Applying Forensic Investigations of Failures of Structural Performance.

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Abstract
Information from rigorous investigations of construction performance failures can be applied to reduce risks and improve construction standards for practicing engineers, within design and contracting organisations, and nationally and internationally in developing improved contracts, standards and guidance.

Keywords: EuroCodes; construction; performance; failure; contract; durability; safety.

1 Introduction
Disaster, Death and Lawyers dominate the public perception of Forensic Engineering. There is a steady publication of summaries of historic dramatic collapses, sometimes with novel re-analysis of causes. Immediate reports of recent failures in the construction press suggest causes, but with little knowledge of the facts.

These opinions are then exaggerated in national media to become established erroneous myths. The truth, from detailed analysis of evidence, too often becomes cloaked under legal constraints and the perceived view that commercial confidentiality is more important than disseminating the truth.

However, the application of Forensic Engineering to construction is developing and there is now a growing body of published reports on detailed investigations of performance failures of all types and analysis of the trends from these reports. IABSE WG8 is facilitating international cooperation on the investigation and reporting of failures and on different national procedures for the resolution of construction disputes.

The relatively rare headline grabbing collapses have far fewer economic and environment consequences than the multiplicity of performance failures (Contract delays and litigation costs e.g. Wembley Stadium, cost overruns eg London Olympic Aquatics Centre, and disproportionate maintenance costs) when structures are not fully fit for purpose. Many defects, like premature deterioration, are usually out of time for litigation, but merit proper investigation because of their widespread long term economic and environmental impact.
Figure 1. Concrete Repair to University Building

Minor deficiencies of serviceability when proliferated by inadequacies in standards or by design fashion can have major economic consequences from remedial measures and consequent disruption.

As the majority of our built infrastructure is aging it is important to be aware, from investigations of older structures, the limitations and best features of past design and construction standards. We must also ensure that current guidance prevents a repetition past failings. Major repairs to an iconic university building, Figure 1, show how the 50 year ‘design life’ for concrete is inadequate and unsustainable.

The objective of this paper is to highlight the need to disseminate information to improve construction practice based on the consideration of the widespread instances of substandard performance where structures fall below the three design ideals “firmitas, utilitas, venustas” – solid, useful, beautiful [Vitruvius c20 BC], which has been more recently expressed as “Structures should be Fit for purpose, Cost effective and Delight the eye”.

Forensic Engineering can improve structural safety but we should also use it to improve the overall economic and environmental performance of construction.

This requires us to facilitate and fund information flows around the Forensic Cycle. The educational links are of particular importance.

2 Understanding failure.

How many architects and engineers really understand how the structures they design and build may fail to meet client’s and users’ expectations in the short or long term? How many individuals and organisations go back to check the functional performance of their construction projects 5, 10, 20 or 50 years later?

Structural engineering design and analysis, as codified, is now narrowly related to the avoidance of idealised ‘collapse’ and ‘serviceability’ limit states. Designers and Code committees need to be better informed and quantify the real limit states found in failing structures.

Few probabilistic models used to derive code requirements are based on actual failure modes which have occurred. Even when the modelling scenario is realistic there is seldom data on the variability of loading and site materials characteristics. The 1970’s Merrison research leading to BS5400 steel bridges is an exception.

Increasingly complex ‘probabilistic’ models have been used to create an illusion of precision. For concrete structures neither the methodology nor the data have been calibrated against actual cases of collapse and serviceability failure and the code partial factors are arbitrary. There is a need to transform codes so they relate to real risks, identified from failures of actual structures, as distinct from the current oversimplified theorising developed on computers and in committee rooms.

In particular we need to quantify the variability of all parameters based on site measurements. Without accurate data probabilistic modelling is a deception. By acquiring and analysing site data on variability progress will be possible.

The accuracy of prediction of flexural behaviour and the requirements for ductile reinforcement yield failure modes with reinforced concrete give reliable prediction of failure loads for which progressive development of deflections and cracking give warning. In contrast shear failure modes are difficult to predict and when lightly reinforced are brittle with little warning. Yet partial factors for shear failure are lower than for
flexural failure, but the risks and consequences are far greater with shear [1].

While ‘collapse’ risk is calculated on the probability of excess loading. Actual failures often arise when a structure is unloaded or lightly loaded. Deterioration, design errors, construction or repair faults and redistribution of forces from thermal and long term creep and shrinkage have contributed to the initiation of collapses, or impending collapses, in low live load conditions. Pipers Row [2] and de la Concorde [3] provide good examples, but there are many others in the literature (eg Ynys –y- Gwas, Mandovi, New World Hotel, Sampoong, CDG terminal etc)

We should not abandon probabilistic approach to setting appropriate factors based on the uncertainties with different types of construction and use. When properly carried out, as for steel bridges in the UK in the 1970s, it has substantially improved design.

For concrete it needs to be reconsidered so that consistent safety is achieved. For long term risks we need to develop better models of deterioration processes [4] and their consequences.

National and Eurocodes have forced many engineers into following formulae without proper understanding of the modes of structural failure which the design needs to prevent. Too often clause by clause compliance, applied part by part fails to consider the overall behaviour of the structure.

Hewlett’s important paper [5] draws attention of the risks created by theoretical EuroNorms in replacing UK best practice, which has been based on Bragg’s classic analysis [6] of a wide range of falsework failures.

Because codes are written for specific types of structure, failures often arise when they are blindly applied to structures where the scale, form or material characteristics differ from those covered by the code.

There is a similar lack of awareness of how the increasingly complex chains of supply and subcontract create risks from departures from the original design intent and specification. These contractual complexities also lead to delays, cost overruns and third party claims which can be many times the original contract value, some examples in Section 7. Most problems can be avoided at small cost by doing it right.

3 Using knowledge from failures

Knowledge of lessons from failures tends to evaporate after 30 years as old engineers retire and reports gather dust in libraries. If comprehensive information is made available online, it should enable us to counter corporate amnesia. Knowledge needs to be refreshed in education and Continuing Professional Development and maintained within specialist groups within consultants and contractors.

It is essential that lessons are also grasped by construction managers and the ever wider range of technical specialists who contribute to construction process. The root causes of many failures are to be found at the interfaces between
individuals and organisations created by complex and fragmented contracts.

4 How to learn as an individual.

Information on failures of strength, stiffness, damping and durability should be integrated into undergraduate design teaching and linked to knowledge about organisational failures. For over 200 years significant failures have been switch points in the evolution of the engineering design [7]. This makes it natural to incorporate failures in the teaching of design and contract management.

Specific modules on failures have been introduced at Warwick and other Universities [8]. The aim should not be the training of forensic engineers to act in litigation, but to train engineers so that they won’t repeat old mistakes and land up in court.

Forensic Engineers in USA have disseminated through ASCE some good sets of support literature for incorporating in teaching. At the student level this covers colourful case studies with clear lessons. There are other initiatives like the IABSE WG8 short course at this conference.

Once graduated and working in an organisation a young engineer should, with support from senior engineers, focus on in-depth study of the specific types of structures and risks he is involved with. Short summaries give but a superficial understanding. Safety requires deeper reading and knowledge. For bridge design and construction start with Yarra/Westgate Bridge report [9] and Smith’s historic review [10]. For bridge inspection, maintenance and management de la Concorde [3]. If working on tunnelling then study the Heathrow NATM collapse [11] [12].

These provide a good start to achieving the deep understanding needed for members of engineering institutions. That will be but a start to a lifelong study of failures related to one’s work through a varied career. If you prefer your local literature there have been suitable failures in most countries and WG8 is promoting wider international publication. An international perspective is important in widening ones reading to cover original reports on diverse cases.

5 Corporate approach to risk

For Consultants and Contractors reducing the risks and cost of failures (eg Heathrow tunnel and Abbeystead) should be a major concern. Risk reduction can be achieved by ensuring in training and in building teams that they are aware of the fundamental technical and contractual causes of failures.

Unclear sub-contracts and specifications devolved to suppliers can create risk and claims for many times the contract value for consequential loss from small defects with major impact.

Overall corporate responsibility for H&S Construction (Design and Management) Regulations 2015 (CDM 2015) focusses on safety. But if the project is safely delivered but is late and is not fit for purpose, the client will claim including for consequential losses. Risk assessments need to cover commercial risks from performance failure as well as safety.

6 Finding reports of UK failures and of code development

There are three major groups of readily available UK literature on failures and the development of BS Codes and Guidance.

The ICE ‘Virtual library’ on line [13] includes detailed reports on failures over the last 200 years. IStructE library covers 100 years of concrete structures. It is salutary to see how similar types of failures recur on a 30 to 40 year cycle [14].
Prof Pugsley led the IStructE Committee on Structural Safety [15] which in 1955 proposed more rational factors of safety in codes. Failures at Ferrybridge, Ronan Point [16], Milford Haven [17] and Yarra [9] created the momentum and funding to develop this approach. The statistically calibrated partial factor method was developed and introduced in the 1970s for steel bridges [18] and, in a very watered down form, for concrete in CP110, which have found their way, little improved, into the EC2 factors.

The proper methodology was set out by CIRIA [19] including the need to have good data from actual construction. Somehow the committees for the fragmented Eurocodes seem to have lost touch with both real structures and the origin and fundamental safety philosophy initiated by Pugsley.

SCOSS standing committee was set up by ICE, IStructE and HSE in 1972 and has periodically reviewed risk to structural safety risks. It has made important recommendations but these have too rarely been followed up. SCOSS set up CROSS for confidential reporting of failures and risks. These have been well publicised to the industry in regular CROSS reports. Recently SCOSS and CROSS have been brought together as Structural Safety [20].

In the late 1990s Ken Carper’s paper to IStructE [21] on ASCE Forensic Engineering triggered a wider UK interest in the investigation and dissemination of detailed reports of failures. The series of ICE Forensic Engineering Conferences, initiated by Brian Neale, have attracted papers on failures from around the world with particular links with ASCE. Taiwan, France, India and others have held similar meetings.

The wide range of ASCE, ICE and IStructE and IABSE journals, as well as specific forensic issues [22] [23], provide a flow of articles and case studies. There are also many specialist conferences which publish failure case studies.

Overall there are now thousands of short papers on failure case studies and hundreds of full detailed reports on failures. The availability of these data sets has enabled researchers like Terwell [24] and Breyssse [25] to identify specific risk factors and provide a better basis for reducing risk in design and construction.

7 Examples of ‘Not fit for purpose’

Since the 1960s I have acted as expert in investigating performance failures of silos [26], bridges, buildings and tunnels for consultants, contractors and insurers and in developing cost effective remedies. Only occasionally have these investigations ended in court proceedings, as full investigations normally enable parties to reach agreement. Lessons from these investigations have contributed to a range of improved standards and guidance.

The following examples show how technical and contractual complexity interact and the scale of costs for remedying performance failures. Those
devising contract innovations need to learn lessons as well as the designers.

A hospital placed a design and build contract for a two storey, 4 span medical records store with rolling shelves. With no experience of design the Contractor sub-contracted the steel frame to one party, the concrete composite slab to another, an inappropriate configuration was specified by architects. The full loading from these shelves was 11kN/m² and deflection control was critical. The slabs were not made continuous to limit slope. The irregularly laid track and lack of knowledge of the rolling resistance by the shelving supplier contributed to the problem. The shelves rolled together in the sagging areas when only half full, seriously disrupting medical record retrieval essential for the hospital.

The hospital wanted a long term solution with minimum disruption. The lawyer required proper diagnosis and recommended remedials to be implemented by the parties rather than protracted litigation. The records had to be relocated while the slab was stiffened with steel plates, the track was precisely re-laid to an initial upward camber of half full deflection and shelves had adjustable rolling resistance. With the records replaced all worked well.

A warehouse floor for builder’s materials on a marshy site was designed and built to resist the highest loading in the BS without checking the client’s requirement for storing lead sheeting. When checked by the racking supplier the slab could not carry loads from the lead. The slab had to be removed and replaced over additional piling. Substantial payment was required for delay, business disruption and extra expenditure.

A new retail development with a rooftop car park required remedial work due to early water ingress into to fashion shops below. Bad detailing, insufficient consideration of thermal and shrinkage movements of the concrete slab and a proprietary edge seal by a major supplier which had far less movement capacity than claimed all contributed to leakage. Substantial temporary measures and remedial work and claims for business disruption due to loss of parking and leakage into premises had to be paid by the contractor.

On a larger scale were problems with a car park for a development for over 30 major retailers. The architect’s concept, was novated to the main contractor, who then subcontracted to various precast suppliers and for construction on site.

The upper floor for over 1200 cars had a structural screed onto precast pre-stressed planks resting on narrow ledges on the main beams. Lack of coordination between sub-contractors led to inadequate tolerances in design and on site and inadequate provision for thermal and other movements. This led to cracking and leakage but more seriously a failure of the end support of a plank, which highlighted errors in design and construction. This necessitated substantial delays to the opening of retail shops and the emergency fitting of a temporary support which cost 1.25 times the original contract sum. Claims from retailers for commercial loss from delayed opening and disruption amounted to 40 times the original contract sum.

Towards the end of the liability period a local authority embarked on a costly and over-elaborate refurbishment of a large public swimming pool. Some tiling was coming loose and appeared to be bedded on sand. The contractor was able to settle for a nominal amount after careful examination of records showed that the pool water pH was badly controlled by the owner’s staff and periods of acidity had dissolved the original cement.

8 Conclusions

Information from the rigorous investigation of failures provides the best basis for improving design and construction practice for individuals, organisations and those developing standards and guidance and construction contracts.

Prior to embarking on any design or construction task engineers at all levels should familiarise themselves with incidents and deficiencies of fitness for purpose in recent and historic precursors of their project.

Investigation of durability failures needs to be given priority, so we can develop a basis for appraising the safety of our decaying
infrastructure and create sustainable durable structures for the future.

Each new generation of engineers must learn ‘the history so far’ if they are to innovate successfully and avoid the repetition of mistakes of previous generations.

Standard committees should compile and maintain a list and obtain full details of relevant failures to guide revisions to standards and guidance documents. They should also clearly state the limits of applicability.

9 References

[20] SCOSS (Standing Committee on Structural Safety)and CROSS http://www.structuralsafety.org/