ENGINEERING FAILURES

LESSONS TO BE LEARNT

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engineering new zealand
te ao rangahau

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This document summarises the webinar by Alex Gray, past president of the New Zealand Concrete Learned Society. Alex has spent over 40 years working as a civil engineer and project manager. He's been involved in major infrastructure projects, including Wellington’s Terrace Tunnel and Ngauranga incrementally launched bridge, and is an expert on risk management for construction projects.

Alex has studied engineering failures since his final year as a student at the University of Canterbury, where he completed the History of Civil Engineering course under the late Professor Harry Hopkins.

1: INTRODUCTION

There are a range of reasons why studying engineering failures are important to our profession. A key reason is to learn from the mistakes of others.

Everyone is fallible. Even experienced engineers make mistakes, including in the design phase, the construction phase and from programme pressure.

Often multiple causes join together to result in an engineering collapse, called the Swiss cheese model.

In some cases, there's only a single cause of failure, such as an earthquake, scour or ship impact.

Risk Management is now commonplace in all projects and under the Health and Safety at Work Act 2015 all participants in a project (including the client) may be liable if they don’t take all practicable steps to ensure no harm occurs during construction. For example, engaging a contractor with no prior experience for a specialist project might be construed as not taking due care. The contractor's expertise in carrying out the project must be confirmed, for example, by reviewing their methodology and/or health and safety plan.

2: ENGINEERING FAILURES (AND SUCCESES)

This section explores a range of engineering successes and failures, mainly in the design and construction of concrete bridges, but also from other engineering disciplines.

WELLLINGTON AIRPORT FOOD COURT INCIDENT (2014)

In 2014, a one-ton model of an eagle (created by Wētā Workshop) collapsed from the ceiling of Wellington Airport onto the food court during a relatively moderate earthquake. Fortuitously it was late afternoon and only one small group was affected, and they suffered only minor injuries.

Why it happened

This collapse is a good example of the Swiss cheese model. Although the design was carried out by a competent Wellington consultant there were a range of factors contributing to the failure as follows.

- There was a design mistake in that four of the nine wires holding up the eagle were stressed beyond the recognised safety limit for the wires.
- Wētā Workshop decided that they didn't need a consultant to supervise construction and would install it themselves:
  - they didn't install one of the wires at all, and
  - used a faulty crimping tool that did not crimp the wires properly.
- Wellington Airport applied and was granted an exemption for a building consent, on the grounds that this one-ton eagle was artwork.

Lesson learnt

Artwork on public display that weighs a ton should be properly supervised when installed.

Source: **Stuff.co.nz**

NGAURANGA PUSH BRIDGE, WELLINGTON (1983)

Ngauranga Southbound flyover bridge over State Highway 2 in Wellington, was the first incrementally launched push bridge in Australasia.

Push Bridges

Push Bridges are incrementally launched bridges, where the bridge is cast behind on the abutment and post tensioned with a launch nose. It's then launched over the piers using steel bearings and Teflon pads (which are fed in to reduce the friction).

Southbound flyover bridge being pushed over the Hutt Road.
PHOTO SUPPLIED BY MAINZEAL CONSTRUCTION LTD

The main advantage of this incremental launch process is that the bridge doesn't need any falsework. In this case, this method was used as the bridge was built over busy State Highway 2 (SH2) with no room for using falsework.

This bridge was designed in the Ministry of Works Bridge Design Office, and the design checked by Leonhardt and Andra West Germany who developed the push bridge construction method. It required very detailed method specification.

Why it happened

A large Ministry of Works team supervised the contractor, as the risk and consequences of failure were very high, as the bridge was being pushed over the Hutt Road without closing SH2. There was a lot of netting underneath the launch nose to make sure that nothing fell off during the launch process.

Ongoing checks included:

- A survey crew checked the tolerances on corners of the casting bed. The casting bed on this incrementally launched bridge had tolerances to achieve of 0.5 millimetre in both plan and elevation, as it was being launched over 320 odd metres on a curve with super elevation. If the casting bed is in the wrong position, the bridge ends up in the wrong position.
- Testing every load of concrete slump.
- Testing all roading materials.

Despite all these checks, one pier on the northbound bridge cracked at the beginning of the incremental launching process. Construction was delayed three months while the northbound piers were strengthened.

Cracking had occurred in the corners from the peak loads experienced during launching. The designers had to come up with a method of strengthening the piers in situ before launching could start again.

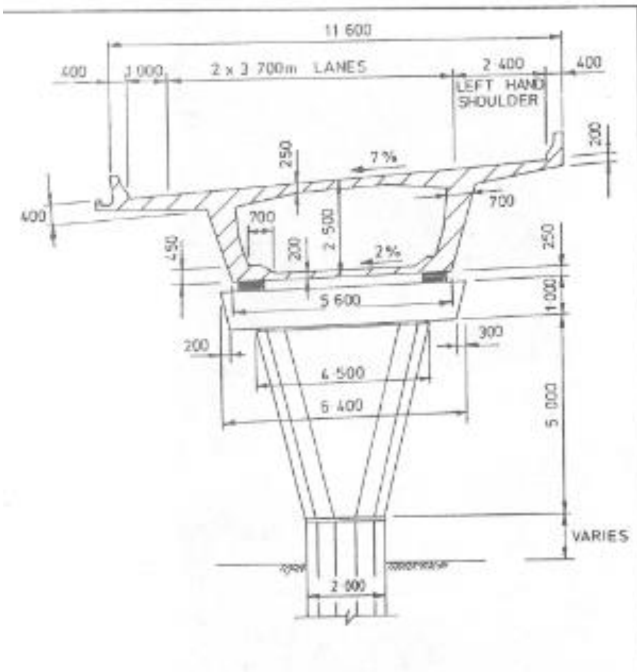


FIGURE 3 CROSS SECTION & PIER

NOTE BOX GIRDER SECTION IS CONSTANT OVER FULL LENGTH EXCEPT FOR LEADING 38m OF NORTHBOUND BRIDGE

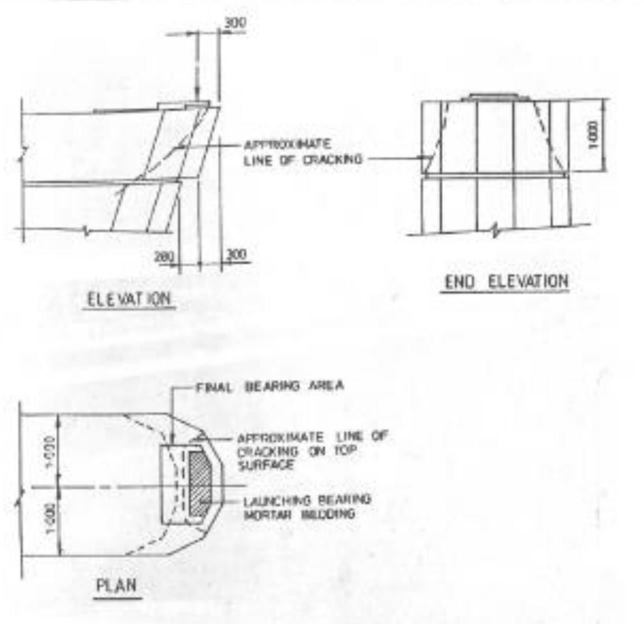
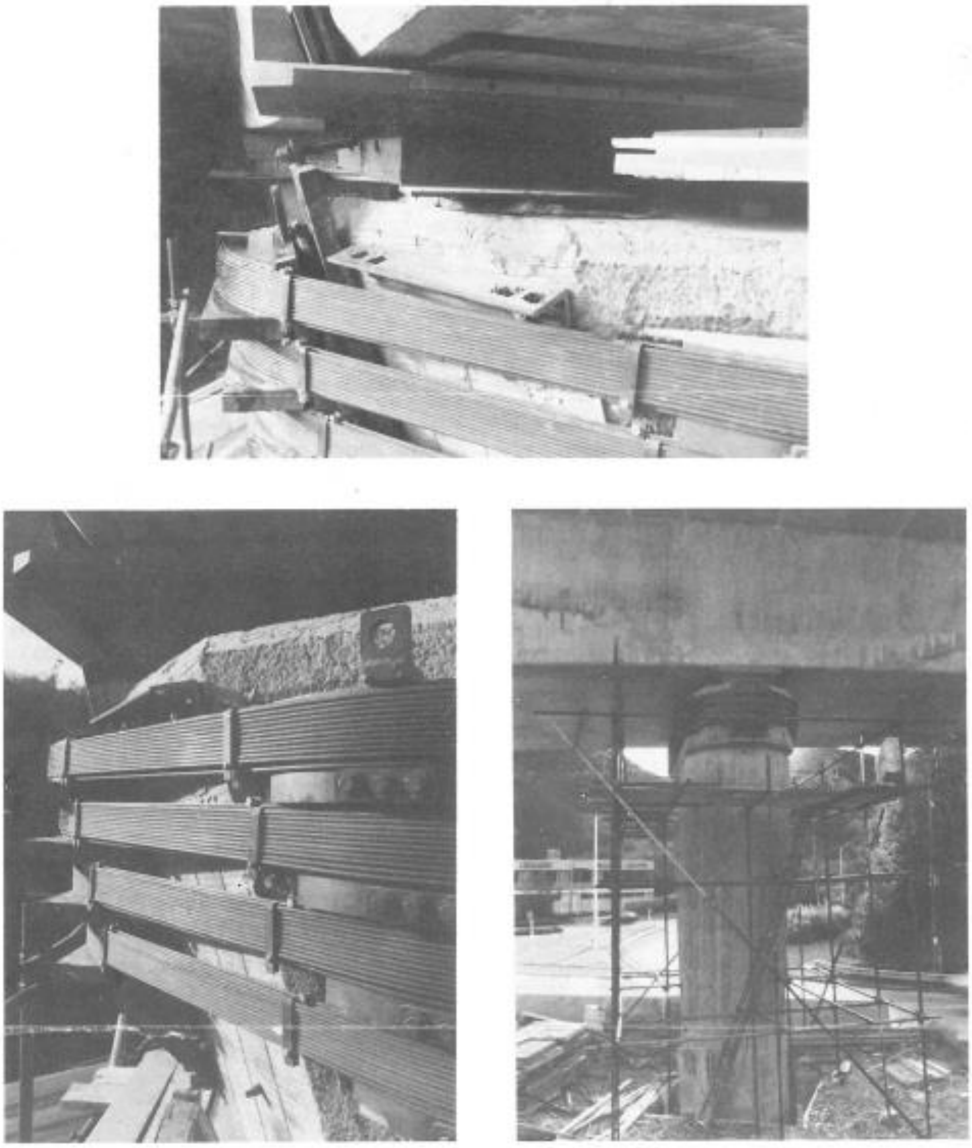


FIGURE 4 LOCATION OF CRACKING IN PIER CAP OF NORTHBOUND BRIDGE

This photo shows the work carried out to strengthen the pier caps. External pre stressing was carried out with a large number of seven millimetre wires installed hard against machine steel surfaces, which had been epoxy glued to the piers. The pre stressing was the post tensioned by inflating two 600 millimetre flat jacks at each end of the pier with Epirez epoxy resin. A concrete cover was then cast around the external post tensioning, so the strengthening wasn't visible in the finished bridge

STRENGTHENING PIER CAPS — NGAURANGA OVERBRIDGE

Small cracks appeared in the cap of pier 3 during a launch of the bridge. The external prestressing shown in the photos encircles the pier cap and bears against machined plates epoxy glued with Epirez 133 to the existing concrete. The prestressing wires were tensioned by two 600 ml flat jacks positioned at each end of the pier and inflated with Epirez 8859 to a pressure of 11.5 MPa.



TERRACE TUNNEL TIED BACK WALL, WELLINGTON (1976)

The Terrace Tunnel takes the Wellington Motorway (SH1) under The Terrace in central Wellington and is 460 metres in length. During the construction there were problems building the tied back wall.

Why it happened

The designers specified the wall to be built from the top down using stressed anchors, and a very high–quality architectural finish. But this design wasn't feasible.

D32 bars at a 100–millimetre centres around each anchor. This section is 14 metres high.

A top-down approach in stages would have required every one of the D32 bars to be butt welded and x-rayed before going down further. Instead, the contractor elected to build the permanent wall full height from the bottom.

To support the ground in the meantime, temporary ground anchors were used with the anchor holes going right down to the anchor drive, which was 70 feet or about 20 metres back from the wall.

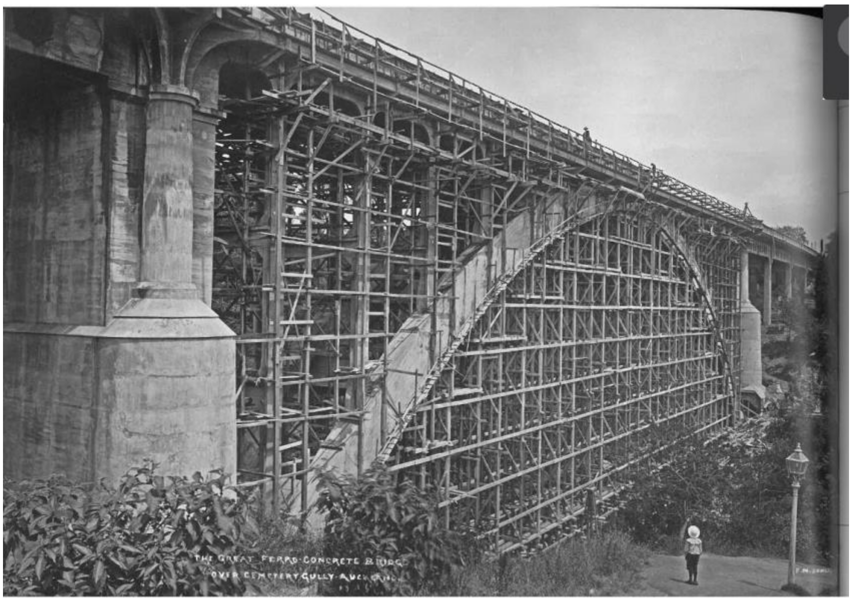
Unfortunately, the pre-cast anchor blocks were not connected to the shotcrete. During the winter of 1976, the ground slipped behind the shotcrete and the wall fell down. This wall was supposed to only be 600 millimetres thick but, in some places, it's two metres thick as it was cast without a back shutter up against the earth.

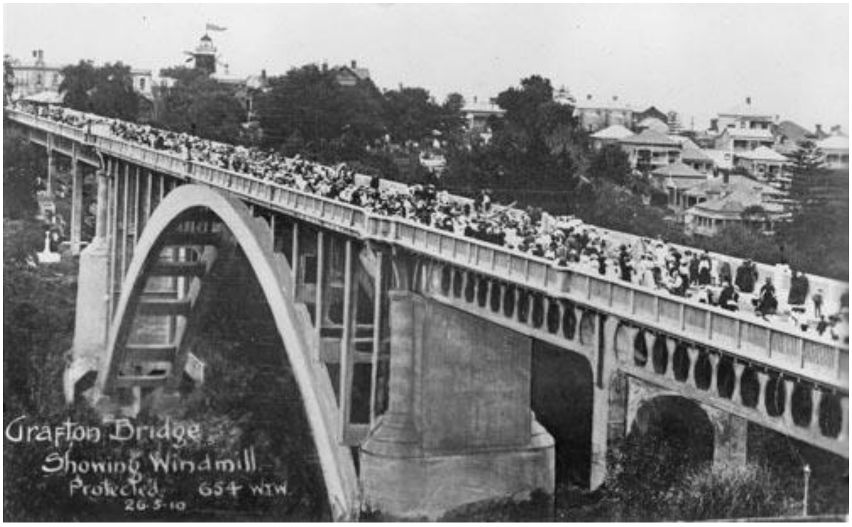
Lesson learnt

The key learning from this project was to show the issues which can arise when you find the original design is not feasible, and you need to redesign part-way through a project.

GRAFTON BRIDGE, AUCKLAND (1908)

Grafton Bridge, still in use today in Auckland, is a positive story.





What happened

Construction started in 1908 using an Australian contractor (probably major contractors in New Zealand at the time).

The bridge has a 93-metre main arch band, which when it was constructed, was the biggest reinforced concrete arch in the world. There were no laboratories for civil engineering materials in New Zealand in 1908. The Australian contractor sent samples of the sand and aggregate to the University of New South Wales for testing before any of the concrete was poured on the site. (Also of note is that all of the concrete was poured by hand!)

On the right, see the opening photograph of the bridge on the 26 May 1910.

Auckland City Council elected to use reinforced concrete rather than steel, because they believed it would last longer and require less maintenance. The Grafton Bridge is still in use today; it has since been strengthened with carbon fibre, so can still be used by heavy vehicles such as buses.

Lesson learnt

The key lesson is that if you're designing bridges, design them to last 100 years like Grafton Bridge!

WESTGATE BRIDGE COLLAPSE, MELBOURNE (1970)

The West Gate Bridge in Melbourne collapsed in 1970, resulting in 35 fatalities.

At the time of the collapse, two halves of the six-lane structure together were being joined together. This meant joining steel box girders 20 metres wide with 110 metre span, 50 metres up in the air.

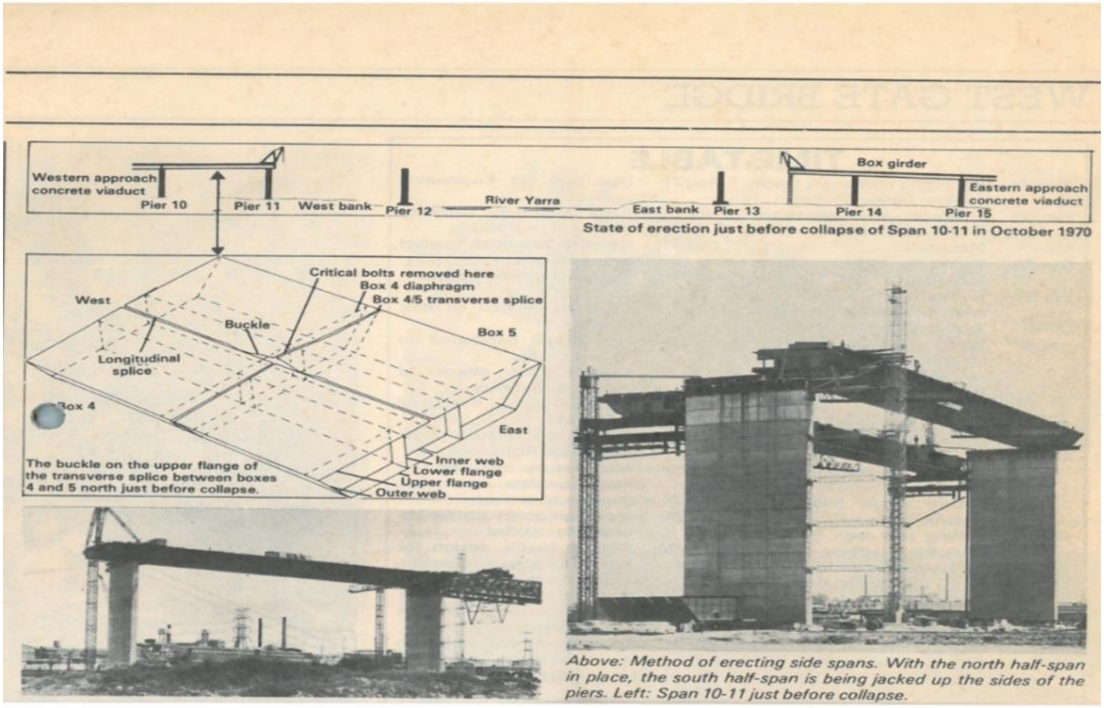
Why it happened

At the time of the collapse, the contractor had no prior experience in this work.

A big problem was that the Melbourne temperatures were causing the top flange to be a lot higher than the bottom flange, so the flanges were distorted. With the site engineer's approval, they used large concrete blocks to try and move the flanges so they could be bolted together.

The design was also under strength.

The reason there were so many fatalities was that the lunch huts for the workers were underneath the span that collapsed.



Above: Method of erecting side spans. With the north half-span in place, the south half-span is being jacked up the sides of the piers. Left: Span 10-11 just before collapse.

Lesson Learnt

The construction method of joining a large steel box girder span in mid-air was flawed due to the effects of differential temperatures between the top and bottom of the box girder. This method is no longer used – other methods e.g. incremental launching are much safer.

BULLS BRIDGE COLLAPSE SH1, NEW ZEALAND (1973)

A section of the Bulls Bridge, on State Highway 1 in New Zealand, collapsed in June 1973. At the time while a bus was driving over. Fortunately, the driver was able to swim to the bank and be rescued by two locals. So, there were no fatalities.

Why it happened

The section of the bridge collapsed during a storm, due to pier scour failure.

This section of the bridge was subsequently rebuilt.

Lesson learnt

Transit New Zealand (now Waka Kotahi) completes regular scour measurements to ensure that this sort of accident doesn't occur again.

INJAKA 300 METRES BRIDGE COLLAPSE, SOUTH AFRICA (1998)

Injaka was a 300-metre incremental launch bridge in South Africa. It collapsed in 1998, resulting in 14 fatalities.

Why it happened

The principal causes were due to the lack of competent personnel supervising construction.

But like all collapses, there was more to it than that. The main cause of the collapse was that the launch bearings were incorrectly placed.

Like the Ngauranga Bridge launch in Wellington, the Injaka Bridge was launched over the piers using stainless steel bearings and Teflon pads, which are fed in to reduce the friction. At Injaka, the launch bearings for some reason were installed underneath the bottom of the box, which is much weaker. This is the wrong place for the bearings and was not noticed.

Other factors led to the collapse and this is another example of the Swiss Cheese model.

- The principal designer wasn't a Registered Engineer and only had three years postgraduate experience. (Sadly, she died in the collapse.)
- The design wasn't peer reviewed.
- The site was over four hours' drive from design office so the designers couldn't easily attend the site and supervise construction and assess problems which arose). (Compare this to the Ngauranga Bridge construction where the designers were a 20-minute drive away.) For example: cracks in bridge deck occurred one month before collapse, and the principal designer advised the design office. Although the senior partner in the design office completed some calculations, there was no site visit, and the design office instructed the launch to proceed.
- The contractor was also negligent, as a competent contractor shouldn't have proceeded with the launch with significant deck cracking.
- The steel Launch Nose wasn't stiff enough.
- The deck slab was under designed.
- There was some incorrect feeding of sliding pads during the launch.
- The temporary works weren't properly designed or reviewed by a consultant.

After 24 years of wrangling there has been no criminal prosecutions. The senior partner was fined $5,000 for unprofessional conduct.

RUAHIHI CANAL COLLAPSE, NEW ZEALAND (1981)

The canal supplied water to the Ruahihi power station and was three kilometres long and six metres deep with a six-metre trapezoidal cross-section.

The failure occurred on Sunday 20 September 1981. Only 24 hours after the official opening, an area of the canal failed, eroding 200 linear metres, and causing 1.5 million cubic metres of earth and water to wash downhill and block the Tauranga to Hamilton State Highway. Fortunately, there was no loss of life.

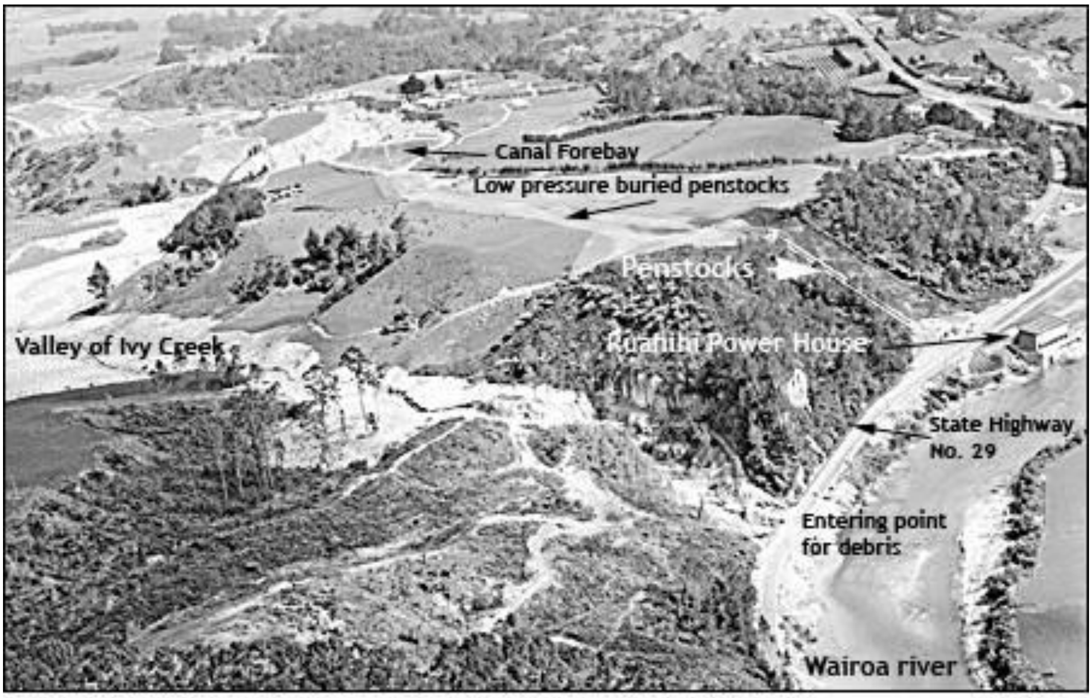
Why it happened

The original canal design was lined in concrete, but to save costs, the design was changed to an unlined canal – to be formed using compacted-sensitive volcanic soils. Note: the canal had been in use for four months and the area that failed had persistent leaks prior to the collapse.

Lesson learnt

Repairs involved shortening the canal by 500 metres and lining the canal with plastic and concrete pavers. These repairs took two years and cost $17 million, not including the loss of generation from the 20MW power station over that time.

Since then, very few canals in New Zealand have been built unlined.



Aerial view of Ruahihi Canal after collapse on 20th September 1981 *Photo: David de la Hyde*

HOBART BRIDGE COLLAPSE, TASMANIA (1973)

The Hobart Bridge collapsed in 1975 in Hobart when a 35,000-ton bulk carrier ship going upstream to the aluminium smelter took out three spans of the bridge resulting in 12 fatalities.

Why it happened

The main reasons for the collapse were:

- There was a strong outgoing tide.
- There were foggy conditions at night.
- The captain of the boat was having trouble controlling the boat and it hit one bridge pier.

Lesson learnt

When designing bridges, ensure the piers are protected from potential risk from being hit by a ship. This is shown in the next example of Incheon Bridge in South Korea.

INCHEON BRIDGE, SEOUL, SOUTH KOREA (2009)

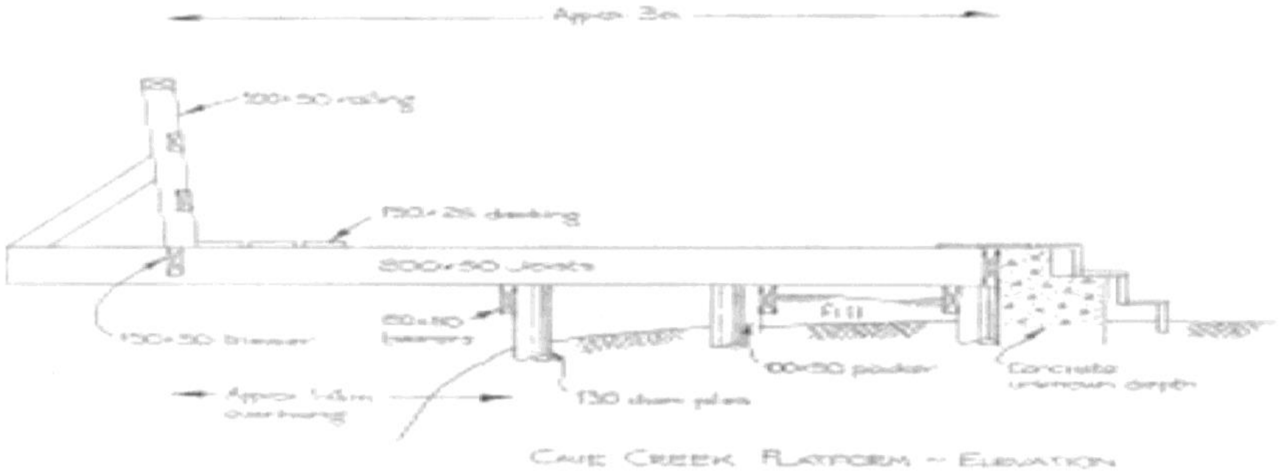
The Incheon Bridge in South Korea is an example of a bridge which has protected its piers from being hit by a ship.

The bridge carries a six-lane freeway to the new Inchon Airport in Seoul, South Korea. It's an 800-metre main span cable stayed bridge. A key feature is the large diameter separate piles used to protect the main piers. They're erected not only around the main piers, but in alternative piers at the ends so that any ship that's lost in the fog will (hopefully) hit one of the sacrificial piers rather than damage the bridge.

CAVE CREEK PLATFORM COLLAPSE, WEST COAST (1995)

On 28 April 1995, in the Paparoa National Park on the West Coast of the South Island, a viewing platform collapsed at Cave Creek.

Seventeen students from an outdoor recreation course and the Department of Conservation's Punakaiki Field Centre manager were on the viewing platform when it fell about 30 metres into the 'resurgence below'. As a result, 14 people lost their lives and another four were seriously injured.



The viewing platform was made up of a timber platform with a cantilever jutting 40 metres into the gorge. It had 200 x 50 timber joists, which were designed to be fixed to bearers, which were then bolted to the piles. There were steel straps designed to strap the platform to the mass concrete steps.

Why it happened

A combination of factors caused the collapse:

- The platform wasn't designed or approved by a qualified engineer, and none of the people involved in building the platform were qualified engineers. The carpenter who fabricated most of the platform was not involved in the construction.
- The piles couldn't be constructed in a straight line due to rock formation.
- The bearers were supposed to be fixed to the piles with bolts but, as a generator was forgotten for the drill, the site team used skew nails instead. Some of the 4-inch nails had only 10mm penetration into the piles.
- Steel straps were drawn to attach the platform to the concrete steps as a counterweight but were never installed.
- No building consent was applied for the structure. The Department of Conservation tried to apply for a building consent after the structure was built, but Council put a large number of conditions on the application. For whatever reason the application was then put in the bottom drawer.
- A warning sign suggesting a maximum limit of five people had been made but wasn't displayed. The platform had 18 people on it when it collapsed.
- The day before the collapse, an identical size group visited the platform, and the Department escort thought the platform 'fluttered'. She advised the Department of Conservation person leading the group the next day to inspect the platform before going onto it. He ignored her suggestion and was one of the 14 fatalities.

Lesson learnt

Systemic failure was given as the cause of the collapse. No one was prosecuted. Since then, the Health and Safety Laws have been changed so that government departments could be prosecuted.

The Department of Conservation (DOC) was a new government department and had only one registered engineer who was supposed to be responsible for the maintenance of 600 structures – an impossible task.

All (DOC) structures are now designed and construction checked by a Chartered Professional Engineer (CPEng).

CTV BUILDING COLLAPSE, CHRISTCHURCH (2011)

The CTV building in Christchurch collapsed in February 2011 as a result of the earthquake resulting in 115 fatalities**.**

The building took nearly all seismic lateral load on the end lift tower. Note: the lift tower at the end of the building, which was designed to take all the seismic load, survived the collapse.

Why it happened

The building was designed and built in 1986 and there were a combination of factors causing the collapse.

- The designers were Alan Reay Consultants.
  - The design had defects. For example, the column stirrups were only six millimetre in diameter at 250 millimetre centres.
  - The designer, Dave Harding, was a civil engineer but had no multistorey experience and believed Alan Reay was supervising his design. But this didn't happen.
  - Alan Reay pressured Council to approve consent and the Council engineer was threatened with loss of job if he didn't sign off consent. Consent was approved.
- The contractor was Williams Construction (who had quality issues on other projects).
  - The Council engineer inspecting the consent application had several major design queries.
- The design wasn't to the current code and construction was of a poor standard.
- After the September 2010 earthquake in Christchurch, the building was inspected and declared safe. However, the building occupiers who survived the collapse reported that, since the previous September earthquake, the building really shook when a large truck drove past.
  - It's possible that the wire mesh, which was the only connection to the lift tower, had failed on some of the floors. But unless you lifted the carpet tiles, the crack in the floor wouldn't be visible.

Lesson learnt

The Royal Commission, who investigated this failure, recommended that designers focus on beam-column joints, connections of floors working as diaphragms and ensuring columns have adequate confinement to ensure ductility.

MORANDI BRIDGE COLLAPSE, GENOA, ITALY (2018)

Morandi Bridge in Genoa was a major structure which collapsed in a storm in 2018 causing the death of 41 people.

The structure was considered innovative when it opened in 1967. It had a 210-metre main span and was 40 metres up in the air. It carried 70,000 vehicles a day, many of these trucks.

Why it happened

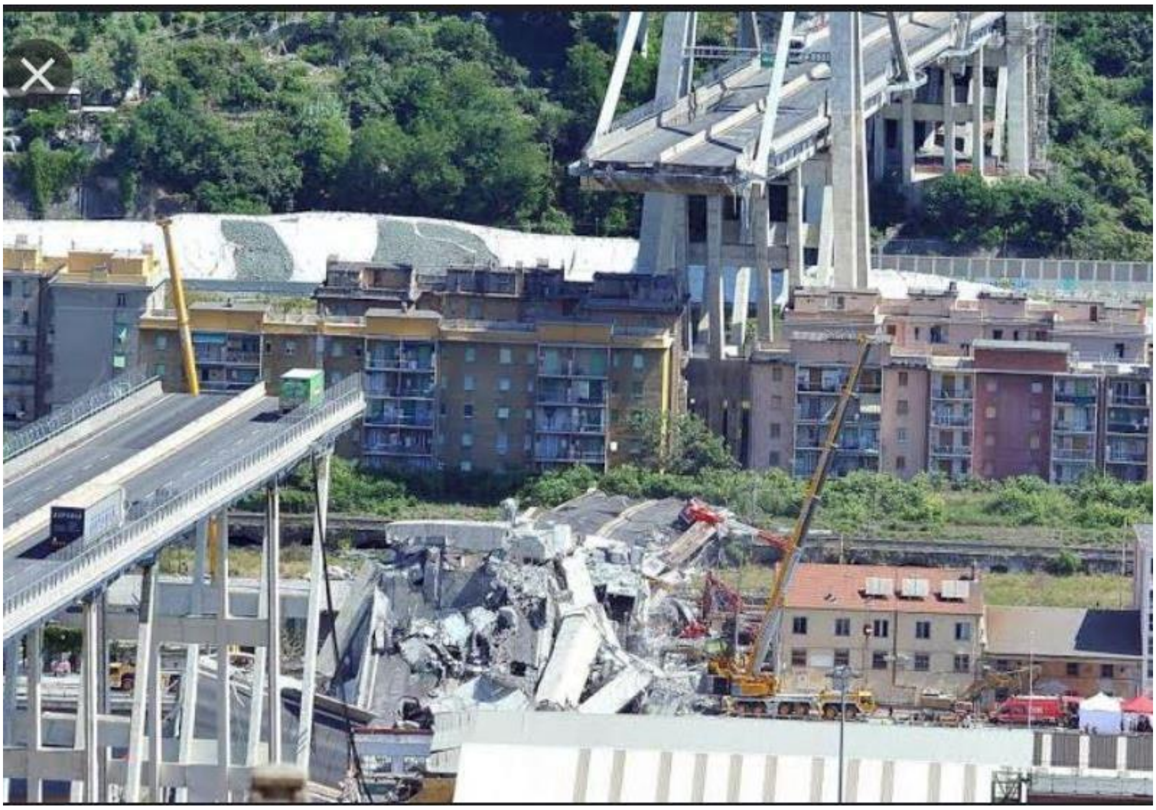
There were a range of reasons this bridge failed:

- The bridge was structurally redundant, and all the stress was carried in one large member.
- The other significant factor were deck cracks that were noticed two weeks before the collapse.
- The lack of maintenance was determined as the primary cause.

Lesson learnt

A significant factor in this collapse was that the firm responsible for the tolls and maintenance on this motorway bridge, the Benetton company in Italy, were well known as a clothing manufacturer rather than for toll bridge or bridge maintenance.

Firms responsible for bridge maintenance need to ensure that they're competent, which would include regular checks.



MIAMI BRIDGE COLLAPSE, UNITED STATES (2018)

The Miami Bridge collapsed in 2018, five days after it opened. It had a very long bridge span - across eight lanes of traffic. When it collapsed, there were eight fatalities and ten injuries.

The bridge was 53 metres long and weighed 950 tonnes. It was an unusual design - a post tensioned concrete truss bridge and was a design-build contract by United States' Figg Bridge Engineers.

The bridge was built off-site and lifted into place during an overnight lane closure.

Why it happened

There were multiple factors which contributed to the collapse:

- During erection, the north end cracked after some temporary pre stressing was released. The contractor advised the designer of the cracking issue.
    - Figg Engineers didn't know why the cracks occurred but expressed no safety concerns.
    - Two days before the collapse Figg Engineers proposed remedial work but didn't consider it necessary to close the road or prop the bridge.
    - The Engineer of Record advised an engineer at the Florida Department of Transport (FDOT) in a voice message of a minor safety issue. Unfortunately, that FDOT engineer was on one weeks leave.
- At the time of the collapse over the live highway, Figg Engineers were meeting with FDOT. The lead engineer at Figg Engineers advised that the structural integrity of the bridge was not compromised and that no safety concerns existed! The bridge collapsed during this meeting.

Lesson learnt

A subsequent inquiry concluded the bridge had design deficiencies, had an inadequate peer review, and that the severe cracking was wrongly ignored by the Engineer of Record. The inquiry also concluded that one node on the truss was grossly under designed.

As a consequence of this collapse the contractor paid out $42 million to the victims and families of the tragedy.

CENTREPORT PASSENGER GANGWAY, WELLINGTON (2011)

CentrePort in Wellington built a new passenger gangway in 2011. Learnings were taken on board from the previous collapse of the Ramsgate gangway in Britain in 1994 (where six people died when the gangway collapsed while in use) to help ensure this CentrePort project was successful.

Ferry gangways are complex to design, being telescopic and very complicated structures. They span from solid land to a moving ship and need to carry a large number of people.

Although the Ramsgate gangway was designed by a competent marine engineer, and the design had been certified by Lloyds of London, it collapsed after only six months. It was found that the designer and the peer reviewer had made an incorrect design assumption on one joint. This joint was assumed to be only loaded in shear, but it actually took torsion as well.

Lesson learnt

They key lesson taken from Ramsgate and applied to the CentrePort gangway was around testing.

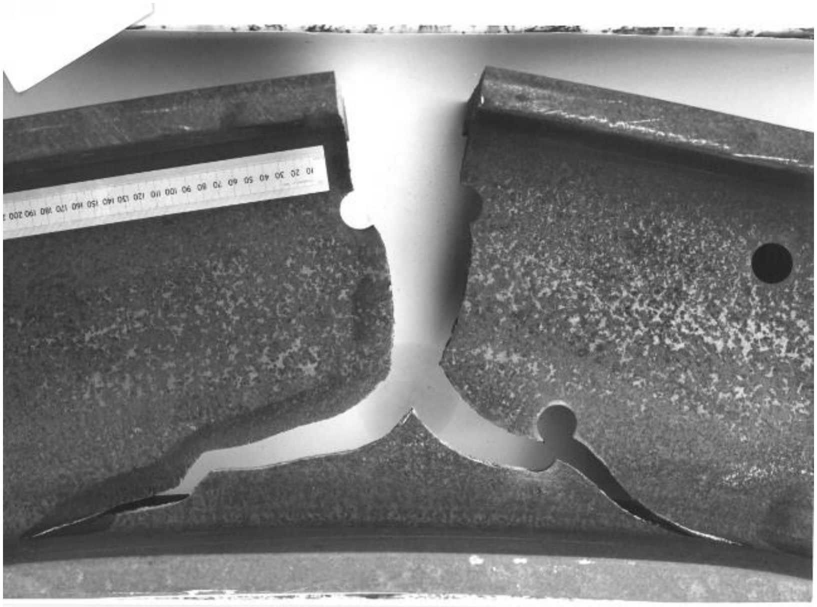
The CentrePort gangway was designed to carry five KPA and we load tested using 11 tonnes of UDL on the structure (using bags of cement).

The test was successful apart from the deflection being more than the designer had expected. So, the designer instructed that an additional jockey wheel be installed to reduce the span.

This gangway is still safely in use today.

TERRACE TUNNEL ARCH, WELLINGTON (1976)

This photo is of a 250mm by 250mm by 90 kilogram universal column section used to form an arch for the Terrace Tunnel.



It broke during pressing to form the tunnel arch. The top flange is 25 millimetres thick so when it broke, it made a noise like a mortar going off

Lesson learnt

A key lesson from the Terrace Tunnel was on standards. In particular, the importance of specifying materials and then ensuring that the materials used meet those standards.

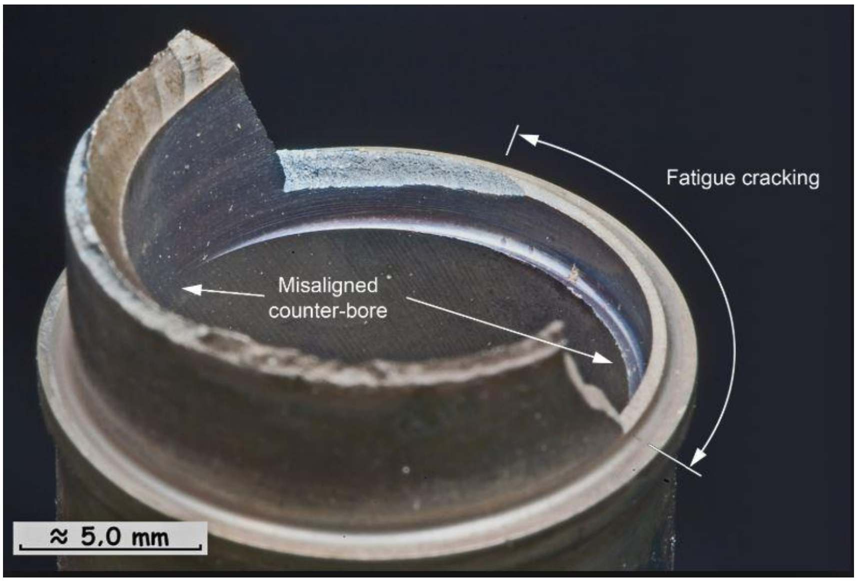
When we investigated this failure, we took a sample of the actual steel and discovered that it was well in excess of the 0.3% carbon that is allowable for mild steel.

We checked the test results that had been supplied with this steel which said that the steel was compliant. It wasn't!

QANTAS QF32 ENGINE FAILURE, MID-AIR (2010)

Four minutes after take-off from Singapore's Changi airport, a Qantas Airbus 380 with 469 on board, suffered a mechanical engineering failure in one of its engines.

A critical 12-millimetre stub oil copper pipe had been manufactured improperly. Instead of its wall thicknesses being symmetrical, on the left-hand side it was almost three millimetres thick and on the other side, it was paper thin, only 0.3 millimetre thick.



When the pipe broke, it squirted lubricating oil into a turbine that was operating at high speed. The engine exploded causing pieces of shrapnel to fly through the wing, which was full of fuel. It also cut off multiple circuits.

The plane landed safety because of the skill and experience of the pilot-in-command, Mr de Crespigny and the support of two additional check captains (who were checking the performance of the pilots).

- The pilot-in-command practiced flying the plane for over an hour to see what he could do with it before he attempted to land. They had no flaps, he couldn't dump fuel and the plane didn't turn as normal.
- The check captains assisted in analysing the problems (they had over 100 error messages).
- They did some calculations on landing the plane back at Singapore. In dry conditions calculations showed that the plane could land with less than 100 metres of runway to spare.

The plane successfully landed even though it was running over speed, 50 tons overweight, with no flaps. It burst three tires during the landing and leaked large volumes of fuel onto white hot disc brakes on the wheels.

The fire crew reduced the temperatures of the discs. They then closed off all the engines, but one of the engines would not stop.

The flight crew decided not to declare an emergency evacuation of the plane because people leaving the upper story of the plane would likely be injured. Passengers were kept on the plane for nearly three hours while the fire crew controlled the situation.

Lesson Learnt

Quality control is crucial for both construction and aerospace industries.

The Qantas plane was subsequently repaired at a cost of $130 million, which was paid by the insurers. Qantas also grounded all their planes.

Qantas discovered that nine of their planes and some others like Lufthansa had the same defect. So, by successfully landing this plane, the pilot probably prevented further explosions, and potential accidents and fatalities.

3: LESSONS TO BE LEARNT

Many types of failures typically involve some form of loss. We can investigate failures to blame or to punish, and also to learn how to avoid similar future failures. Engineering knowledge develops much more by studying failures rather than successes.

Human error is a leading cause of failures – not only in individuals, but at an organisational or project level. Over time we may forget the failures and get over-confident in ourselves and our profession.

Overall, we need to spend more time investigating failures than trying to emulate successes.

KEY POINTS

Here are the key lessons to be learnt.

- Regard design and construction as a team activity. Learn from those who have spent years in construction. It's even better if you can supervise your own designs.
- Don't design anything before you understand how to do it or are competent in it. Ask for supervision or assistance. If your boss/supervisor is too busy, or acts uninterested, look for another job!
- Don't sign anything you haven't read or understood.
- Be inquisitive - raise questions and if you don't get answers elevate the issue until you're satisfied.
- Follow your conscience– if it doesn't look right, it probably isn't.
- Ensure the materials and standards are met in the field to meet the requirements for your designs.
- Ensure the specification is written for the project. It shouldn't be a cut and paste from previous job. It needs to make sense for that project!
- Be wary of clients who don't want to pay for the required level of supervision. Construction tolerances may not meet expectations on your drawings, i.e. the model eagle that fell at Wellington Airport.
- Be hungry for new ideas or information.
- Attend technical groups to expand knowledge.
- Learn from your and others' mistakes!

4: QUESTIONS AND ANSWERS

Alex Gray concluded the webinar with the following question and answer session.

For the Ngauranga Bridge, what was the cause of the pier crack during the launching of the girders? Had this not been considered during the design and not picked up during the peer review?

The answer is a combination of factors.

The piers were designed to be quite slender, so they matched the profile of the box. So, there was some very high forces on the corners of the piers. And this wasn't picked up in the peer review, which was done by Leonhardt and Andra in West Germany.

We did come up with a solution and we did stop launching without carrying on - which is not what happened in the horrible collapse at Injaka in South Africa.

Also, the designers were only a 20-minute drive away, compared to the collapse in South Africa that was a four-hour drive to the site (and where the senior partner was either too busy or couldn't be bothered driving to site).

What are your top tips for avoiding engineering failures?

There are often multiple reasons which are difficult to pin down. But the two which stand out in my mind are probably human fallibility and pressure to meet either cost or programme time constraints.

- The Ruahihi canal failed 24 hours after Prime Minister Muldoon had opened it. And yet the engineers knew that it was already leaking. Likely they didn't want to suffer loss of face by postponing the opening by the Prime Minister while they sorted out the leak problem. And so, they went ahead with the opening even though the canal was four months old and leaking.
- You've got to be very wary of pressures, both cost and time, ask yourself if there is a serious problem? Do I need to stop work and sort out this problem rather than carrying on regardless?

How would you advise guarding against human fallibility and cost and time constraints? What sort of processes would you suggest putting in place to try and guard against those? And what have you seen works?

If possible, supervise your own designs. Because one, you're the best person to be able to resolve problems. And two, you can learn whether your design is buildable in the field. I think when you're a designer, you always must bear in mind how is the builder going to build your design safely and to have adequate levels of construction monitoring because it gets you out into the site. For example:

- Three months out of university I still remember a construction foreman coming in to see me one morning and crashing his fist down on the desk and saying, "Your name is on the bottom of this damn drawing. How the hell am I supposed to build this?" And I looked up to him with some temerity and said, "Let's see what we can work out together."
- The Terrace Tunnel wall initially was supposed to be built from the top down and had a very complex architectural finish on it. This was impossible and had to be redesigned using temporary support and building the wall from the bottom upwards.

- The one-ton Eagle crashed to the floor because Wētā Workshop decided that they didn't need any engineering supervision. When their crimping tool was faulty and when they erected their eagle, they missed out one of the wires. And there were some design issues in terms of four of the nine wires didn't have an adequate factor of safety.
- An incrementally launched bridge is a very high-risk project, even if it's not going over a live highway. If that fails during launching, you will have fatalities. It's as simple as that. And so, the level of supervision has to be balanced, against:
    - How new or innovative is the design?
    - How competent is the builder?
    - What are the risks during construction?
    - Is the team working together for a successful outcome?

What's your view on independent testing on concrete, even though a lot of specifications require this?

Concrete is a variable material. In the Ngauranga project, we slump tested every load of concrete, and I learnt later that the concrete we rejected was sent to another project that wasn't slump testing. So, for critical materials I see that you need to do independent testing.

Block tests are normally taken by the concrete manufacturer who have processes and are audited, so that their tests are reliable. New Zealand is fortunate in that the level of corruption is relatively small.

I'd encourage designers to actually visit the concrete plant and check out the laboratory that most concrete plants have and observe crushing of concrete samples. Because trying to take your own samples and independently testing them, unless there are very specific reasons, is a very expensive process.

How do we share knowledge of failures or difficulties encountered in a collaborative and informative manner?

Here are a few ideas.

- Use Engineering NZ **Library of webinars** (growing all the time).
- Subscribe to CROSS-AUS or similar in your discipline. Look at the **Engineers Without Borders** failures website.
- The Engineering General Practitioners Group has examples in their quarterly newsletter of lessons to be learnt.
- Write an article to the technical group that you're most involved with, whether that be CSOC or the Geo technical group or whatever discipline of engineering that you're involved with.
- Present to others – failures as well as successes.
- Contact experts (such as someone's name on a paper or standard) with questions. Also respond to those wanting to ask you questions. We need to keep sharing knowledge and make sure that we don't lose knowledge and experience, for example, as engineers retire. We also need to bridge the gap left by the Ministry of Works where there were experts in specific fields like bearings, corrosion, bridge design, or whatever.
- New Zealand's a small community, so you can frequently pick up the phone and talk to experts who are willing to share their knowledge most of the time. There is no substitute for talking to people and having a two-way conversation. You get much more detail that way.

How frequently are the bridges in New Zealand inspected for maintenance and what sort of process is used?

Waka Kotahi is best to ask, as they have maintenance contracts for all their structures and inspection procedures including looking at scour quite regularly on bridge piers.

What are your views on the self-certification philosophy adopted in the industry?

I think self-certification is probably okay for minor things that are not unusual. But anything which is complex or unusual, needs to be peer reviewed by somebody separate who has a level of independence.

What are some of the technological advances over the years that have helped prevent potential disasters and where could it be improved still?

Some of the advances are:

- Computers have made things a lot faster such as calculations and modelling.
- Mobile phones have improved instant communications, and people can send photos and videos of problems from remote sites.

But the downside is this continual desire to do things for less cost. And less cost means less design fees and less construction cost and less construction supervision costs. For example, in the Canadian supermarket roof collapse in 1988 design fees were 0.25% of the total costs (when a Commission of Inquiry found it should've been around 7-8%). If people are working on a complex structure, they need to stand up and say how many hours, or the fees, that are required to do the job properly.

Also, there is now a reliance on computer modelling, rather than hand sketching out, identifying the load parts, and then building the model from there.

Do you think that a graduate structural engineer should be trained on site before he or she starts to design?

I think it's a combination of both. I don't see a need for designers to go to site straight away. But I do see benefits in them going to site after say no more than a year.

Any recommendations for site contractors who are advised by subcontractors of extra faults (where it should have been planned prior to erection as per the Health and Safety Guides)?

If the subcontractor raises an issue of health and safety, if I was a supervising engineer, I'd probably ask what the issue was and see if I agreed with them. If I did agree, I'd basically say to the main contractor I'm not signing off the project until these additional measures were taken, because they're usually quite small in terms of the whole project costs and the consequences are probably large.

In your opinion is increased pressure on cost and duration affecting quality?

As quality is part of the design and its specifications, and supervision is required to ensure the final outcome conforms to the specification, then pressures on cost and duration are likely to affect the quality.