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The art of the forensic engineer

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ABSTRACT: The first part of the paper discusses the role of the forensic engineer in investigating and determining the causes of structural failures, and how that role differs from that of the design engineer. The forensic engineer's "deliverables" and "clients" require specialised skills directed to answering and communicating "why" the failure occurred. Recommendations are made for the appropriate engagement of a forensic engineer. The second part of the paper reviews the application of forensic engineering in the public reports of several structural failures. The direct "technical" causes of failure were accompanied by contractual and project execution deficiencies that did not prevent or detect the onset of disaster before it was too late. The "non-technical" lessons learnt include implementing the appropriate contractual mechanisms for managing the project risks, the appropriate engagement of the design and checking engineers, the designer's involvement during the construction, and the ongoing requirement for monitoring and inspection of constructed facilities.

1 THE ROLE AND ENGAGEMENT OF THE FORENSIC ENGINEER

1.1 *Introduction*

One definition of forensic engineering is: the application of the art and science of engineering in the jurisprudence system, requiring the services of appropriately qualified and experienced professional engineers. Forensic engineering may include investigation of the physical causes of accidents and other sources of claims and litigation, preparation of engineering reports, testimony at hearings and trials in administrative or judicial proceedings, and the delivery of advisory opinions to assist the resolution of disputes affecting life or property (Carper 2001).

However, the scope of forensic engineering is broader than in connection with the legal system, as forensic engineers may also be required to provide a report to a client as to the cause and reasonable options for replacement or repair, or desirable procedural changes to avoid future failures.

Forensic engineers are usually, although not exclusively, involved in investigations of "failures", where a failure is an "*unacceptable difference between expected and observed performance*" (Leonards 1982). Perceived "failure" of a structure is thus not confined to a failure to carry the required load, but includes any shortcoming in meeting the client's expectations in respect of time, cost or quality.

1.2 *The forensic engineer's role in legal disputes on structural "failures"*

There are two distinct roles that a forensic engineer may undertake in connection with a (potential) legal dispute – an expert consultant who acts as part of a legal "team", and an independent expert who is not part of the legal team, and gives testimony in a court or arbitration hearing on the basis of his/her independent assessment of the cause of the failure.

It is important that a forensic engineer understands clearly the role that she/he has been engaged for, as it determines how she/he is engaged and instructed, what documents are provided, what investigations should be conducted and what type of report will be required.

1.2.1 *Expert consultant*

An expert consultant acts as a member of a legal "team", and accordingly may be privy to confidential details about the legal "case", including the client case theory and the opinions of other experts acting for the client. Given such close association with the legal preparation of the client's case, it may be difficult for an expert consultant to be seen by a judge or arbitral tribunal to exercise his/her independent judgement, without regard to the exigencies of the case.

An expert consultant (sometimes referred to as a "dirty" expert) can provide forensic engineering advice at all stages of a dispute on a structural failure, including the identification and engagement of suitable independent experts. However, because such an expert consultant may be perceived as "tainted" by the client's case, she/he is usually not the appropriate person to give forensic engineering evidence in court or before an arbitral tribunal.

1.2.2 *"Independent" or "clean" experts*

An independent (or "clean") expert who is not part of the legal team and is not privy to confidential aspects of the client's case will be suitable to provide an expert opinion on forensic engineering issues that will be seen by a tribunal to be independent. To maintain the independence of such an expert, it will be necessary to ensure that she/he is appropriately briefed, does not have any inappropriate contact with the legal team and is not provided with any documents that could taint his/her independence or ability to express an independent view.

Engagement of an independent expert requires careful documentation by the legal team so that all communications are transparent and the evidentiary material on which the expert opinion is based is clear. Independent experts in some jurisdictions have obligations to formally acknowledge that they have formed an independent opinion, and that they are not acting as an advocate for their client's case.

1.3 *The forensic engineer's skills*

Forensic engineering, in common with every other branch of engineering, involves the application of both science and art.

The fundamental skill needed by a forensic engineer is a deep knowledge of the science of engineering relevant to the issues that need to be investigated. This is gained through training, study and experience. A perceived lack of this relevant expertise by a legal tribunal may disqualify an independent expert from giving expert evidence.

Equally important to the science of engineering is the "art" of how a forensic engineer should apply his/her engineering knowledge to prepare and conduct investigations to determine the facts, apply the relevant engineering principles to effectively determine the cause of failure, and to prepare reports or testimony that are soundly based, relevant, cogent and persuasive.

The art of the forensic engineer who is required to investigate and report on a failure is fundamentally different to the art of the engineer who designs a facility. The fundamental question addressed by the design engineer is "how" to apply the art and science of engineering to synthesise all the required elements into a functional and operating whole to satisfy the client's requirements. By contrast, the fundamental question addressed by the application of the forensic engineer's skills is "why" did the failure occur. The forensic engineer must keep an open mind whilst making observations, collecting evidence and planning and conducting the necessary investigations. She/he may need to carry out complex and sophisticated analyses to determine why the failure occurred. The results of theoretical analyses will need to be reconciled with all the available evidence of the failure.

The forensic engineer needs to have refined observation and recording skills, to take note of and document all possibly relevant features observed at a site inspection of a "failed" structure. It is important that a forensic engineer takes note of all matters that may have an influence on the cause of the "failure", whether or not they appear to be consistent with a particular theory of failure.

The "art" of the forensic engineer importantly includes good written and oral communication skills. The design engineer communicates the design to be constructed by means of drawings and specifications to those in the construction industry who understand the "language". The forensic engineer usually communicates his/her findings to those not knowledgeable in engineering or construction – a Board of Directors, corporate counsel or a judge. The ability to communicate complex engineering concepts in simple understandable terms is an essential aspect of the art of the forensic engineer. Appropriate photographs, models or simplified diagrams or animations are usually more effective in communicating complex technical issues to lay people than a detailed technical description. A brief but comprehensive executive summary at the start of a report is important to convey the fundamental findings to senior people.

A forensic engineer may be engaged to provide an opinion as to whether the original design was prepared on a reasonable basis. In such a case the forensic engineer should have relevant recent design experience and maintain an analytical approach to determining whether the original designer acted reasonably, rather than opining on what the forensic engineer might have done if she/he was the designer.

This emphasises the importance of the forensic engineer maintaining the highest professional and ethical standards. A forensic engineering report may have dire consequences for the professional career of the designer of a failed structure. A further aspect of the forensic engineer's ethics is the obligation to advise the client if she/he does not possess all the skills required for the investigation.

1.4 *Engagement of a forensic engineer*

A forensic engineer is usually engaged by a lawyer acting on behalf of a client with an interest in a structure to be investigated. This is particularly important if legal professional privilege is to be asserted. If it is not known whether or not litigation or arbitration might ensue, it may be appropriate in the first instance to engage an expert consultant who can assist the legal team in whatever manner is appropriate and to the fullest extent possible, recognising that an independent expert may have to be engaged at a later time.

In principle, engagement of a forensic engineer is no different to engaging an engineering consultant for any design or construction task. It is necessary to define the scope of the forensic engineer's work, select a forensic engineer with the appropriate skill and experience to carry out the scope of work, and execute a consulting agreement with appropriate terms and conditions that specify the requirements of time, cost and quality.

Defining scope with precision is fundamental to selecting the most appropriate forensic engineer, because it is the scope that determines the threshold issue of the skills required. Of course, the scope may evolve over time: the engaging lawyer may not understand the full ramifications of the issue at the outset, or have insufficient knowledge of the technical requirements, or the forensic engineer's investigations may go in a different direction to that initially anticipated.

Part of the scope of the forensic engineer may be to define the full scope of services required, after an initial investigation of the facts and the issues. Nevertheless, the initial scope should be defined by the engaging lawyer as clearly as possible, particularly what are the "deliverables": those outputs of the forensic engineer's intellectual property provided to the client, e.g. a report on the causes of failure, or a presentation to senior management as to the recommended further investigations necessary.

Inevitably there is a trade-off between the conflicting demands of completing the scope to the appropriate quality within the required time frame at an acceptable cost. In selecting the most appropriate forensic engineer, the engaging lawyer will have to make his/her own value judgment on where the appropriate balance lies. In this author's experience, the emphasis should undoubtedly be on the quality of the forensic engineer and his/her support organisation, and not on ad hoc determinations of budget cost or timeframe. Typically, the skills and experience that will be required for a high-level forensic investigation will only be available in very senior individuals with years of experience. Such individuals are usually very busy, and inevitably have a high charge rate, particularly in circumstances where they are required to commit significant periods of time for court appearances.

It is suggested that typically, a forensic engineer should be selected on the basis that she/he can provide the required quality, and the conditions of engagement should be tailored to ensure that the services are delivered within the required time and budget. Detailed suggestions for the engagement of forensic engineers are made by Charrett & Potts (2012).

2 PUBLIC INQUIRIES INTO STRUCTURAL FAILURES

2.1 *Introduction*

Public inquiries into structural failures are important not only for establishing the causes of the failures, but for identifying changes that need to be made to avoid future failures from similar causes. Such public inquiries invariably rely heavily on forensic engineers to assist the investigating tribunal to determine the causes of failure, both technical and non-technical. This paper draws on some reports of public inquiries into high profile structural failures to identify some relevant "non-technical" issues that have invariably accompanied the direct "technical" causes of failure.

Public inquiries have a number of unique features that make them an especially valuable resource for the assessment of structural failures. Although only conducted for a small number of high profile failures, typically involving loss of life, public inquiry reports are of greater significance then their conclusions on the particular failure. In contrast to the judicial inquiry a judge or arbitrator makes in civil litigation to determine legal liability for failure as between the litigants, a public inquiry is an administrative process in which the objective is to determine the cause of the failure and the lessons learned from it, in order to guide actions in the future to avoid a repetition. Typically, the report of a Public inquiry contains detailed technical information on the engineering "state of the art" relevant to the failure.

In the common-law world, public inquiries are conducted along similar lines to adversarial court proceedings. Counsel are appointed to assist the tribunal, and interested parties engage their own counsel to represent their interests in the inquiry. Lay and expert evidence is adduced in a similar way to court proceedings. Forensic engineers may be called as expert witnesses on behalf of the inquiry itself, or a party whose interests may be affected by the outcome of the inquiry.

The details of the failures discussed in this paper, as revealed by the reports of the public inquiries that ensued, highlight many issues relevant to the contracts and the execution of those contracts. In each case the direct "technical" causes of failure were accompanied by contractual and project execution deficiencies that did not prevent or detect the onset of failure before it was too late. No doubt all of the disasters had their genesis in human failings, generally and perhaps invariably in a combination of individual failures. The importance of identifying the "non-technical" issues contributing to failures is in determining what changes to project execution procedures and contractual arrangements are required to prevent a repetition of failures from similar causes.

The failures listed in the following sections all resulted in loss of life, and were followed by public inquiries that determined and documented both the technical and non-technical causes of failure. Following a brief description of each of the failures and its subsequent inquiry, some of the lessons learned from these failures are discussed. The discussion of lessons learned highlights the similar findings on important contractual and procedural issues that have contributed to the different failures. Further details on the public inquiry reports referred to can be found in Charrett (2008), Charrett (2009) and Charrett (2012).

It will be noted that most of these failures occurred a long time ago, and are still remembered by structural engineers today for the technical issues they identified, and the impact they have had on the practice of structural design. However, in this author's view, the contractual and procedural lessons learned appear to be forgotten by subsequent generations. Revisiting these historical reports reinforces the importance of designing and constructing structures within contractual arrangements that encourage and support clear lines of authority and communication, with appropriate allocation of risks and an appropriate balance between the required time, cost and quality for project execution.

2.2 *Québec Bridge, Canada (1907)*

The Québec Bridge over the St Lawrence River is a steel cantilever bridge with a main span of 548 m. It was procured by a company specifically incorporated to finance, build and operate a toll bridge, which called tenders on minimal documentation, including a clearance diagram and specifications. The company's consulting engineer, Theodore Cooper, recommended an increased span and increases in the allowable steel stresses, significantly above those in common use at the time.

The construction contractor, Phoenix, entered into a contract to design and construct the bridge to the satisfaction of Cooper and the company's engineer. Whilst Phoenix was responsible for preparing the design, Cooper approved all of the designs on behalf of the company. However, he was only concerned with the bridge in its final constructed configuration, and had no involvement with the erection engineering, or with any inspections in the shop or in the field, and made no inspections during construction.

During erection of the suspended span the south anchor arm of the bridge collapsed completely, resulting in the death of 74 men. Many of the joints were not fully riveted, and major compression members suffered from increasing lateral deflections, which gave prior warning of substantial structural distress. Unfortunately, the site personnel did not have sufficient experience to recognise the impending danger, and Cooper was only made aware of it too late.

After the collapse, the Government appointed a Royal Commission, comprising two practicing civil engineers, and a professor of engineering. The Commission's report determined the technical causes of the failure, and made a number of observations on the contractual and procedural issues that were relevant. This report was for many years regarded as a classic of its kind, and many of its conclusions are still relevant to the practice of structural engineering today.

The technical reason for the collapse was the failure of the lower chords in the anchor arm near the main pier, due to their defective design. The stresses that caused the failure were not due to abnormal weather conditions or accident, but arose because of the errors in judgment on the part of the designer and Cooper.

The collapse of the bridge is still remembered by engineers because it drew attention to the lack of knowledge on the behaviour under load of built up columns with lattice bracing. It is interesting to note that although considerable theoretical work on the design of large compression members was carried out after the failure of the Québec Bridge, testing of major compression members were still regarded as prudent in structures designed in the 1920s such as the Sydney Harbour Bridge.

2.3 *Westgate Bridge, Melbourne Australia (1970)*

Westgate Bridge comprises a total of 21 concrete spans, with five steel box girder spans over the Yarra River. It was procured under a forerunner of modern Public-Private Partnership. The design of the steel box girder spans was prepared by consulting engineers engaged directly by the Principal, and contractors under the consulting engineer's supervision carried out fabrication and construction.

After the original contractor for fabrication and erection fell seriously behind schedule, the Principal appointed an erection contractor to complete the erection under a "cost plus" labour management contract. The method of erection chosen by the original contractor was unusual, using two half spans jacked into position and joined along the longitudinal centreline. The erection contractor experienced difficulties because of unequal deflections of the half spans, and applied kentledge to correct the difference in camber. The application of this additional weight caused a buckle near a splice at the middle of span 10–11. In an attempt to eliminate this buckle, about 30 bolts were removed. The span collapsed and 35 workers died.

The Government appointed a Royal Commission, comprising a Supreme Court judge, a professor of civil engineering and a distinguished bridge engineer. The Royal Commission sat for 80 days, hearing evidence from 52 witnesses. It was required to enquire into and report on the circumstances surrounding and the cause or causes direct and indirect of the failure of span 10-11, and whether any aspect of the design was inadequate or undesirable.

The Royal Commission found that the immediate cause of the collapse was the removal of the bolts. However it made forthright comments that the design was approached in a "*disorganised and unsystematic manner and without any real guidance being given to the engineers doing the work*" and "*the calculations contain a great many errors of arithmetic and engineering principle*". It found that the primary cause of the collapse was that the consulting engineer "*failed altogether to give a proper and careful regard to the process of structural design*".

2.4 *Milford Haven Bridge, Wales UK (1970)*

Westgate Bridge collapsed shortly after the steel box girder Milford Haven Bridge in Wales (now the Cleddau Bridge) collapsed during construction. The UK Government appointed a technical Committee of Inquiry to investigate the collapse of the Milford Haven and West Gate bridges, their terms of reference being to consider whether it was necessary to reconsider the design and method of erection of box girder bridges about to be erected in the UK, to draw up technical guidelines for bridge engineers, to advise on any special matters affecting contract procedures and to recommend further research and development.

The 5 man Committee was chaired by Dr Merrison, whose name is often associated with the technical recommendations on the design of box girder bridges made by the Committee. It concluded that the collapse of the bridge was caused by the inadequacy of the design of a vertical pier support diaphragm, which failed in compression over the column.

The lessons from Milford Haven primarily concerned the inadequacy of the design methods used for the permanent design and checking the safety during erection. The "Merrison Rules" in the final report, comprehensive design and workmanship rules for the stress analysis and design of steel box girder bridges, are still used today in the design and checking of steel box girder bridges.

In its Final Report, the Committee accepted the Royal Commission's assessment of events which led to the collapse of the Westgate Bridge, and drew considerable support from its recommendations on contractual and procedural aspects: *"While there were also fundamental defects in the erection procedure and permanent design of the West Gate Bridge, we regard the failures of site organisation and of communication between the principal parties – client, engineers and contractors – as of more general significance in this case."*

2.5 *De La Concorde Overpass, Quebec Canada (2006)*

The de la Concorde Overpass was a prestressed concrete bridge, built in the 1970s and designed and constructed generally in accordance with the prevailing standards. In 2006 a span collapsed under light traffic load, killing five people. The Government established a Commission of Inquiry, with an attorney President and two engineer Commissioners.

The Commission conducted its inquiry in accordance with the principles defined by the Canadian Supreme Court, and concluded that, whilst there were a number of defects and shortcomings, both technical and procedural, none of those by itself would have caused the collapse which resulted from a chain of causes.

The reason for the failure of the overpass was a shear failure in a reinforced concrete cantilever slab, the concrete of which had deteriorated over the years. The reinforcement design satisfied the code requirements at the time, but would not do so now, nor would the detailing of the reinforcement be regarded as satisfactory today. The weakness of the detail was due to errors in placement of the reinforcement (a quality-control failure during construction), and low quality concrete that was not suitable to resist freeze-thaw cycles (arising from ambiguity in the specification). There were further contributing causes that the thick slab was not watertight (the specified waterproof membrane had apparently not been installed) either originally or during subsequent refurbishment), and refurbishment work in 1990 caused damage that was not evaluated.

In addition to these technical issues, the Commission identified a number of procedural failures in respect of both design and construction.

2.6 *Procedural and contractual lessons*

The following are some of the contractual and project execution lessons relevant to major engineering projects extracted from the public inquiry reports discussed above.

2.6.1 *Quebec bridge*

- The difficulties and time involved in raising finance for a project should not preclude sufficient time allowance for the preparation of initial studies, the design, tender documentation and the execution of the works.
- Unquestioning reliance on the skill and experience of an individual engineer may be misplaced without adequate peer review.
- A project owner requires adequately qualified and experienced technical staff with the appropriate authority for both the design and erection phases, even if it procures its project via a design and construct contract.
- An independent engineer should review the engineering design of a major project, without reference to the designer's calculations.
- The scope of the engineer's engagement should include responsibility for both design and erection, with compensation commensurate with the proper execution of that scope.
- An owner with limited financial resources may be subject to cost pressures that result in inappropriate engineering decisions.
- The construction contractor needs to have an appropriately qualified and experienced erection engineer on site with an understanding of the design and full authority for the erection.
- Appropriate allowances should be made for the additional risks inherent in unusual structures or structures of a scale not attempted before, and this may require testing of components.

2.6.2 *Westgate bridge and Milford Haven bridge*

- The client must be assured that the engineer will have adequate and appropriate resources.
- A certified independent check should be carried out to confirm that the permanent design is adequate and complies with the relevant technical requirements.
- There should be a clear division of responsibilities between engineer and contractor, and the contracts between the parties in a major project should reflect their practical engineering relationship.
- A certified independent check of the erection method should be performed by an engineer independent of the design engineer, who should be given full details of the erection method and have a right of veto over it.
- The contractor should submit a construction programme to the engineer for its approval.
- The independent checks of the permanent design and of the erection method should be complete when work starts and the erection of the relevant part of the superstructure starts respectively.
- The contractor should be allowed sufficient time to prepare itself for the start of work and the client

and the engineer should be prepared to consider a revision of the programme in the event of slippage.
- The engineer should carefully monitor the progress of construction to ensure compliance with the agreed erection method, and should scrutinise the contractor's site staff and where necessary exercise the powers under the contract.
- The client should satisfy itself as to the adequacy of the engineer's site representatives, and the functions and tasks of the engineer's site representatives should be defined in writing.

Note the close similarity to the issues identified by the Quebec Bridge Royal Commission, 65 years previously.

2.6.3 *De La concorde overpass*

- A transparent process should be used for selecting consulting engineers based on competency and past performance, with cost only considered for those firms meeting the competence criteria.
- A responsible engineer should validate the concept, drawings and calculations of structural designs.
- Contractors should be prequalified on the basis of their ability for the type of structure to be built, with cost only considered for contractors meeting the competence criteria.
- When awarding contracts for consulting engineering or construction, it is important to ensure that the key personnel on which prequalification was based will be available for the duration of the work.
- Subcontracting requirements should be identified in bids, and contractors required to produce a work quality control plan for their own and subcontract work.
- On completion, an engineer should certify that the structure was built in accordance with the drawings and specifications and all the documents associated with the work and structure should be assembled and kept during the entire life of the structure to assist with inspection and maintenance programs.
- Owners of structures need to evaluate the performance of consulting engineering firms and contractors on completion of a project, and keep the evaluations on record.

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