An evaluation of design issues identified during reviews of structural designs of buildings from 2015 to 2020

Patrick Crean[1], Richard Obsorne[2]
[1]School of Civil and Structural Engineering, Technological University Dublin, Bolton St., Dublin 1, Ireland
[2]Waterman Moylan Engineering Consultants, Block S, East Point Business Park, Dublin 3, Ireland
email: patrick.crean@tudublin.ie, r.osborne@waterman-moylan.ie

ABSTRACT: A process to carry out independent design reviews of structural designs was developed in Waterman Moylan Engineering Consultants in 2015 to complement existing quality management procedures. This process has been successful in highlighting and addressing issues during the design phase, thus reducing re-work and risk of issues carrying through to the construction phase. This paper presents an evaluation of issues found during 36 design reviews carried out between 2015 and 2020. The purpose of this paper is to improve awareness of recurring design issues and disseminate lessons learned from the design reviews.

KEY WORDS: Independent design review, peer review, structural safety, prevention of structural failures, robustness

1 INTRODUCTION

In many parts of the world statutory peer reviews of structural designs are a requirement of building regulations. The core purpose of a review is to ensure the safety of a design through the identification of human error. It is, therefore, of interest to study design errors that have caused structural failures as well as statutory design review processes that have been developed primarily in reaction to these failures.

The design review process developed in Waterman Moylan, as well as an evaluation of design reviews carried out by the Author between 2015 and 2020, are presented in this paper.

2 BACKGROUND

2.1 *Independent Design Reviews*

Requirements for independent checking of building designs vary across the globe. The following section sets out the position in a number of jurisdictions.

In 2008, New York City Department of Buildings introduced a requirement for structural peer reviews of buildings that meet certain criteria. Included are major structures that would meet Consequence Class 3 criteria in Eurocode 0, and buildings greater than 7 stories that require consideration of disproportionate collapse. In the past, structural design reviews had been performed by the Department of Buildings, however these were ceased in 1975 [1]. Peer reviews are carried out by principals of engineering companies based in New York with sufficient technical qualifications to carry out the review. Miami Florida, also introduced a requirement for peer reviews based on New York City's model.

In the UK, the Design Manual for Roads and Bridges (DMRB) [2] requires different levels of checking of designs of bridges in various Consequence Classes. An independent review is required for Consequence Class 3 structures. No such statutory requirements are in place for building structures.

In Scotland, a system was introduced in 2004 for certifying compliance of building structures with the building regulations. To certify building designs, one must be an Approved Certifier. Different levels of checking are required depending on the Consequence Class of the structure. Third party design reviews are a requirement for Consequence Class 3 structures.

In Australia, independent design reviews are only a statutory requirement in the state of Victoria at present. However, in 2017, a report was commissioned on behalf of the Building Minister's Forum to undertake an assessment on the compliance and enforcement systems for the building industry [3]. The report recommended that independent third-party reviews be carried in each territory for certain building types. In 2019, Engineers Australia, responding to the report recommended mandatory peer assessments for buildings of importance levels 3, 4 and 5 in accordance with Australian Standard AS/NZS 1170.0 [4]. These importance levels describe buildings with a high consequence of failure, similar to Consequence Class 3 structures in the Eurocode 0, where third party checking of calculations, drawings and specifications is recommended [5].

In Ireland, as in the UK, independent design reviews are required for certain bridge structures. Again, there is no statutory requirement to have independent design reviews carried out for building structures. The Building Control (Amendment) Regulations, updated in 2014 requires that an Assigned Certifier be appointed to provide design certification as well as inspections during construction to ensure compliance with the Building Regulations. However, design certification is provided without a design review of structural documentation being carried out.

The introduction of independent design reviews as a statutory requirement has generally been in response to structural failures or poor building practice. For example, the UK DMRB introduced independent checking in the early 1970's following failures of bridges in Australia, Wales, Germany and Austria [2]. The 16th Biennial report from SCOSS (Standing Committee on Structural Safety) notes that "*history shows us that in order to ensure compliance there needs to be independent assessment and supervision*." [6].

2.2 Design Errors and Structural Failures

Design errors have been found to be the primary cause of 25-35% of structural failures globally [7]. There have been extensive studies that discuss recurring design errors and the root causes of these errors that contribute to failures [8], [9], [10]. Some are listed below:

- Foundation movement;
- Connection failures;
- Buckling;
- Lack of bracing;
- Overloading;
- Fatigue;
- Inadequate structural redundancy;
- Calculation errors;
- Misusing computer software;
- Constructability problems;
- Unclearly communicated design intent;
- Contractual inhibitions;
- Inappropriate application / use of the design codes;
- Human error;
- Lack of experience of the designer.

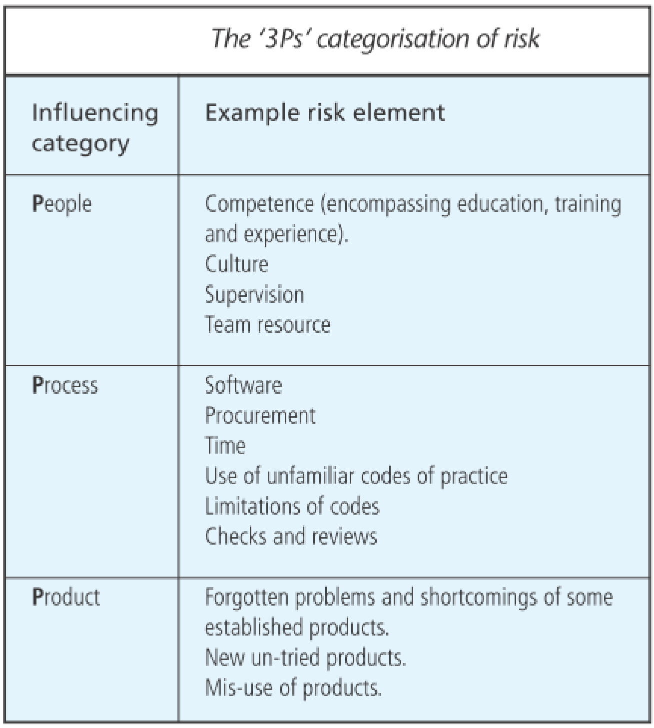
SCOSS uses a 3P's model to illustrate the broad range of issues on risk in structural safety, refer to Table 1 [10]. It is clear that many interrelated factors contribute to design errors and not simply technical errors. These include management and organisational factors as well as time and cost pressures [11].

Many errors in construction documentation are found during construction and never result in a failure, however these issues often cause re-work and can increase the project contract cost by 5% [12]. Some of these errors in fact lead to independent design reviews, for example in 2019, in New South Wales, Australia, during construction of a 7-storey building, a potential issue was highlighted by a sub-contractor. The developer chose to have an independent review of the design carried out. Major flaws in the design were uncovered resulting in remedial works to the basement that had been already constructed [13].

Engineering design companies often have checking procedures as part of their quality assurance procedures, but this is not always the case. Design errors can be reduced significantly when design checks are carried out in design offices. Research has shown that design checks can detect 32% of errors if carried out in-house and if independent parties are used then up to 55% of design errors can be eliminated [14]. While independent design reviews are useful in detecting design errors, they can be also be useful in knowledge sharing, which can drive standards and quality [1]. Furthermore, lessons can be learned from previous projects and used to guide appropriate training and knowledge development for younger engineers.

2.3 Design Review Process at Waterman Moylan

The review process in Waterman Moylan began in 2015. Reviews are most often carried out just before the tender issue. On very large projects, a scheme stage review is often carried out also, prior to 40% design documentation when there is still scope to affect the design in a positive manner [15]. At scheme stage, it is possible to assess the appropriateness of the structural scheme, buildability, materials used, and detailing for simplicity and ease of construction. Carrying out the review at tender stage allows for amendments to the design or omissions to be included in the Tenderer's price. Post tender, there can be resistance contractually to making alterations. One drawback of carrying out the review at tender stage is that RC drawings have generally not been produced. Often, it is in the detailing where issues arise.



The '3Ps' categorisation of risk

Influencing category	Example risk element
People	Competence (encompassing education, training and experience). Culture Supervision Team resource
Process	Software Procurement Time Use of unfamiliar codes of practice Limitations of codes Checks and reviews
Product	Forgotten problems and shortcomings of some established products. New un-tried products. Mis-use of products.

Table 1. Broad range of influences on structural safety [10]

The following tasks are performed on each review:

1. **Design Loadings.** Confirm that the appropriate loads and load cases have been considered.
2. **Design Criteria.** Confirm that the structural design criteria are in accordance with codes of practice and design assumptions are appropriate.
3. **Calculations.** Perform independent calculations for a representative number of elements including columns, beams, floor slabs and transfer structure to check their adequacy. Review structural analysis and finite element model assumptions, inputs and outputs versus independent hand calculations (where available).
4. **Load paths.** Review load paths and overall loads on columns & foundations, on area basis.
5. **Lateral Stability.** Check overall system and load path down to foundations.
6. **Robustness/Accidental Loading.** Review ties, loads, and confirm code provisions have been complied with.
7. **Foundations.** Review geotechnical investigations, confirm that the foundation and structural design properly incorporates the results and recommendations of the investigations including contamination, gas and water level.
8. **Basements.** Review principles of design, tanking, and potential for buoyancy.
9. **Performance-specified structural components** (such as certain temporary works and precast concrete elements)**.** Verify that these have been appropriately specified and coordinated with the primary building structure.

10. **Drawings, BIM models and specifications**. Check clarity, presentation and completeness of information. Confirm that the structural plans and BIM models are in general conformance with the architectural plans regarding loads and other conditions that may affect the structural design.
11. **Fire Protection.** Review fire rating and method used.
12. **Health and Safety Risks**. Review risk assessment, design stage mitigation measures, and any remaining risks.

Following the review, a written report is provided to the project lead along with comments marked on the structural drawings. The report also includes lessons learned, and recommendations for future projects. The project lead responds to the comments either accepting the comment, clarifying the structural design intent or disagreeing with the comment. Following the response to the report, a meeting between the reviewer and project lead is held to close out the comments and responses. Generally, issues are resolved here or a difference of opinion is accepted. This is can in fact be a positive outcome [15].

3 EVALUATION OF REVIEWS

An evaluation of design issues found during reviews was carried out. The study sought to assess whether common issues in designs existed across different structure types and design teams. The evaluation was limited to issues that were identified in the reviews and were agreed with by the project lead. Each of these issues resulted in a revision to the structural documentation. Differences of opinion and issues that did not affect safety or utility of structure were not included. The evaluation is the subjective opinion of the Author. It is possible that a different engineer may have drawn different conclusions during the evaluation and may have found a slightly different set of issues in each review. The review findings from housing projects as well as refurbishment projects have been omitted, as these projects typically have different sets of issues.

The approach consisted of the categorisation of issues identified into the following groups:

- Members supporting vertical loading at ULS
- Members resisting wind / lateral loading
- Foundations
- Robustness

Design issues found in various member types were collated together along with the primary failure mode for each element and the likely primary cause of the design issue. The results are tabulated in the following sections.

There were 36 projects in total reviewed. Figure 1 provides a breakdown of the building types.

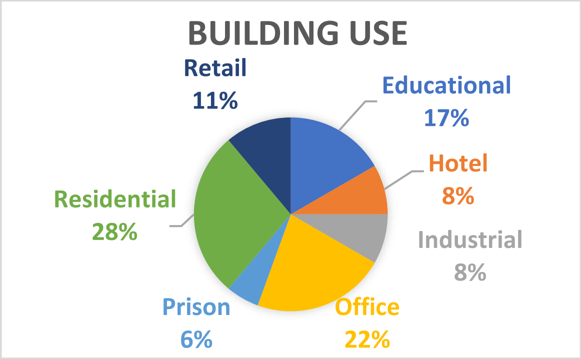


Figure 1. Breakdown of Projects by Building Use.

Figure 2 provides a breakdown of the structural solutions used in the buildings reviewed.

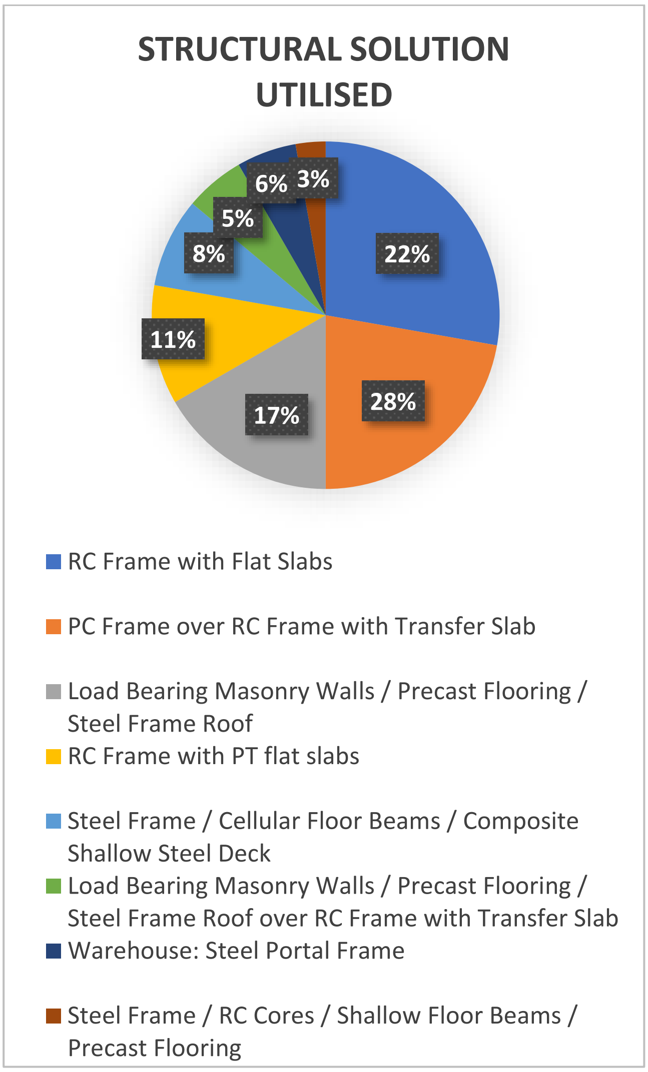


Figure 2. Breakdown of Projects by Structural Solution.

Consequence Class: There were two Consequence Class 3 structures, twenty-five Consequence Class 2B structures and 9 Consequence Class 2A structures in the sample. Commentary is provided on a number of the important findings.

4 RESULTS

KEY:
A. Element within structure
B. No. of projects with occurrences of issues
C. No. of projects that utilise element
D. Percentage of projects where issue was found
E. Most common issue with element
F. Primary cause of issue
I. Lack of experience by designer
II. Human error
III. Inappropriate use of design codes
/ Not evaluated

4.1 Members supporting vertical loads at ULS

The following table presents a summary of results of the evaluation of members supporting vertical loads.

A	B	C	D	E	F
RC Column	8	24	33%	Buckling	I
RC Transfer Slab	6	10	60%	Bending / Shear	I
Steel Beam	4	14	29%	Bending	II
RC Basement Slab	4	12	33%	Buoyancy	II
Steel Column	3	10	30%	Buckling	III
Masonry Pier	3	8	38%	Compression	II
RC Flat Slab	2	9	22%	Punching Shear	II
RC Transfer Beam	2	5	40%	Bending / Shear	I
Precast Pier	1		/	/	/
PT Flat Slab	1		/	/	/
RC Beam	1		/	/	/
Steel Transfer Beam	1		/	/	/
Precast Floor	1		/	/	/
RC Transfer Wall	1		/	/	/

Table 1. Results of evaluation of issues found in members supporting vertical loads.

There were eight instances of design issues with columns. These columns tended to be over capacity by codified calculations for buckling due to slenderness effects. This accounts for 33% of projects where RC columns were used. Slender columns are quite sensitive to magnitude of bending moment, and if the moment is applied in an incorrect direction, it can have a marked effect on the effective length of the column for buckling. Of course, a non-linear analysis could have been carried out in order to justify a design by directly calculating the 2nd order effects, which may show that the magnified moment is less than that calculated by simplified code rules.

In assessing the risk associated with this design issue, columns identified were often in office buildings where actual measured imposed loads are typically much lower than those stipulated by clients [16]. Nonetheless, to address the issues, columns were typically increased in size, higher concrete strengths were specified or additional reinforcement was added.

There were six projects where some amendment was required to transfer slab designs. This amounted to 60% of projects where transfer slabs were used. Often these issues were localized, where the transfer slabs were insufficient by calculation for either bending, punching shear or face shear. Four projects required localized or general increases in the depth of the transfer slab and two projects required amendments to detailing of shear reinforcement. Two projects had issues with RC transfer beams undersized in bending and shear. Both projects required increases to the size of transfer beam.

One of the primary causes of issues found in transfer beams and slabs appeared to be a lack of experience by designers in modelling and in interpreting results. Issues around the use of computer software and analyzing results are well documented [17]. Modelling without consideration of the stiffness of elements being supported, often results in the actual loads carried by transfer structures being underestimated.

In building models where transfer structures support long walls (for example residential and hotel buildings), the walls that are stacked through the building tend to be much stiffer than the transfer slabs that support them. The walls tend to 'hang' the transfer slab under, providing support to it, and distributing the load back towards the stiff points such as supporting columns. There are several reasons why this is not a realistic representation of how the structure will act in reality. The walls would have to be designed for high tension forces and the bearing stresses at the ends of the walls are often well beyond design limits. If the walls are to be constructed of precast concrete, the joints in the walls create discontinuities. These joints are typically not designed for the forces that would need to be transmitted here. Figure 3 shows an extract from a finite element analysis model showing arching of walls, tensile forces developed and high bearing stresses over a column support.

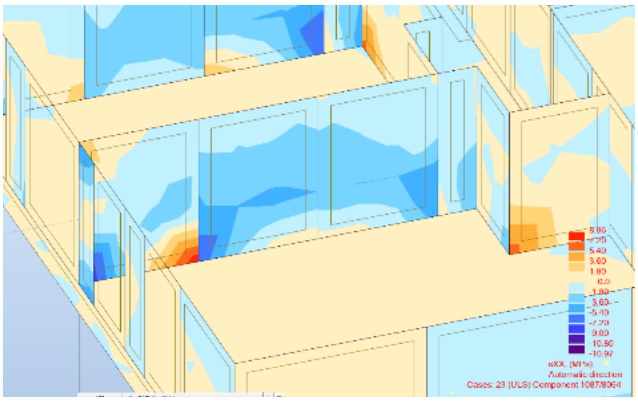


Figure 3. Extract from Finite Element Analysis Model of a transfer slab supporting long walls.

When transfer slabs are modelled to support columns at a change of grid between floors (for example in an office over a car park), the loading from the columns supported on the transfer slab causes it to deflect. Columns that continue below the transfer slab and are not transferred act as stiff points, while the transfer slab acts like a spring support to the transferred columns. If the structural frame over has moment capacity at its joints, and thus a stiffness, it will attempt to span over the 'spring' support. This reduces the force in the column supported on the transfer slab. Again, this is not a true representation of how the structure will act. The propping sequence of the structure will have a large effect on the stiffness of the frame supported by the transfer slab during construction and hence will affect how much permanent load is actually supported by the transfer slab. This depends on when temporary props are removed and whether they are temporarily released and re-propped. A time history analysis could be performed to take the propping sequence into account, however the relative stiffness of the frame versus the transfer slab will also change over time due to creep and shrinkage effects. Furthermore, if the potential stiffness of the frame within in the finite element model was to be realised, each connection would have to be designed for the moment and shear force associated with the vierendeel type action induced.

Following a number of reviews, a standardised process for modelling transfer slabs was developed that accounts for the phenomenon described above. The Author has noted a reduction in issues associated with transfer slabs since its introduction.

4.2 Members or Systems that resist Lateral Loads

The following table presents a summary of results from the evaluation of issues arising in members and systems resisting lateral loads.

A	B	C	D	E	F
Roof	7	15	47%	No bracing provided	II
Wall	4	15	27%	No support to top of wall	II
Slab diaphragm	4	33	12%	Discontinuity prevents load transfer	II
RC Core	2	17	12%	Major torsion induced on core	II

Table 2. Results of evaluation of issues found in members or systems that resist lateral loads.

There are a wide range issues related to lateral loads that may cause instability of an element or of the structure as a whole. There were seven projects that had issues with steel framed roofs. Six of the seven projects had bracing missing on plan or had discontinuities in the roof bracing system that meant there was no route back to the vertical lateral stability elements. These roofs would be detailed for fabrication by a sub-contractor, so it is possible that a number of these omissions would have been picked up prior to construction. The most likely cause of these omissions is human error.

On four projects there was no lateral restraint to the top of walls indicated on the drawings below the steel framed roofs.

On two projects the location of RC cores documented on plan would have resulted in a major torsional moment being induced onto the RC core, potentially causing instability of the building. A shear wall was introduced in one instance, in the other a building expansion joint was moved, which balanced the lateral loading on the RC cores.

On four projects, the shape of floor diaphragms as documented prevented the slab transferring lateral loads back to the vertical shear walls or RC cores. One of these issues occurred on a major project with a number of buildings over a podium slab and two storey basement. On this project, expansion joints were provided in perpendicular directions through the podium level and level -1 basement slab. However, these expansion joints prevented equalisation of earth pressures acting on the basement walls. This lateral earth pressure was too great to be supported by the RC shear cores that provided lateral stability against wind loading. To address the issue, a shear connection across the expansion joint was introduced to allow the RC slab diaphragms distribute the lateral loads to the perimeter basement walls as was the original design intent. In assessing the cause of the issue, there were a number of design teams working on different buildings on this project and a number of finite element models were developed to analyse the structures. In the basement model, pin supports were evident supporting the top of the RC retaining walls. This was an un-conservative assumption because of the presence of the expansion joints. This issue is likely to have been caused by a combination of a breakdown in communication and human error. It must be noted that projects of this size in Ireland are rare, and issues not seen before can manifest due to problems of scale.

On one major city centre site, it was noted that planned future excavation at an adjacent site would un-balance lateral earth pressures across the basement. It was possible on this project to design the lateral resisting systems for an unbalanced earth pressure, However new projects often require temporary propping to be provided to ensure stability of adjacent existing developments. This potential issue has also been picked up by Dublin City Council in their new basement development policy document, which includes a requirement for a basement impact assessment [18].

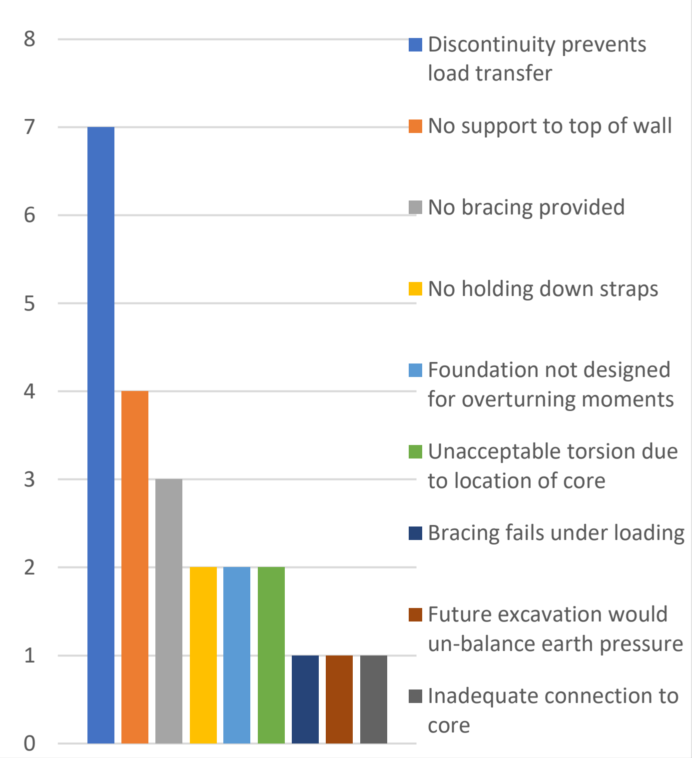


Figure 4. Common issues related to lateral loading identified across projects

4.3 Foundations

The following table presents a summary of results from the evaluation of issues arising in foundations.

A	B	C	D	E	F
Differential settlement	3	36	8%	/	Human error
Foundation insufficient to resist buoyancy	4	12	33%	/	Human error
Foundation insufficient for vertical loads	4	36	11%	/	Human error
No restraint to top of pile	2	21	10%	/	Human error

Table 3. Results of evaluation of issues found foundations.

A risk of buoyancy in four projects with basements was identified where foundations supporting podium areas between buildings had insufficient dead loading in the structure to counteract the uplift forces due to ground water pressure. This issue was found on 33% of projects with basements. These projects were in Dublin City in close proximity to the river Liffey where the ground water level is quite close to surface level.

Four projects contained foundations insufficient to resist vertical loads. Issues included too few piles being provided, pads undersized for allowable bearing pressure, or pads undersized for punching shear. In one case the suspended ground floor slab was not included in the analysis model, which resulted in too few piles being provided.

On three projects, the documentation showed one half of the building supported on rock and the other half on clay. Had the buildings been constructed in this manner, differential settlement may have occurred. It is quite possible that these issues would have been picked up during site inspections, resulting in an increase to project costs rather than a more serious outcome. Each of these issues appear to be associated with human error, where the issue was missed or not considered.

4.4 Robustness

The following table presents a summary of results from an evaluation of robustness issues arising in reviews.

A	B	C	D	E	F
Horizontal Ties	7	20	35%	Precast floor detailing	II
Lack of Redundancy	4	36	11%	Steel columns supporting RC structures	III
Vertical Ties	3	27	11%	Masonry walls	II

Table 4. Results of evaluation of issues found with robustness on projects.

Seven projects had issues with detailing of horizontal ties. Five of these projects were associated with precast floors onto precast or masonry walls. The two other projects involved steel frames where the tie force to be designed for by sub-contractors was underestimated.

Elements of four projects were considered to have a lack of sufficient redundancy and required key element design. One of these projects was a Consequence Class 3 structure, where a systematic risk assessment was also required to be performed in accordance with Eurocode 1 [19]. On this project, a corner column supporting a large floor area was located adjacent to a turn on a busy bus corridor. In this case, following the review, the column was designed for accidental vehicular impact.

5 CONCLUSIONS

This paper describes the design review process developed in Waterman Moylan and discusses a number of the recurrent issues found during these reviews. Issues were most frequently found in a number of elements including: slender RC columns; RC transfer structures; isolated masonry piers; basement slabs subject to bouyancy; and detailing of horizontal ties in precast structures. The results indicate more detailed consideration could be given to these elements at scheme design stage.

The paper also demonstrates that peer reviews are an effective means of reducing errors in designs, thus making for safer structures. Another benefit of design reviews is that they provide the opportunity for knowledge sharing and educating young engineers. It is clear that issues are often caused by an error due to human nature and it is difficult to propose interventions in these scenarios. However, a lack of experience can also be a major cause of design errors, which was the case in the computer modelling examples presented. Here, a design process for computer modelling as well as education of younger staff has improved design outcomes.

Finally, given the recognised benefits of design reviews on structural safety, one could ask whether independent design reviews should become a statutory requirement in Ireland.

REFERENCES

[1] Eschenasy, D. (2018). 'Structural Peer Review Practice in New York City', *Proceedings of the 2018 ASCE Structures Congress: Buildings and Disaster Management*, Forth Worth, Texas, 201-207.

[2] Design Manual for Roads and Bridges, *'Technical Approval of Highway Structures'*, HE-DMRB-HSB CG 300 (formerly BD 2/12) (2020), Highways England.

[3] Australian Institute of Architects, *'Summary of the Shergold/Wier Report and the Impact of the Recommendations on Architects'*, [Online], available from https://wp.architecture.com.au [accessed 26/05/2020].

[4] AS/NZS 1170.0:2012, *Structural Design Actions – Part 0: General Principles*, Standards Australia, 2005.

[5] I.S. EN 1990:2002, *Eurocode 0 - Basis of Structural Design*, NSAI, 2005.

[6] Standing Committee on Structural Safety, '*16th Biennial Report'*, [Online], available from www.scoss.org.uk/publications [accessed 24/05/2020].

[7] Structural Engineers Registration Ltd (Scotland), '*Guidance Note 11 – Guidelines for Checking the Structural Design of Buildings*', [Online], available from https://www.ser-ltd.com/ser-scotland/resources [accessed 20/05/20]

[8] Blockley, D. I. (1977), 'Analysis of Structural Failures', *Proceedings from the Institution of Civil Engineers, Part 1*, 51-74

[9] Oana-Mihaela, et al. (2008), Understanding Failures, a Useful Tool in Structural Robustness Evaluation. *Bulletin of the Polytechnic Institute of Jassy, Constructions, Architecture Section. LIV (LVIII).*

[10] Capenter J. N. (2008), *'Safety risk and failure: the management of uncertainty'*, The Structural Engineer, IStructE, July, 100-105.

[11] Love, P.E.D. et al. (2011), 'Learning from Construction and Engineering Failures', *Twelfth East Asia-Pacific Conference on Structural Engineering and Construction*, 844–850.

[12] Cusack, D. (1992), 'Implementation of ISO 9000 in construction'. *ISO 9000 Forum Symposium*, November, Gold Coast, Australia.

[13] Engineers Australia (2019), '*Building Stronger Foundations*', [Online], available from https://engineersaustralia.org.au/ [accessed 19/05/20].

[14] Schneider, J. (1997), *'Introduction to Safety and Reliability Analyses'*, Structural Engineering Documents 5, International Association for Bridge and Structural Engineering, Zurich Switzerland.

[15] Association of Consulting Engineers NSW, *'Practice Paper 24 – Peer Review'*, [Online], available from https://www.acse.org.au/resources [accessed 18/05/20].

[16] Minimising Energy in Construction, '*Floor Loading Occupancy Calculator — Minimising Energy In Construction'*. [Online] Available at: www.meicon.net/floor-loading-occupancy-calculator [accessed 28/05/2020].

[17] Macleod, I. A (2006). *'Taming the finite element tiger'*, The Structural Engineer, IStructE, February, 16-17.

[18] Dublin City Council (2020), *'Basement Development Policy Document'*. [Online], available from http://www.dublincity.ie/main-menu-services/planning [accessed 20/05/2020].

[19] I.S EN1991-1-7:2002, *Eurocode 1 - Actions on Structures – Part 1-7: General Actions – Accidental Actions*, NSAI, 2006.