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The roles of technical engineering experts in construction disputes

Engineering experts are often engaged in construction disputes involving defects and collapses to opine on both the cause of a failure and the technical aspects relating to whether or not the structure was designed and constructed in compliance with the relevant legal requirements. This article explores the material and processes typically utilised by experts in reaching such opinions and discusses why addressing the causation question requires forensic expertise, while the compliance question requires design expertise, both of which are quite distinct.

Introduction

Legal teams regularly encounter construction disputes involving questions of delay and quantum, and as a consequence regularly brief experts to opine on them. They are therefore relatively familiar with the material these experts require and are aware – at least to some degree – of the technical processes the experts rely upon. Less common, however, are disputes arising from defects or physical failures, with legal teams typically having less familiarity with how experts engaged on such matters proceed. These engagements can quickly become black box in nature, presenting difficulties in assessing an expert's progress and the robustness of their opinion.

This article introduces two of the major roles technical engineering experts play in defect disputes: opining on the adequacy of a design; and opining on the cause of the defect or failure. We will explore these two different roles using a case study – the investigation into the 2007 collapse of the I-35W Highway Bridge in Minneapolis.

The I-35W Bridge

The I-35W Highway Bridge in Minneapolis, Minnesota was designed by engineering consulting firm Sverdrup & Parcel and Associates, and was opened to traffic in 1967. It was more than half a kilometre long, consisted of fourteen spans and was eight lanes wide. The main span was a steel truss, supporting a reinforced concrete deck, which stretched over the Mississippi River. By 2004 it carried a daily average of 141,000 vehicles, and had undergone three major modification projects – including the replacement of a median barrier, the upgrade of the outside concrete traffic railings and the installation of an anti-icing system – two of which added loading to the bridge.

The third project involved replacing the concrete wearing course, and as part of these works Progressive Contractors Inc (PCI) were preparing for a 160m long concrete pavement pour on the southbound lanes. Seven previous pours had been completed since the project's commencement in June 2007 and for this, the eighth, 50mm of existing concrete wearing course had been removed in preparation for a planned pour at 7pm on the evening of 1 August.

The pour never took place. At 6:05pm a 300m section of the deck truss collapsed, with a 140m piece falling 33m into the river below. A total of 111 vehicles were on the collapsed section, but only 17 were recovered. Tragically, 13 people lost their lives and 145 were injured.

A formal investigation into the collapse was undertaken by the National Transportation Safety Board (NTSB). The complete report is available on the NTSB's website, but rather than stepping through the NTSB's findings in detail we will instead use portions of their report to illustrate the steps involved in undertaking a forensically sound investigation.

Generally speaking, the questions that require examination following such a failure can be separated into two broad, but distinct, categories:

- Was the structure designed and constructed in compliance with the relevant legal requirements?
- What caused the failure or defect?

Compliance

Depending on the circumstances of the matter, the relevant legal requirements might typically include those imposed by a contract, a standard of care in tort, an obligation or duty imposed by statute or a combination of the above. Determination of the relevant legal requirements is therefore a legal concern, so for the purposes of this article, in order to focus on engineering aspects, we will limit ourselves to consider whether or not the designers of the I-35W Bridge designed the structure in compliance with the relevant design codes (we will not explore whether or not a failure to comply with the relevant design codes constituted a failure to comply with the relevant legal requirements).

To assess if a structure was designed in compliance with the relevant codes, the expert will typically use a *design process* to review the initial design. Before examining how the process is used in this manner, we will first explore its use in everyday engineering design. At its most fundamental, the goal of the design process is to produce a structure that meets client expectations from a functional perspective, is elegant, is economical and complies with the relevant design codes. To ensure compliance from an overall strength perspective – that is, to ensure the structure is at a very low risk of collapse – a designer typically utilises highly prescriptive design codes, which specify the loading to be applied to the structure, as well as the methodologies used to determine if the structure's response to this loading is satisfactory. The designer will also undertake a range of serviceability checks, such as

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ensuring the structure does not excessively vibrate or deflect, which if not considered appropriately can lead to defects. We, however, will only explore the issue of compliance from an overall strength perspective.

Once the relevant design code is selected, the designer applies the design process. The subtleties of the design process vary across structural engineering industries, so for this article we will limit ourselves to the broad process set out below:

- The designer estimates the design loading that applies – essentially the estimated maximum loading that the structure will be exposed to throughout its design life (eg, wind loads, seismic loads, traffic loads). This design loading also includes Factors of Safety that increase the loading and introduce conservatism into the process. These Factors of Safety are often playfully referred to as *Factors of Ignorance*, which gives an illustration of how the design process focuses on managing, as opposed to investigating, unknowns.
- The designer makes an educated guess as to the preliminary sizes of the structure's members (eg, beams, columns, slabs) and connections based on experience, rules of thumb or industry guidance.
- The designer estimates how that structure will respond and perform when subject to the applied loading, before ensuring that the individual members/connections have the required strength and stability to safely resist it. In broad engineering terms, the designer is estimating *loads*, calculating the *actions* of these loads on individual members/connections and ensuring each of these members/connections has the required *capacity* to resist the loads. This is one of the key compliance steps: if the action on a member/connection is less than its capacity, it is typically considered to comply with the design code; if the action is greater, it may be considered as a lack of compliance.
- There are also checks for the stability of the structure as a whole.

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The designer is striving for efficiency – the elements must have the required capacity, but should not have excessive over-capacity, which would make them inefficient. The process is, therefore, one of synthesis, highly reliant on experience of what has worked in the past. In this process the computer may play a role, particularly when it comes to determining the actions on the individual members/connections. A virtual model is built of the structure using an analysis software package (eg, finite element analysis), the loading is applied to the model, and the actions in all the members/connections determined.

When providing an opinion as to whether or not a designer complied with the appropriate design codes, this is the process the expert will typically utilise – albeit without the need to determine the preliminary size of the members because they are already defined in the design documents. If any members/connections have actions greater than their capacity, the expert may conclude that the structure fails to comply. Therefore, the expert relies on their design expertise, which is based on knowledge of how their industry approaches the design of such structures, along with material in the form of the design documents, including the drawings and specifications.

In the case of the I-35W Bridge, the NTSB concluded the design did not comply with the relevant code. The bridge's main span was comprised of steel members connected by gusset plates - flat steel plates riveted to individual members. The NTSB found that eight of these connections had gusset plates that did not comply – rather than being 25mm thick as per the code, they were only 12mm thick. In structural engineering terms they were under-designed, which resulted in dramatically weaker connections.

So there was a lack of compliance with the design code, but did this lack of compliance actually contribute to the collapse?

Causation

Just because a structure does not comply with a design code does not necessarily mean it will fail. The I-35W Bridge is a good example: it gave 40 years of satisfactory service despite having a significant design error – doing so as a result of the inherent conservatism in structural design. Conversely, just because a structure is designed properly does not mean it will not fail, for example, it could be subject to loads greater than designed for or it may not have been constructed in accordance with the design. So how would an expert determine causation? And how would they determine if the under-designed gusset plates played a role?

To answer these questions the expert uses the forensic process – a process quite different to the design process. The process is one of analysis, as opposed to synthesis, and has the following key stages:

- *Evidence*: Evidence collection is the most critical, yet often the most poorly executed, stage of the process. The expert collects the available physical evidence in an objective manner, typically by taking photographs, measurements and retrieving physical samples. In construction failures the timely collection of this evidence is important because of its perishable nature: for example, steel failure surfaces corrode quickly if left exposed to the elements, and the urge to *clean up* on failure sites can be very strong – evidence can be quickly moved elsewhere.
- *Hypotheses development*: At this stage the expert develops a wide range of hypotheses regarding the cause of the failure. This stage tends to be iterative, introducing new hypotheses and refining others as the investigation proceeds. While this stage can occur interchangeably with the evidence collection stage, there is significant merit in keeping them as separate as practicable to avoid early fixation on a specific cause, which can lead to confirmation bias.

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- *Hypotheses testing*: In this stage the expert tests each of the failure hypotheses against the available evidence – a stage we will explore in further detail below.
- *Cause of failure*: Ideally, by this stage of the investigation a range of failure hypotheses will have been ruled unlikely based on physical evidence, with the one hypothesis most consistent with the evidence being considered the likely cause. This is not to suggest that there is a single cause of failure – there may be multiple contributing causes – but this single hypothesis represents the one sequence of events (or contributing causes) that resulted in failure. Often, however, it is not possible to arrive at a single hypothesis; there may remain multiple hypotheses that are consistent with the evidence, but this situation typically eventuates when there is an absence of further evidence to separate the remaining hypotheses.

We will return to the investigation of the I-35W Bridge collapse to illustrate these various stages. Beginning with evidence collection, the following key pieces of evidence are usually present in all failures:

- *Post collapse configuration*: Capturing the state of the collapsed structure before it is disturbed is a key step. Of course, all safety and rescue attempts will take precedence over evidence collection, but outside of these tasks any disturbance should be minimised. Photography and video records are valuable tools, and in the case of the I-35W Bridge the NTSB combined this information with evidence captured by a surveillance camera showing ten seconds of the collapse.

  One of the primary reasons for capturing the post collapse configuration is that it typically provides information about the failure sequence. For example, if Beam A lies beneath Beam B, then Beam A hit the ground before Beam B. This evidence is important when large, complex structures – like the I-35W Bridge – are involved because of what is known as progressive collapse. Typically, one or more members/connections will fail – what we call the *initiating event* – which will then precipitate the progressive collapse of the structure as a whole, with damage to further members/connections ensuing. The expert involved in a causation investigation needs to determine the member/connection that initiated the collapse, which is the physical cause of the failure, as opposed to the damage that was sustained afterwards. Detailed knowledge of the failure sequence can prove invaluable in this process.
- *Critical geometry*: Recording the dimensions of the critical members/connections is important for the obvious reason that it allows confirmation that their dimensions are consistent with the design documents. It is, however, remarkable how many experts do not take such records and rely on the details presented on the design documents

alone. At a basic level, in order to effectively and efficiently rule out a fabrication or construction error, this step is critical.

In the case of the I-35W Bridge, the NTSB determined that the geometry of the key elements in the structure was indeed consistent with the design documents.

- *Material properties*: It is also on occasions important to confirm the material properties of the critical members/connections to ensure they comply with the design specification. While the testing of this material may not be required in the short term, samples should be collected and stored appropriately to ensure testing can be undertaken at a later date if deemed necessary.

  In the case of the I-35W Bridge, samples were taken of structural members/connections, including from the under-designed gusset plates. In all cases the NTSB confirmed the material properties were largely consistent with specifications.

- *Actual loading*: Knowledge of the actual in-service loading on the structure at the time of failure is also a primary input into the process. For example, wind loading can be estimated from meteorological data, seismic loading can be determined from seismic data, and snow loading can be estimated by measuring, in a timely manner, the depth of snow on nearby roofs.

  When it came to determining the loading on the I-35W Bridge the NTSB had a stroke of good fortune. Two hours and fifteen minutes before the collapse a passenger in a commercial airliner departing Minneapolis/St Paul International Airport took a photograph of the bridge as they flew over it. This photograph showed substantial construction loads on the bridge, and along with other data allowed the NTSB to estimate the loading at the time of the failure. This construction loading was in place as part of the concrete wearing course replacement works - the contractor stockpiled gravel and sand on two of the bridge's southbound lanes. This was the result of the Minneapolis Department of Transport's specification providing only a one hour window between initial concrete mixing and final screeding. The contractor, without the appropriate permission, decided to mix the concrete as close to the placement site as possible. So by 2:30pm that afternoon, 84 tonne of gravel, 90 tonne of sand and 90 tonne of construction vehicles, equipment and personnel – totalling 264 tonne spread over an area of approximately $300m^2$ – was in place for the pour. In engineering terms this was equivalent to four times the design load of the bridge,

Aerial view of the I-35W Mississippi River Bridge and the surrounding area. The bridge collapsed in August 2007. Just to its right is the older 10th Avenue Bridge. Credit: U.S. Geological Survey

assuming it had actually been designed in compliance with the design code, and we know it had not.

- *Other*: Each individual failure typically has other pieces of critical evidence which are failure specific, and in the case of the I-35W Bridge it was in the form of photographs of the under-designed gusset plates. In 1999 and 2003 the firm URS and the University of Minnesota were engaged to undertake strain measurements on the bridge. Both took photographs of the bridge's main span truss, which clearly show significant distortion in most of the under-designed gusset plates – a level of distortion that should have raised the alarm that these gusset plates were distressed (as an aside, despite the bridge being inspected regularly, these distortions went largely unnoticed by bridge inspectors).

So before undertaking engineering calculations, the evidence paints a compelling picture: there was abnormal loading to the tune of four times the design load on the day of the failure and there were under-designed gusset plates that exhibited distress more than eight years prior to the collapse. This evidence points to a hypothesis where the abnormal loading, either with or without the presence of a design error in the gusset plates, caused the failure. In order to test this, the NTSB, along with others, developed a computer model of the bridge – a virtual model they could manipulate and test. The model indicated that when the structure was subject to the abnormal loading it would likely collapse, with the analysis predicting that failure would initiate in the under-designed gusset plates, which distorted and fractured in a manner consistent with the evidence collected in the post collapse configuration. This is an example of the appropriate use of computer modelling in a failure investigation: the model inputs were confirmed with physical evidence - in the form of geometry, material properties and loading – and similarly the model outputs were also confirmed using the post collapse configuration. Where possible this *bookending* with evidence is essential for a forensically sound investigation.

So did the under-designed gusset plates play a role in the collapse, or was the abnormal loading the sole cause? In other words, would the structure have collapsed even if it had been designed in accordance with the design code? To investigate this hypothesis the NTSB increased the thickness of the gusset plates in the computer model to 25mm, as if they had been designed correctly. When the abnormal loading was applied to this model it indicated that the structure was unlikely to fail – the under-designed gusset plates, therefore, contributed to the failure.

Through a similar form of hypothesis testing the NTSB were able to rule out other potential causes of failure and determine that the abnormal loading, in combination with a lack of compliance with the design code, was the cause of the failure in August 2007. Loading added as part of earlier modification works also contributed. This investigation highlights that when answering the causation question the expert relies on their forensic expertise, which is based on investigative skills, evidence collection, and knowledge of how structures fail in practice, with physical evidence being the key material they rely upon.

Closure

The investigation of the I-35W Bridge illustrates the two very different roles that engineering experts can play in construction disputes involving defects. The causation investigation relies on evidence, the forensic process and forensic expertise. The compliance investigation relies on the design documents, the design process and design expertise. Both types of expertise are quite different: design is a process of synthesis, with an expert opining on *what should have happened* in order to comply with the relevant legal requirements; forensics is a process of analysis, with the expert opining on *what actually happened* in the real world.

Interestingly, many of the issues with engaging engineering experts on such matters arise from a lack of separation between the two roles. For example, in the absence of evidence the causation expert may begin to rely on the design documents, along with the conservative assumptions that underlie them, which may not be representative of how the structure is performing in practice. Similarly, the compliance expert may be unduly influenced by evidence from the failure, which may change how they approach their design review.

Ultimately these two roles are quite different, require different expertise, experience, processes, and rely on very different material. Separation of these roles is the key.

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