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Citation: Edmondson, Vikki and Sheratt, Fred (2022) Engineering judgement in undergraduate structural design education: Enhancing learning with failure case studies. *European Journal of Engineering Education*, 47 (4). pp. 577-590. ISSN 0304-3797

Published by: Taylor & Francis

URL: <https://doi.org/10.1080/03043797.2022.2036704>
<<https://doi.org/10.1080/03043797.2022.2036704>>

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**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 **1.0 Introduction**

2

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

10

11 Zhou (2012) argues that ‘engineering in practice’ is difficult to define; it certainly
12 embraces complex systems of uncertain heterogeneous interacting components
13 including ‘science, technology, economic, human and sociology’. To deal with such
14 complex systems the ability to make creative judgements, despite uncertainty, is
15 accepted more-or-less as an axiom in the engineering profession, as an attribute of the
16 practicing engineer (Gunaratne, 1995; Jonassen *et al*, 2006; Kazerounan and Foley,
17 2007; Cowen, 2010). The tenants of uncertainty, complexity and constraint are never
18 truer than in the discipline of structural engineering where design often has a bias
19 towards bespoke solutions.

20

21 Within civil engineering undergraduate programmes, approaches to simulate design
22 practice have generally focused on problem solving (Donald, 2011; Murray *et al*, 2019;
23 Sheppard *et al*, 2008) and encouraging creativity (Lui and Schöwetter, 2004; Daly *et al*,
24 2014). McNeill *et al* (2016), researched students’ beliefs around problem solving in the
25 classroom. That study found that the expectation that known concepts relating to the

26 curriculum of a module would be tested, combined with the presentation of problems in
27 a written form, led to classroom based problems being viewed as simple and less
28 constrained than workplace problems from the perspectives of the nine students
29 interviewed. Arguably the framing of classroom design problems can lead to the
30 narrowing of opportunity for students to make judgements autonomously. Daly *et al*
31 (2014), studying seven engineering courses developed to foster cognitive creative skills
32 to solve design problems, found a lack of evidence of the development of skills
33 revealing relationships, or processes of elaboration and metaphorical thinking. Daly *et*
34 *al*'s (2014) results suggest that those encouraging creative thinking in undergraduate
35 civil engineering programmes must find new approaches to prompt deeper student
36 enquiry, to synergise ideas and prompt innovative judgment.

37

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

49

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

56

57 **2.0 Context**

58

59 *Defining Judgement*

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

74 concerning what type of accuracy is important and which analytical methods should be
75 applied.

76

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

88

89 *The Case for Case-Histories*

90 Khun (2012:43) sheds some light on how judgement is developed, stating that a
91 conceptual framework or paradigm develops within a professional community centred
92 on the problem-solving achievement of its theories. '*Close historic inspection of a given*
93 *speciality at a given time discloses a set of recurrent and quasi-standard illustrations of*
94 *various theories in their conceptual, observational and instrumental applications. These*
95 *are the community's paradigms...*' The community's paradigm adds value to
96 engineering practice, for example reducing technical uncertainties and leading to
97 efficiencies in the use of human effort, materials energy and environmental disturbance
98 (Trevelyan and Williams, 2019). Structural engineering practice has its own literature,

99 chiefly case history publications encapsulated in accident reviews, consulting or
100 contracting organisation ‘watch-it’ notes, and articles appearing in the magazines of
101 professional bodies. These documents are subject to the peer-review scrutiny of the
102 professional community, they serve to inform judgement in practice.

103

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

117

118 The concept of case based learning is also not itself new, and it has been explored as an
119 alternative to informative didactic delivery, with results confirming the relevance of the
120 approach as a mechanism for increasing student engagement, attendance and fostering
121 the relevance of real world problems (Yadav *et al*, 2010; Scherer and Landel, 1995;
122 Fuchs, 1970; Hoag *et al*, 2005; Vesper and Adams, 1969; Raju and Sanker, 1999;
123 Thurston, 1994). Case based instruction has also been recognised to support the

124 development of problem-solving skills (Chinowsky and Robinson, 1997; Henderson *et*
125 *al*, 1938). However, further work is still required to better understand the effectiveness
126 of approaches that specifically mobilise case studies of failure, and the outcomes of
127 their adoption on the manifestation of engineering judgement within educational
128 contexts.

129

130 **3.0 Research Design and Method**

131 *Theoretical Framework*

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

139

140 The aim of this study to understand whether introducing 'learning from failure',
141 centralised around 'real-world' case studies, serves to facilitate the use of engineering
142 judgement in structural design among undergraduate students. We therefore ask the
143 research question 'does the introduction of learning from failure real life case studies
144 facilitate students' use of engineering judgement?' To answer this question, we look to
145 the empirical space of a specific module on a UK undergraduate degree course, and its
146 assessed coursework for our data. Analysis of this data will enable the identification
147 and exploration of demonstrable uses of engineering judgement, independently and in
148 combination, as part of these coursework submissions. This enables us to answer our

149 research question both bluntly, in terms of yes or no, but also with nuance, as *how* this
150 use manifests within the data is explored.

151

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

158

159 *Empirical Context*

160 Here, case-based learning is examined as introduced to a first year structural design
161 module for civil engineering students, and which ultimately formed part of their module
162 assessment. The students were enrolled on an undergraduate bachelor degree in civil
163 engineering at a UK university. One of six first year engineering modules, ‘Introduction
164 to Structural Design’ was undertaken over a full academic year. Students had three
165 hours of direct instructional contact a week with the same academic tutor who had
166 gained structural engineering experience in professional practice. Sessions were
167 delivered in the format of a two-hour lecture and one-hour seminar, with an allocation
168 of a further five hours and twenty minutes for self-study weekly. The learning aim of
169 the module was to disseminate the foundational principles of structural design and the
170 communication of design work. The cohort consisted primarily of direct school entrants
171 aged eighteen, with a predominantly 90% to 10% male to female gender split. Within
172 the first two weeks of their studies as an inaugural activity students were asked to
173 autonomously research case histories of previous engineering failure within a peer

174 group setting. At this stage in the academic year students had no experience of structural
 175 design. The cohort (n=60) formed into groups (n=15), and each group was provided
 176 with two case study project titles and the dates of the failures that had occurred by the
 177 lecturer. One project title was selected from a recent failure occurring in the last twenty
 178 years and the other an older project. Students were then asked to define the principal
 179 structural form and behaviour of the structure involved in the failure, thus mirroring the
 180 diagnostic element of engineering judgement. Furthermore, they evaluated the project
 181 against various themes of failure as given in Table 1 (a topic on which lectures were
 182 also provided), thereby requiring the students to use inductive reasoning, considered the
 183 second aspect of engineering judgement, to assess the engineering parameters of the
 184 case history project. Finally, the students were asked to interpret the outcomes of the
 185 evaluated themes and to determine the key lessons to be learned from the failure, and
 186 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	
--	--	--	--	-----------	--

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

189
 190 *Data Collection*

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

196
 197 *Analytical Framework*

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

202

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	
--	----------------	--

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

205

206 As noted in the final column of Table 2, this study adopts both content and thematic
 207 analysis in its approach to the data, informed by a wider constructivist methodology.

208 For the first aspect of engineering judgement, content analysis was applied to reveal
 209 how the students defined the problem itself (the diagnostic aspect). More nuanced

210 thematic analysis was then used to reveal how they brought together different evidence
 211 in the forms of the ‘themes of failure’ to support this positioning (the inductive aspect).

212 Patterns were revealed by this analysis through an inclusive coding process, which was
 213 also able to reveal their relative prominence and relationships within the data as a

214 whole. The final aspect of engineering judgement, the interpretive aspect, was explored
 215 through a thematic approach that looked to the data as a whole, able to illuminate and

216 present the *ways* (as distinct from the content) in which the students positioned and
 217 understood failure within wider engineering contexts. In mobilizing these different

218 approaches to qualitative data analysis in these complementary ways, we can determine
 219 the use of engineering judgement in practice whilst also revealing how it has been used

220 by the students.

221

222 *Data Analysis*

223 Content and thematic analysis was used to explore the text and images found within the
 224 students’ group poster presentations. A data-driven coding process was used to ensure

225 the approach was as inclusive as possible, to allow major themes and interpretations as
 226 associated with engineering failure to be identified.

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

234

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

240

241 For the inductive aspect, more complex coding naturally emerged and the subsequent
242 discussion process between the researchers distilled the codes into a manageable
243 number of inclusive categories, with relevance to both engineering judgement and the
244 wider context of construction, whilst retaining the finer-grained analysis beneath. This
245 approach necessitated drawing on the experience and knowledge of the two researchers,
246 one of whom is a Chartered Structural Engineer and the other a Chartered Construction
247 Manager, to enhance validity. For example, the code of 'excessive working hours' was
248 included within the category of 'management', as was the 'lack of a clear reporting
249 structure on the site', whilst a 'lack of connection detailing' was included within the
250 category of 'design'. This approach reveals the dominance of particular patterns and
251 associations as linked to both the diagnostic and inductive elements of engineering

252 judgment. The appropriate allocation of sub-codes to the higher level categories was
253 consequently able to provide a determination of ‘quantification’ within the data to
254 enable evaluation of student judgement, as well as an evaluation of its depth and
255 complexity.

256

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

267

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

277 knowledge and judgement) in the identification of patterns and variations is itself
278 critical (Potter and Wetherell 1992).

279

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

285

286 **4.0 Results**

287

288 **4.1 The Diagnostic Element of Engineering Judgement**

289

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

297 *‘signs of deformation that continued until the collapse... a result of creep and*
298 *shrinkage in the concrete’ [and that] ‘cracks had developed where the*
299 *footbridges were fixed...cut into the concrete shell [which] severely weakened*
300 *the structure’*

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

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

309 *‘...a section of the approach ramp collapsed from over 30 meters in the air over*
310 *an island in the river...after 8 months the investigation revealed a number of*
311 *factors that may have caused the disaster: ...’*

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

321

322 **4.2 The Inductive Element of Engineering Judgement**

323

324 Analysis of the themes of failure codes and the patterns of their use in terms of
325 complexity and combination enabled evaluation of the inductive element of engineering

326 judgement, exploring how the students positioned the case study within the wider scope
 327 of engineering failure. The data ultimately generated five codes for the different themes
 328 of failure used within this diagnostic element: Design, Management, Loading, Materials
 329 and Profit. For coding to be assigned, the students were deemed to have clearly
 330 articulated this activity appropriately within their poster submission, and positioned it as
 331 a causal factor for failure within the case study. The analysis showed that in all of the
 332 case studies the students had identified and explicated at least one appropriate theme of
 333 failure, as found in Table 3.
 334

Theme of Failure	Example
Management	<i>‘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’</i>
Design	<i>‘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’</i>
Loading	<i>‘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.’</i>
Profit	<i>‘The store’s owner, Joon replaced the original contractor,</i>

	<i>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'</i>
Materials	<i>'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'</i>

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

336 Failure

337

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

345 The two most frequently mobilised themes were those of Management (51 instances in
346 total) and Design (29 instances in total), arguably reflecting the realities of structural
347 failure within civil engineering, which readily result from a combination of design and
348 site management issues. However, this can also in part be explained by the finer-grade
349 analysis and sub-codes that sit behind these themes of failure. This analysis was able to

350 reveal how the students demonstrated their awareness and understanding of the different
351 aspects of the practices of Management and Design, adding depth and detail to the
352 inductive aspects of their engineering judgement. For example, within the Newport
353 Docks case study Management was underpinned by the three sub-codes below, with
354 quotes from the text also included for illustration:

- 355 (i) project blame culture: *“Workers were concerned about reporting*
356 *possible dangers...as they could have lost their jobs”*
- 357 (ii) reporting issues: *“the lack of a defined route of action for the walking*
358 *ganger to take upon receiving reports of movement...”*
- 359 (iii) drive for profit: *“the wealth increase in import and trade suggested the*
360 *people were more driven to expand the docks, arguably this lessened*
361 *their attention to detail in design and implementation.”*

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

- 363 (i) inaccuracy in loading calculations: *“the design was well known...but*
364 *these structures didn’t face the same forces that a railway bridge*
365 *would...”*
- 366 (ii) a lack of design experience and knowledge: *“Bouch had not assessed the*
367 *new loads on the bridge so that the strength of the bridge could be*
368 *adjusted subsequently.”*
- 369 (iii) inaccuracy during changes to the original design: *“reduced the number*
370 *of piers making the spans of the superstructure girders much*
371 *longer...without taking into account wind loadings”*
- 372 (iv) under specification of connection details: *“Bouch didn’t specify well*
373 *enough if he wanted the holes drilled or not, so the metalwork company*

374 *used the cheaper option which subsequently had two-thirds of the*
375 *strength calculated.”*

376

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

386

387 **4.3 The Interpretive Element of Engineering Judgement**

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

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

399

400 *Engineering Practice – ‘The design was wrong’*

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

420

421 This multi-faceted theme drew on a language of calculations, stresses, loads, stability,
422 geotechnical knowledge, restraints and detailing to develop highly technical design

423 discussions, able to generate relatively simple cause and effect pathways to the failure
424 itself, as one student group summarised quite simply:

425 *'the design was wrong'*

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

434

435 *Causality: 'No single fault'*

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

447

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

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

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

472

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

482

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

488

489 However, this segregation of engineering and construction practice also at times led to
490 the development of a schism between the themes, which, instead of acknowledging the
491 role of complexity within the causes of failure, sought to other blame away from
492 engineering practice and design. For example, in the case of the Almuñécar Falsework
493 collapse, despite the students stating that: ‘*load transfers that needed to occur during*
494 *construction were difficult*’ they then only included discussion of construction
495 management and construction practice failure, opting out of wider considerations of
496 multiple causality and with no recourse to engineering practice. In the Almuñécar case,
497 the students swiftly moved to “*failure of workmanship*” and focused on the construction

498 processes. Such disassociation was however actually very limited within the data, and
499 only four instances of such positions were identified within the data as a whole.

500

501 *Learning from History?*

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

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

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

514

515 **5.0 Discussion and Implications for Teaching Practice**

516

517 Overall, the findings from this study support suggestions made by others (e.g. Love *et*
518 *al*, 2013; Petroski, 1999; Alexander 1964) that the use of failure case studies could be
519 beneficial for engineering students, and here more specifically the manifestation of
520 engineering judgement skills within undergraduate students. The diagnostic, inductive
521 and interpretive elements of design judgement (Vick 2002) were all identifiable within
522 the analysis, further indicating that this approach would support Daly *et al*'s (2014) call

523 for new approaches to prompt deeper student enquiry, to synergise ideas and prompt
524 innovative judgment. Specifically, 69% of the posters demonstrated diagnostic
525 judgement, 64% inductive judgement and the emergence of three dominant themes with
526 further associated complexity and depth, indicates the presence of interpretive
527 judgement.

528

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

548

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

570

571 The prominence of the failure themes of 'Management' and 'Design' within the
572 inductive judgement displayed by the students, in both the single root cause analysis and

573 within the more complex analyses of failure, is promising as it reflects the critical role
574 played by engineers as both managers and designers, and thus acknowledgement of the
575 consequences of a lack within either for engineering failure. The use of a variety of
576 combinations of other themes and sub-themes alongside Management and Design
577 within this aspect of engineering judgement was also promising, reflecting deeper and
578 more nuanced analysis by the students as they unpacked the more complex case studies.

579

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

587

588 The students' work showed understanding of the interrelationships between structural
589 engineering practice and Management (both professional and site), thus situating their
590 own role and associated responsibilities (Design) appropriately within wider industry
591 practice and enhancing the associated learning. This is important for practice, given the
592 need for designers to fully appreciate the close relationships between design and
593 construction and therefore use their structural design judgement appropriately, duly
594 cognisant of the potential consequences for practice. The use of blame allocation for
595 failure by the students was also interesting, demonstrating a reductionist analysis of the
596 overall failure to those at fault, whilst also reinforcing the role of the professional
597 engineer and their responsibilities in practice. Taken together, this suggests the use of

598 case studies actually enhances the exercise of interpretive engineering judgement
599 through this assessment, as students naturally developed a narrative able to support
600 specific lessons learnt (Vick 2002) from each failure case study.

601

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

614

615 **7.0 Conclusions**

616

617 This research aimed to explore whether the development of judgement skills in
618 structural design could be facilitated by the introduction of 'learning from failure' case
619 studies into the structural design modules of the first year of an undergraduate civil
620 engineering degree programme. Analysis of the students' group assessment
621 submissions found that their use of case studies demonstrated all three aspects of
622 engineering judgement: diagnostic, inductive and interpretive. In addition, the way in

623 which diagnostic and inductive judgement subsequently informs and supports the
624 exercise of interpretive judgement within this context is also worthy of note.

625

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

637

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