to be identified.

To provide inter-rater reliability in this subjective process, two researchers coded the data independently, in order to explore the patterns of use with regards to the ways in which the students defined the problems, and drew on combinations of evidence for failure. The coding was initially framed through the aspects of engineering judgement as in Table 2, with sub-codes generated by the data itself, as specific to each case study. Once the coding process had been undertaken independently, the two coding matrices were shared, discussed and ultimately combined.

For the diagnostic aspect of engineering judgement, content analysis was used to initially determine their delivery of the criteria as required by the marking scheme, but also the patterns found within the data as a whole. This relatively simple analysis was also retrospectively checked against the formal marking of the assessments (undertaken prior to this study), and was found to correlate precisely.

For the inductive aspect, more complex coding naturally emerged and the subsequent discussion process between the researchers distilled the codes into a manageable number of inclusive categories, with relevance to both engineering judgement and the wider context of construction, whilst retaining the finer-grained analysis beneath. This approach necessitated drawing on the experience and knowledge of the two researchers, one of whom is a Chartered Structural Engineer and the other a Chartered Construction Manager, to enhance validity. For example, the code of 'excessive working hours' was included within the category of 'management', as was the 'lack of a clear reporting structure on the site', whilst a 'lack of connection detailing' was included within the category of 'design'. This approach reveals the dominance of particular patterns and associations as linked to both the diagnostic and inductive elements of engineering judgment. The appropriate allocation of sub-codes to the higher level categories was consequently able to provide a determination of ‘quantification’ within the data to enable evaluation of student judgement, as well as an evaluation of its depth and complexity.

To reveal the interpretive aspect of engineering judgement through the context and influences on failure, a less structured approach was used. This involved the development of detailed notations on copies of the posters themselves, which over time supported the development of a ‘mapping’ of the dominant themes, again developed first independently and then collaboratively by the researchers. These themes, once crystalized within the mapping, were reconsidered within a holistic interrogation of the data which focused on patterns of consistency and inconsistency, variations, emerging themes or representations, and patterns of nuance, contradiction and repetition (Wildemuth 2016). Again, a flexible approach allowed for the dominant themes as labelled by the researchers to emerge or disappear as the process continued.

Throughout both analyses, a constant comparison method (Silverman 2001) was used, with evaluation both within and between the data sources part of an ongoing process which led to the development or collapse of the coding framework/mapping over time. Consequently, multiple and repeated passes were made of the data, developing a high level of individual researcher confidence in its processing, but also enhancing the validity and accuracy of the findings as they emerged, as supported by the use of inter-rater reliability. Systematic investigation is essential to ensure rigor within the analytical process (Taylor 2001), and although thematic analysis is an interpretive process, and the researchers’ skill (and in this instance their own professional knowledge and judgement) in the identification of patterns and variations is itself critical (Potter and Wetherell 1992).

Results are presented here in a narrative form. Where examples are used they are representational of the wider data as a whole. This approach has been taken in large part to reflect the exploratory nature of this work, and thus to tell the story of our findings, rather than present quantitative analyses, for example, that would lack validity given the small sample size.

4.0 Results

4.1 The Diagnostic Element of Engineering Judgement

Analysis of the diagnostic element of engineering judgement revealed how students defined the case study failure event. Benchmarked against the assessment criteria 'to define the principal structural form and behavior of the structure involved in the failure', findings showed that over half (n=19) of the case studies submitted, the students correctly applied diagnostic engineering judgement in their definition of the problem. For example, the group presenting the Charles De Gaulle Airport roof failure in 2004 noted that there were:

> *'signs of deformation that continued until the collapse… a result of creep and shrinkage in the concrete' [and that] 'cracks had developed where the footbridges were fixed…cut into the concrete shell [which] severely weakened the structure'*

identifying the behaviour of the structure that led to the collapse, alongside further consideration of the causes and consequences of that behaviour.

Where students did not achieve this, the analysis showed that in all cases the students explication of the case studies was descriptive not analytical, and they presented their research as the 'story' of the case study without further evaluation or a stated problem definition, despite the explicit inclusion of this element within the marking scheme for the assessment. For example, in their consideration of the Can Tho bridge collapse, the group noted that:

> *'…a section of the approach ramp collapsed from over 30 meters in the air over an island in the river…after 8 months the investigation revealed a number of factors that may have caused the disaster:…'*

With these factors then simply listed in the poster text. However, this list was that published following the formal investigation, and lacked any additional analysis from engineering perspectives by the students, with reference to the principal structural form and its behaviour during the failure. It should be noted here that three of the groups failed to achieve the demonstration of diagnostic engineering judgement in both of their case studies, whilst the other three groups only lacked this element within one of their submitted case studies, meaning from a cohort perspective the majority of the groups demonstrated this aspect of engineering judgement within at least one aspect of their submitted work.

4.2 The Inductive Element of Engineering Judgement

Analysis of the themes of failure codes and the patterns of their use in terms of complexity and combination enabled evaluation of the inductive element of engineering judgement, exploring how the students positioned the case study within the wider scope of engineering failure. The data ultimately generated five codes for the different themes of failure used within this diagnostic element: Design, Management, Loading, Materials and Profit. For coding to be assigned, the students were deemed to have clearly articulated this activity appropriately within their poster submission, and positioned it as a causal factor for failure within the case study. The analysis showed that in all of the case studies the students had identified and explicated at least one appropriate theme of failure, as found in Table 3.

Theme of Failure	Example
Management	'*The tie system failed mainly at the lugs. This fault was also due to poor management by Bouch as he didn't specify well enough if he wanted the holes drilled or not so the metal work company used the cheaper option which subsequently had two thirds of the strength he calculated'*
Design	'*The Heron Bridge was designed as a determinate structure. It was constructed with a balanced cantilever design. The intermediate spans were comprised of two cantilever sections, as well as there being a simply suspended beam*'
Loading	*'Wind speeds were calculated over an average of a one-minute period and the engineers did not consider that the structure may be vulnerable to strong short gusts. The safety factor had not covered the uncertainties in the variable action due to the wind.'*
Profit	'*The store's owner, Joon replaced the original contractor,*

	Woosung Construction, as their employees tried to inform Joon the modifications he wished to put in place would put far too much strain on the structure's supports. Joon then dismissed the company, replacing them with his own construction company (Sampoong Construction) to finish the construction of the building. The design modifications were illegal'
Materials	*'Concrete typically is considered to be at its full strength after 28 days however lift 28 had been in position for less than 24 hours before it was loaded. This may have resulted in the compressive strength being far too low and contributing to the collapse'*

Table 3: Inductive Engineering Judgement: Empirical Examples of the Themes of Failure

The students also demonstrated a multiplicity of themes within their analysis. In the majority of the case studies, n=22 or 79%, the students had drawn on more than one theme of failure within their assessments, bringing them together in a synthesis of the evidence (Vick 2002) thus demonstrating the inductive aspect of engineering judgement. Within the majority of the case studies where inductive engineering judgement was exercised, the students actually mobilised between 2 and 5 themes (n=14 or 64%), and in over one-third they drew on more than 5 (n=8 or 36%).

The two most frequently mobilised themes were those of Management (51 instances in total) and Design (29 instances in total), arguably reflecting the realities of structural failure within civil engineering, which readily result from a combination of design and site management issues. However, this can also in part be explained by the finer-grade analysis and sub-codes that sit behind these themes of failure. This analysis was able to reveal how the students demonstrated their awareness and understanding of the different aspects of the practices of Management and Design, adding depth and detail to the inductive aspects of their engineering judgement. For example, within the Newport Docks case study Management was underpinned by the three sub-codes below, with quotes from the text also included for illustration:

(i) project blame culture: "*Workers were concerned about reporting possible dangers…as they could have lost their jobs"*

(ii) reporting issues: *"the lack of a defined route of action for the walking ganger to take upon receiving reports of movement…"*

(iii) drive for profit: *"the wealth increase in import and trade suggested the people were more driven to expand the docks, arguably this lessened their attention to detail in design and implementation."*

Whilst on the Tay Bridge case study Design was underpinned by four sub-codes:

(i) inaccuracy in loading calculations: *"the design was well known…but these structures didn't face the same forces that a railway bridge would…"*

(ii) a lack of design experience and knowledge: *"Bouch had not assessed the new loads on the bridge so that the strength of the bridge could be adjusted subsequently."*

(iii) inaccuracy during changes to the original design: *"reduced the number of piers making the spans of the superstructure girders much longer…without taking into account wind loadings"*

(iv) under specification of connection details: *"Bouch didn't specify well enough if he wanted the holes drilled or not, so the metalwork company*

used the cheaper option which subsequently had two-thirds of the strength calculated."

It must be noted that the complexities of this judgement were naturally dependent on the bespoke nature of the case studies themselves, and thus not all case studies can generate equal levels of complexity behind their failures, hence no further analysis of the strengths or details of these relationships has been carried out, and we have refrained from more detailed quantitative analyses here. However, this does suggest that use of failure case studies is to some extent effective in facilitating students to develop their diagnostic engineering judgement, considering, analysing and combining a number of factors and different sources of evidence from their case studies, and this is unpacked further in the following section.

4.3 The Interpretive Element of Engineering Judgement

By mobilising thematic analysis in a way that encompassed the data as a whole, taking a broader and more holistic point of departure for the coding process, the students' interpretive understandings of the wider contexts of failure were explored. This approach was able to provide broader insights from the ways in which the students drew upon and positioned various influences, including those revealed through the previous analysis, within their case study assessments. Building upon the foundations of diagnostic and inductive judgement, this analysis sought to illuminate the contextualisation and 'meaning' the students then presented for case study projects – the reasons why things went wrong.

The dominant themes that emerged from this part of the data analysis were: engineering practice; causality; and learning from history.

Engineering Practice – 'The design was wrong'

Perhaps unsurprisingly, prominent within the data surrounding the case-history failures was a theme of 'engineering practice', closely associated with the two themes of failure of Management and Design. This engineering practice theme drew on a professional context from both structural engineering and construction management activities and mobilised them through practical and tangible examples as contributory 'factors' of failure. This was also often associated with blame, at times even directed at specific individuals such as the engineers who led the projects, and responsibility for the failures positioned as either a consequence of individual poor practice or in the mismanagement of subordinates. As highlighted above in the Tay Bridge case study, the students were quick to judge the lead engineer personally, stating that *"poor workmanship and management from Thomas Bouch had allowed corners to be cut…"* The need for experience, training and qualification in order to make engineering judgements was prominent within the data, again often closely associated with assigned ownership of the decisions that led to the failure. For example, in the case of the Barton Bridge case study, the students highlighted that the *"tower designer was a 24 year old draughtsman at the scaffolding company with no formal qualifications",* whilst in the case of the Quebec Bridge, that the lead engineer delegated site management to another who *"was not up to the task of supervising the construction on site due to previously being a desk engineer"*

This multi-faceted theme drew on a language of calculations, stresses, loads, stability, geotechnical knowledge, restraints and detailing to develop highly technical design discussions, able to generate relatively simple cause and effect pathways to the failure itself, as one student group summarised quite simply:

'the design was wrong'

And by logical extension, so was the designer(s). A further consideration was the positioning of rigour in the processes of engineering as a contributory factor to support the technical aspects of practice. The need for checks, approvals and appraisals of design, both initially and after any project or design change, was frequently positioned as a potential point of failure by the students, adding further aspects of professionalism and 'good practice' to the wider theme of engineering practice. In the case of Barton Bridge, the students noted that *"...such operations should not take place without the approval of a structural engineer."*

Causality: 'No single fault'

Alongside the theme of engineering practice, other themes were identifiable that positioned this technical engineering discourse within a more practice-based, real-world context. Dominant here was the consideration that causality was and is itself complex, countering the relatively simplistic allocation of failure to design 'fault' and instead developing more nuanced understandings of failure as a complex and multi-faceted 'thing', in and of itself. This theme was very much connected to the inductive aspect of engineering judgement, where students first realised the variation and nuance in the evidence, linked back further to the failure itself as diagnosed through the problem definition. The prominence of this theme within the data therefore suggests that interpretive judgement is itself facilitated and strengthened by the outcomes of first diagnostic then inductive judgements.

Although student ability to explore and unpack such complexities varied, this theme could be found in some form within all the case studies, drawing on ‘a combination of errors’ to illuminate the various ‘factors’ that created such complex causality in practice. For example, the students examining the West Gate Bridge case study concluded that *“the failure of the bridge was down to uncertainty in extreme loading which led to serviceability and elastic instability failures. Those on the other hand were caused by the unusual method of construction…”*

This theme of complexity in causality mobilised two key strands for its development: the consideration of aspects associated with construction management and aspects associated with construction practice, as identified within the wider themes of failure. As with the sub-themes found within the inductive theme of Management, here production pressures in the form of time and money as contributory factors to failure were identifiable sub-themes, as well as procurement routes, client decisions, project change, subcontracting, contractual arrangement and other more intangible aspects, such as project prestige. For example, several of these could be identified in the Tacoma Narrows Bridge case study, for which the students noted: *“social demands…economic need…cost savings”* as drivers within the project, but also aspects of poor construction practice, notably *“the seals were damaged when the bridge was sand-blasted before being painted so the effectiveness of the hydraulic dampers was nullified”*.

The influence of such aspects on engineering practice, including specifically that of engineering design in the form of ‘value engineering’, could be found throughout the data. Failure within this theme becomes a consequence of (often commercial) practice, as draw on by the students in their understandings of failure within the wider construction industry context.

Construction practice more specifically focused on the site itself and was utilised by students to bring considerations of site conditions, workforce competency, material quality, and the influence of proceeding and subsequent trades to their understandings of failure in practice. For example, in the Cần Thơ bridge case study, the students explicitly noted the *"…contractor had decided to cut costs by not using the correct number of supports per bridge section and removing them before the concrete had cured."* Within both sub-themes, the understanding of construction team coherence and good communication was also prominent, particularly in case-histories where early warnings of failure were evidenced, yet unacted upon.

Interestingly, both of these themes were also frequently interwoven with notions of blame and responsibility for the failure. In some instances, blame was also allocated by students onto those outside of the engineering profession, for example it was associated with 'poor workmanship', 'poor leadership', or with other named parties in the project, such as subcontractors or fabricators, as well as those responsible for the design.

However, this segregation of engineering and construction practice also at times led to the development of a schism between the themes, which, instead of acknowledging the role of complexity within the causes of failure, sought to other blame away from engineering practice and design. For example, in the case of the Almuñécar Falsework collapse, despite the students stating that: *'load transfers that needed to occur during construction were difficult'* they then only included discussion of construction management and construction practice failure, opting out of wider considerations of multiple causality and with no recourse to engineering practice. In the Almuñécar case, the students swiftly moved to *"failure of workmanship"* and focused on the construction processes. Such disassociation was however actually very limited within the data, and only four instances of such positions were identified within the data as a whole.

Learning from History?

An interest shift in the students' analysis and demonstrations of interpretive judgement occurred depending on the age of the failure case-history. For older projects (notably pre-2000) students' mobilised a more 'dismissive' attitude to the failure, suggesting that such actions and consequences would simply not happen within contemporary construction operations. However, this was itself countered by a identifiable theme of 'surprise' when the failures were found in more recent case-histories. As one student group noted:

> *[it was] 'a surprise that the [company name] were responsible for such big failures'.*

This is a welcome understanding to emerge from this analysis. That the use of real life case studies has created the space for students to learn that all engineering design, be it historic or contemporary, is vulnerable to failure in practice.

5.0 Discussion and Implications for Teaching Practice

Overall, the findings from this study support suggestions made by others (e.g. Love *et al*, 2013; Petroski, 1999; Alexander 1964) that the use of failure case studies could be beneficial for engineering students, and here more specifically the manifestation of engineering judgement skills within undergraduate students. The diagnostic, inductive and interpretive elements of design judgement (Vick 2002) were all identifiable within the analysis, further indicating that this approach would support Daly et al's (2014) call for new approaches to prompt deeper student enquiry, to synergise ideas and prompt innovative judgment. Specifically, 69% of the posters demonstrated diagnostic judgement, 64% inductive judgement and the emergence of three dominant themes with further associated complexity and depth, indicates the presence of interpretive judgement.

The diagnostic element of engineering judgement was explicitly requested in the assessment criteria for this submission, and as such should have been responded to directly by the students. This initial step in the analytical process is critical in supporting more sophisticated applications of engineering judgement, yet in some case students did not specifically focus on this element, describing rather than analysing the engineering failures in the cases. This could be a potential issue with the use of case studies, which always contain a descriptive 'story to tell', and indeed a detailed and chronological description of the case study (even if not presented explicitly in the submission) should be undertaken prior to the application of engineering judgement to ensure all facts and evidence associated can be collated and reviewed as part of this process. However, the fundamental difference between description and analysis can be a problematic distinction for first year students to make, and the relative ease with which the case study stories could be told could have blurred the line between description and analysis, as perceived by the students. It was this ultimate analytical step that was missing from some of the submitted work, and it is suggested that clearer direction within the brief to that end could resolve this issue. However, despite such concerns, the majority of the students did undertake such analysis and so successfully demonstrated the diagnostic element of engineering judgement within their submitted case studies.

The use of case studies has been recommended as a valuable approach in terms of learning from failure (e.g Mottram, 2013; Love *et al*, 2013; Lewis, 2012).. This study further supports this notion, also finding them to be beneficial in enabling the students to identify and analyse the themes of failure found therein. More specifically, and perhaps more importantly, this study found that the use of case studies also provided the students with a rich context for them to unpack and consider, with regards to the potential combinations and interactions of evidence that contributed to such failure. Whilst all students successfully applied this inductive element of engineering judgement in the analysis of at least one theme of failure within their case study, the majority brought together more than one theme in their analysis, suggesting that this use of case studies was able to support, if not encourage, enhanced evaluations of failure, drawing on the inductive element of engineering judgement to combine themes as appropriate. This has implications for the case studies used, and these should be selected to optimise the complexity that surrounded the failure, and thus provide students with the opportunity to enhance and optimise their learning through the assessment process. It also recommended that a combination of historical and contemporary case studies are used, to ensure students can both appreciate the developments in the industry that have been undertaken for the better (such as those around workplace and labour conditions), but also a realisation that such factors have long shadows and traditional ways of working (such as lowest cost tendering) do still hold influence in contemporary construction activities, avoiding complacency in that regard.

The prominence of the failure themes of ‘Management’ and ‘Design’ within the inductive judgement displayed by the students, in both the single root cause analysis and within the more complex analyses of failure, is promising as it reflects the critical role played by engineers as both managers and designers, and thus acknowledgement of the consequences of a lack within either for engineering failure. The use of a variety of combinations of other themes and sub-themes alongside Management and Design within this aspect of engineering judgement was also promising, reflecting deeper and more nuanced analysis by the students as they unpacked the more complex case studies.

The appreciation and understanding of complexity carried through to the findings focused on the interpretive element of engineering judgement, as the dominant themes within the work also reflected the wider activities and factors that, through combinations of errors or failures, resulted in the case study failure itself. This aspect of engineering judgement built upon the appropriate exercise of diagnostic and inductive judgements, which in turn combine and support the application of interpretive judgement both specifically and more broadly.

The students' work showed understanding of the interrelationships between structural engineering practice and Management (both professional and site), thus situating their own role and associated responsibilities (Design) appropriately within wider industry practice and enhancing the associated learning. This is important for practice, given the need for designers to fully appreciate the close relationships between design and construction and therefore use their structural design judgement appropriately, duly cognisant of the potential consequences for practice. The use of blame allocation for failure by the students was also interesting, demonstrating a reductionist analysis of the overall failure to those at fault, whist also reinforcing the role of the professional engineer and their responsibilities in practice. Taken together, this suggests the use of case studies actually enhances the exercise of interpretive engineering judgement through this assessment, as students naturally developed a narrative able to support specific lessons learnt (Vick 2002) from each failure case study.

Without the use of case studies, it is arguable that the depth and nuance found here within the students' assessments (and thus learning through assessment) would be much harder to achieve. Classroom based problems are often more simple than workplace problems (McNeill *et al* 2016), inevitably limiting the learning potential therein. For example, findings show that in this study the use of specifically selected case studies enabled the students to better appreciate and analyse the impact of perceived 'non-engineering' considerations, such as site management or profit prioritisation, on engineering practice, and more importantly how they had impact. As the influence of such factors for failure can be significant, this is arguably a vital learning essential in helping student develop a deeper structural engineering judgement, able to find resonance and relevance with real-life situations and the actual environment of engineering practice.

7.0 Conclusions

This research aimed to explore whether the development of judgement skills in structural design could be facilitated by the introduction of 'learning from failure' case studies into the structural design modules of the first year of an undergraduate civil engineering degree programme. Analysis of the students' group assessment submissions found that their use of case studies demonstrated all three aspects of engineering judgement: diagnostic, inductive and interpretive. In addition, the way in which diagnostic and inductive judgement subsequently informs and supports the exercise of interpretive judgement within this context is also worthy of note.

Further work is required to refine this approach, and to determine which types of case study are able to maximise student familiarisation with, understanding of and ability to adopt the different elements of engineering judgement. The strengths and weaknesses of this approach, as compared to other methods, should also be explored through comparative control group analyses to enable the development of an optimal approach to the teaching analytical skills to students and thus optimise the development of their structural design judgement throughout their courses as a whole. It is also accepted that engineering judgement is not constrained to structural design, and thus this work can inform other aspects of engineering education where judgement is also necessary and can be informed by learning from failure, for example in the consideration of ethics within engineering.

References

Addis, W. (1990) 'Structural Engineering: The Nature and Theory of Design' Ellis Horwood: Chichester. ISBN-100138506116

Alexander, J. (1964) Notes on the Synthesis of Form, Harvard University Press, Cambridge. ISBN-109780674627512

Bornasal, F., Brown, S., Perova-Mello, N., Beddoes, K. (2018) Conceptual Growth in Engineering Practice, Journal of Engineering Education, 107 (2) pp 318-348 https://doi.org/10.1002/jee.20196

Cowan, J. (2010) ‘Developing the ability for making evaluative judgements’, Teaching in Higher Education, 15 (3), pp. 323 to 334. https://doi.org/10.1080/13562510903560036

Chinowsky, P.S, Robinson, J. (1997) ‘Enhancing Civil Engineering Education Through Case Studies’, Journal of Engineering Education, 86 (1) pp 45 to 49 https://doi.org/10.1002/j.2168-9830.1997.tb00264.x

Daly, R.D, Mosyjowski, E.A., Seifert, C.M. (2014) ‘Teaching Creativity in Engineering Courses’, Journal of Engineering Education, 103 (3) pp 417 to 449 https://doi.org/10.1002/jee.20048

Donald, J.G (2011) ‘Learning to Think: Disciplinary Perspectives’ Jossey-Bass: San Fransisco, ISBN-109780787910327

Fuchs, H.O (1970) ‘Outside reality inside the classroom’, Journal of Engineering Education, 69 (7) pp 745 to 747

Gunaratne, M., (1995) Integrating Professional Experience in Geotechnical Class Designs, Journal of Engineering Education. 84 (2) pp 117-119 https://doi.org/10.1002/j.2168-9830.1995.tb00157.x

Hoag, K., Lillie, J., Hoppe, R (2005) ‘Piloting case-based instruction in a didactic clinical immunology course.’ Clinical Laboratory Science 18 (4) pp 213 to 220

[Online] Available at: https://www.ncbi.nlm.nih.gov/pubmed/16315738 (Accessed 2nd May 2020)

Henderson, J.M., Bellman, L.E., Furman, B.J (1983) ‘A case for teaching engineering with cases’, Engineering Education, 73 (4) pp 288 to 292

Institution of Structural Engineers (2013) ‘Risk in structural engineering’, Institution of Structural Engineers, London. ISBN - 9781906335083

Jonassen, D., Strobel, J. Lee, C.B., (2006) ‘Everyday Problem Solving in Engineering: Lessons for Engineering Educators’. Journal of Engineering Education, 95 (2) pp 139 to 151 https://doi.org/10.1002/j.2168-9830.2006.tb00885.x

Kazerounain, K. and Foley, S. (2007) ‘Barriers to creativity in engineering education: a study of instructors and student perceptions.’ Journal of Mechanical Design, 129, pp. 761 to 768. https://doi.org/10.1115/1.2739569

Khun (2012) ‘The Structure of Scientific Revolution’ 50th Anniversary Edition, The University of Chicago Press: Chicago. ISBN-100226458121

Lewis, W.J (2012) ‘The question of structural form: educational aspects.’ Civil Engineering Proceedings – Forensic Engineering 165 (3), pp.103 https://doi.org/10.1680/feng.11.00029

Love, P.E.D. Lopez, R. Edward (2013) ‘Reviewing the past to learn in the future: making sense of design errors and failure in construction’ Structure and Infrastructure

Engineers, Maintenance, Management Life Cycle Design and Performance, 9 (7) pp. 675 to 688. https://doi.org/10.1080/15732479.2011.605369

Lui, Z. Schöwetter D.J. (2004) 'Teaching creativity in engineering' International Journal of Engineering Education, 20 (5), p 801 to p808. [Online] Available at: https://www.ijee.ie/articles/Vol20-5/IJEE1511.pdf (Accessed 2nd May 2020)

Nervi, P.L (1956), 'Structures' F.W.Dodge Corporation: New York ISBN-100070462704

McNeill, N.J., Douglas, E.P, Koro-Ljungberg, M., Therriault, D.J., Krause, I. (2016) 'Undergraduate Students' Beliefs about Engineering Problem Solving' Journal of Engineering Education 105 (4) pp 560 to 584 https://doi.org/10.1002/jee.20150

Mottram, T. (2013) 'The importance of teaching civil engineers about learning from failure' Civil Engineering Proceedings 166 (3), pp103 https://doi.org/10.1680/cien.2013.166.3.103

Murray, J.K., Studer, J.A., Daly, S.R., McKilligan, S., Seifert, C.M., (2019) 'Design by taking perspectives: How engineers explore problems' Journal of Engineering Education. 108 (2) pp 248 to 275 https://doi.org/10.1002/jee.20263

Peräkylä, A. (2005) ‘Analysing Talk and Text.’ In: N.K. Denzin and Y.S. Lincoln (eds.) The Sage Handbook of Qualitative Research. 3rd ed. London: Sage Publications Limited, pp. 869-886 [Online] Available at: https://psycnet.apa.org/record/2005-07735-034 (Accessed 2nd May 2020)

Petroski, H (1991) ‘Human Error and the Case for Case Histories in Design’, Journal of Engineering Design 2 (1) 1991 pp 81 to 88 https://doi.org/10.1080/09544829108901672

Petroski, H. (2006) ‘Success Through Failure the Paradox of Design’, Woodstock: Princeton University Press ISBN-109780691180991

Raju, P.K., Sankar, C.S (1999) ‘Teaching real-world issues through case studies’, Journal of Engineering Education, 88 (4) p375 to 381 https://doi.org/10.1002/j.2168-9830.1999.tb00479.x

Scherer, W.T., Landel, R.D (1995) ‘Promoting Active Learning with Cases and Instructional Modules’. Journal of Engineering Education. 84 (4) pp 375 to 381 https://doi.org/10.1002/j.2168-9830.1995.tb00193.x

Sheppard S.D., Macatangay, K., Colby, A., Sullivan, W.M. (2009) ‘Educating Engineers: Designing for the Future of the Field’. Jossey-Bass: San Francisco [Online] Available at https://eric.ed.gov/?id=ED504076 (Accessed 2nd May 2020)

Silverman, D. (2001) Interpreting Qualitative Data: Methods for analysing talk, text and interaction. 2nd ed. London: Sage Publications Limited ISBN-101412922453

Trevelyan, J., Williams, B. (2019). 'Value creation in the engineering enterprise: an educational perspective.' European Journal of Engineering Education, 44 (4) pp 461-483 https://doi.org/10.1080/03043797.2017.1421905

Thurston, H M (1994) 'Influential Structural Engineers: A project in a Third-year Structural Analysis Course'. Journal of Engineering Education. 83 (2) pp 156 to 160 https://doi.org/10.1002/j.2168-9830.1994.tb01096.x

Vesper, K.H., Adams, J.L (1969) 'Evaluating learning from the case method' Engineering Education 60 (2) pp 104 to 106

Vicks, S.G (2002) 'Degrees of Belief: Subjective Probability and Engineering Judgement'. American Society of Civil Engineers: USA ISBN-100784405980

Yadav, A., Shaver, G.M., Meckle, P (2010) 'Lessons Learned: Implementing the Case Teaching Method in a Mechanical Engineering Courses' Journal of Engineering Education pp 55 to 69 https://doi.org/10.1002/j.2168-9830.2010.tb01042.x

Weatherell, M., Taylor, S., and Yates S.J. (2001). Discourse as Data: A Guide for Analysis. Sage Publications Limited in association with the Open University, London, UK. ISBN 9780761971580

Wiggins, S. and Potter, J. (2007). Discursive Psychology. The Sage Handbook of Qualitative Research in Psychology, C. Willig and W. Stainton-Rogers, eds., Sage Publications Limited, London, UK, 73-90. https://dx.doi.org/10.4135/9781848607927.n5

Wildemuth, B.M. (2016). Applications of Social Research Methods to Questions in Information and Library Science, Libraries Unlimited, Santa Barbara. ISBN 9781440839047

Zhou, C. (2012) ‘Fostering creative engineers: a key to face the complexity of engineering practice’, European Journal of Engineering Education, 37 (4), pp. 343 to 353. https://doi.org/10.1080/03043797.2012.691872