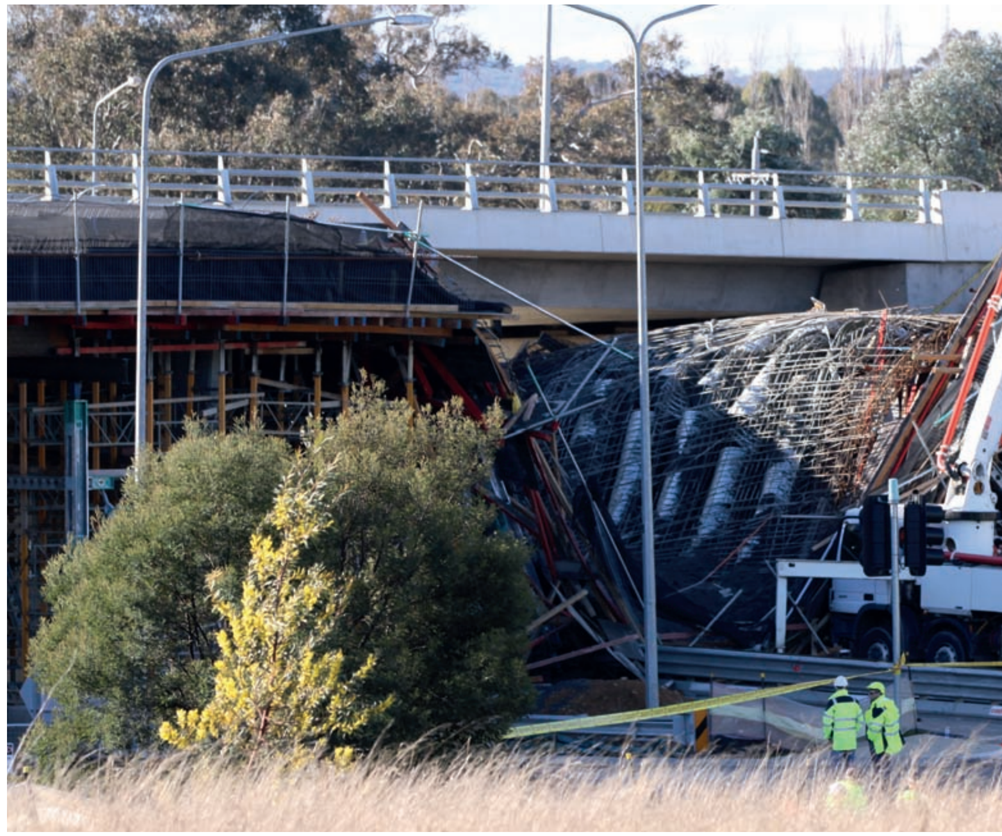
Human factors and bridge failure

Sean Brady stresses the importance of managing "human factors" to reduce human error within bridge projects, citing international examples from which lessons can be learned.



The engineering profession is well aware that lessons learned from past failures can play an important role in preventing reoccurrence. Ken Carper, the US forensic engineer, suggests that failures result from a variety of causes involving both technical and "human" factors (human error/procedural issues). While knowledge of technical factors is critical, it is often the human factors that allow these technical factors to culminate in failure. At their most basic, human factors can be summarised in what forensic engineer Neal FitzSimons described as the four horsemen of the engineering apocalypse: ignorance, incompetence, negligence and avarice[1]. The management of human factors is not only critical during a bridge's design and construction phases, but is equally important throughout its lifetime. However, managing these human factors is not a new challenge.

As far back as the 1700s, John Smeaton, the founder of the Society of Civil Engineers, described a similar issue: "Stone, wood and iron are wrought and put together by mechanical methods, but the greatest work is to keep right the animal part of the machinery". In modern times, of course, the "animal part of the machinery" is typically managed through the creation and implementation of Quality Assurance programmes aimed at identifying human errors and omissions before negative consequences ensue. Therefore, a review of recent bridge failures provides a useful reminder of the typical human factors that may be encountered by engineers involved in the design, construction, operation and maintenance of bridges.

> "It is often the human factors that allow these technical factors to culminate in failure"

While the vast majority of bridge structures perform satisfactorily throughout their lifetime, bridge failures still continue to occur throughout the world, with the collapse of temporary formwork during a bridge's construction in Canberra, Australia, being a recent example (Figure 1). Fortunately, the failure resulted in no fatalities, but it was the third such temporary works collapse in recent years - a cable-stayed pedestrian bridge failed during construction in the US in 2008, and a 20m long section of formwork collapsed during a concrete pour for a partially cable stayed bridge in the Pyrenees in 2009. In addition to these construction failures, there have also been a number of catastrophic bridge collapses in service:

I-35W Highway Bridge: Minneapolis, USA

Just after 6pm on Wednesday 1 August 2007, the main span of the I-35W highway bridge in Minneapolis collapsed into the Mississippi River, resulting in 13 fatalities (Figure 2). The subsequent National Transportation Safety Board (NTSB) investigation identified under-sized gusset plates, in combination with increases in dead and live load on the bridge, as the cause of collapse.

While the under-sized gusset plates, which were the result of a design error, initiated the bridge's collapse, it was human factors that permitted this error to go unnoticed for 40 years, despite numerous opportunities for its identification. Among the human factors identified by the NTSB investigation were:

- "Even though the bridge design firm knew how to correctly calculate the effects of stress in gusset plates, it failed to perform all necessary calculations for the main truss gusset plates of the I-35W bridge, resulting in some of the gusset plates having

inadequate capacity"[2]

- "The design review process used by the bridge design firm was inadequate in that it did not detect and correct the error in design of the gusset plates"[2]
- "Neither Federal nor State authorities evaluated the design of the gusset plates for the I-35W bridge in sufficient detail during the design and acceptance process to detect the design errors in the plates, nor was it standard practice for them to do so"[2]
- During the bridge's lifetime a number of load ratings were undertaken. However, the NTSB investigation found that the capacity of the gusset plates was not evaluated as part of these load ratings and concluded that had the "American Association of State Highway and Transportation Officials guidance included gusset plates in load ratings, there would have been multiple opportunities to detect the inadequate capacity of the U10 gusset plates of the I-35W bridge deck truss"[2]
- The potential for failure was exacerbated "because bridge owners generally consider gusset plates to be designed more conservatively than the other members of a truss"[2].

An assumption that proved incorrect in this case.

Figure 1
Bridge over Barton Highway, Canberra, Australia. 15 workers were injured

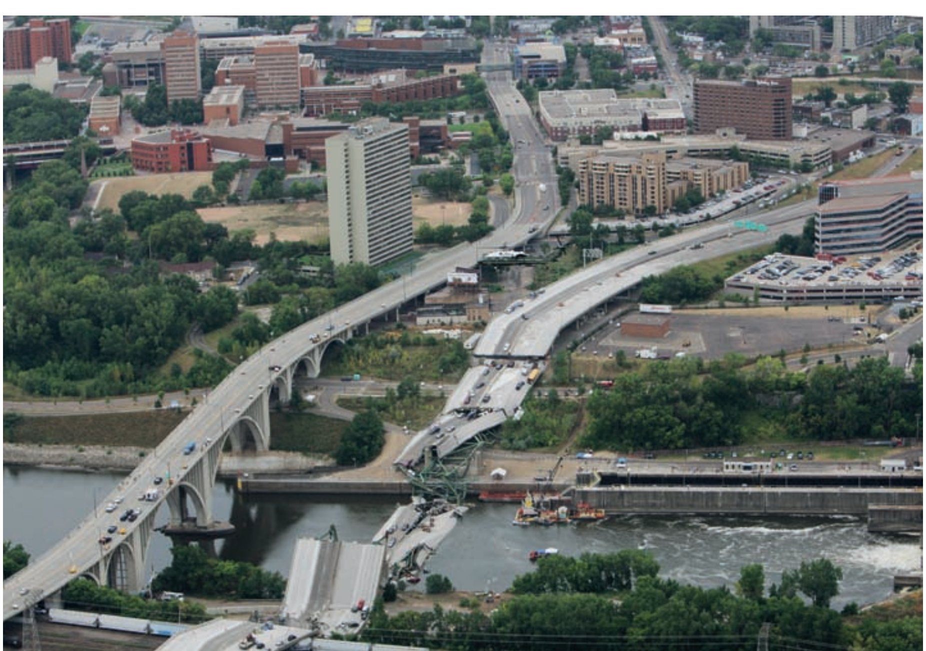


Figure 2
Collapse of I-35W Highway Bridge into Mississippi River, USA. 13 people were killed

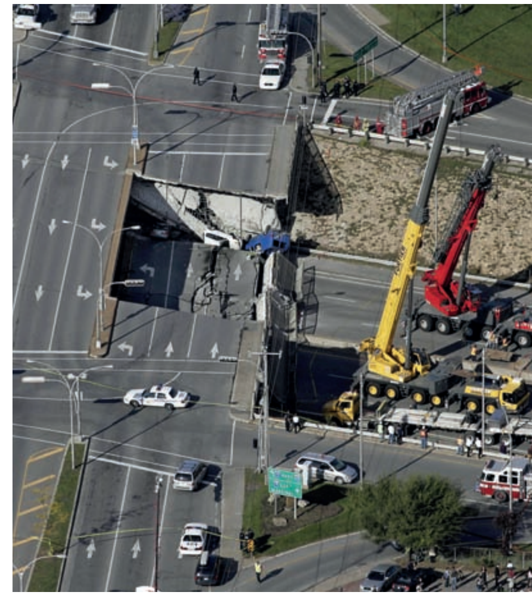


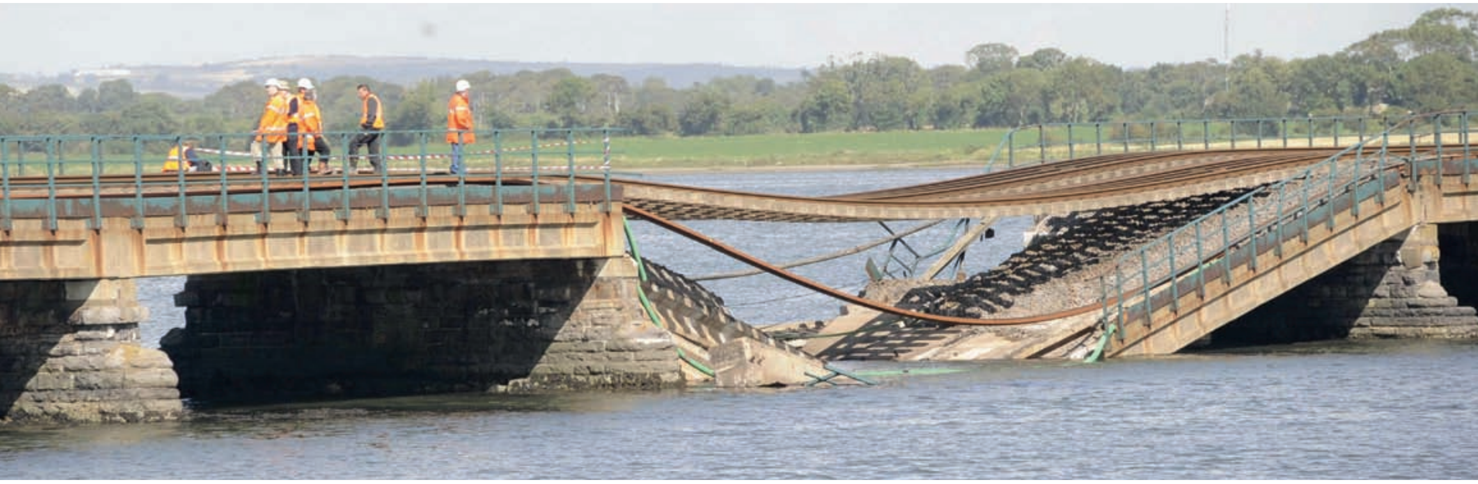
Figure 3
Five fatalities as a result of shear failure of a cantilevered slab through concrete deterioration: de la Concorde Overpass, Montreal, Canada

de la Concorde Overpass: Montreal, Canada

A year prior to the I-35W failure, the collapse of an overpass in Montreal, Canada, resulted in five fatalities (Figure 3). The overpass consisted of a drop-in span comprised of prestressed concrete box girders, which were supported by cantilevered slabs, via halving joints. The Commission of Inquiry into the collapse concluded that the failure of the overpass was a result of a shear failure of a cantilevered slab. The Commission concluded that the shear failure was caused by concrete deterioration, with a number of other contributing factors playing a role in the collapse, such as a lack of shear reinforcement in the cantilevered slab, a lack of watertightness in the slab, and damage caused in previous rectification works.

The Commission found that while the bridge's design met with the code requirements at the time of its construction, human factors during both the bridge's construction and operation phases contributed to the failure. Among the human factors identified by the Commission's investigation were:

- The Commission blamed the contractor for "failing to meet their legal and contractual obligations"[3]. It also blamed the principal subcontractor "for failing to adequately control the quality of the work by passing on their responsibilities to the workers and to the supervising consulting engineer"[3]. The Commission stated that this lack of quality control allowed the faulty



installation of some steel reinforcement in the cantilevered slab, "one of the main physical causes of the collapse"[3]

- The Commission also blamed the bridge designer, as well as its supervising engineer, for "not fulfilling their contractual obligation to exercise full-time supervision of the construction of the overpass and therefore, for not preventing the faulty installation of the steel reinforcement that resulted in a structure not in accordance with the drawings and specifications"[3]
- With respect to the bridge operator (the Ministry of Transport of Quebec), the Commission found that the presence of the halving joints presented inspection difficulties that were not adequately taken into account by the Ministry: "In its interventions, the MTQ did not rigorously and effectively deploy all the means at its disposal to properly evaluate the condition of the overpass despite numerous signs of deterioration; it also failed to maintain adequate records that could have better guided its inspectors and maintenance workers"[3]
- Further, the Commission found that "the overpass inspections were at times deficient, lacking adequate quantification of the deterioration, sometimes incomplete because not enough time was devoted to the inspections, and not thorough because the inspectors failed to look for the reasons behind the deterioration"[3]

Malahide Viaduct collapse: Dublin, Ireland

In 2009, just outside Dublin, Ireland, Pier 4 of the Malahide Viaduct collapsed into the Broadmeadow Estuary, resulting in the partial failure of two spans. An investigation by the Railway Accident Investigation Unit (RAIU) identified the cause of the failure as scour action undermining the rock weir that surrounded and supported Pier 4, leading to the pier's failure.

While the technical cause of failure was straightforward, human factors played a significant role in the collapse, culminating in what the RAIU investigation termed as "corporate memory loss"[4]. This corporate memory loss occurred because "former Iarnród Éireann [national railway system operator of Ireland] staff left the Division, which resulted in valuable information in relation to the historic scouring and maintenance not being available to the staff in place at the time of the accident"[4]. Specifically, these human factors included:

- "Iarnród Éireann's likely failure to take any action after an independent inspection carried out on the Malahide Viaduct in 1997 identified that scouring had started at the base of Pier 4 and that the rock armour weir was 'too light for the job'"[4]
- Historically, in order to manage the risk of scour to the viaduct, it appears a continuous maintenance regime was required. But "the historic maintenance regime for the discharge of stones along the Malahide Viaduct appears to have ceased in 1996, resulting in the deterioration of the weir which was protecting the structure against scouring"[4]
- "A scour inspection undertaken in 2006 did not identify the Malahide Viaduct as a high-risk structure to the effects of scouring"[4]
- "An inspection carried out on the Malahide Viaduct three days before the accident did not identify the scouring defects visible at the time"[4]

Closure

These cases illustrate the critical role played by human factors in bridge failures when Quality Assurance approaches become ineffective or neglected over the course of a bridge's lifetime. Not only were many of the above failures avoidable, but numerous opportunities were missed to identify the potential for failure. These cases remind engineers that ensuring Quality Assurance approaches are effective, both in their conception and implementation, is perhaps the best defence against the inevitable human factors that will contribute to structural failure.

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Figure 3
Sudden collapse of Malahide Viaduct's Pier 4, Ireland

REFERENCES:

1) FitzSimons, N. (1986) 'An Historical Perspective of Failures of Civil Engineering Works', in *Forensic Engineering: Learning from Failures*, New York: ASCE, pp.38-45

2) National Transport Safety Board (2008) *Highway Accident Report, Collapse of I-35W Highway Bridge, Minneapolis, Minnesota, August 1, 2007* [Online] Available at: http://www.dot.state.mn.us/i35wbridge/ntsb/finalreport.pdf (Accessed: October 2012).

3) Commission of Inquiry into the Collapse of a Portion of the de la Concorde Overpass (2007) *Report of the Commission of Inquiry into the Collapse of a Portion of the de la Concorde Overpass* [Online] Available at: http://www.cevc.gouv.qc.ca/UserFiles/File/Rapport/report_eng.pdf (Accessed: October 2012).

4) Railway Accident Investigation Unit (2010) *Malahide Viaduct Collapse on the Dublin to Belfast Line on the 21st August 2009* [Online] Available at: http://www.raiu.ie/download/pdf/accident_malahide.pdf (Accessed: October 2012)