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INNOVATION – THE NEXT BIG THING OR THE NEXT BIG FAILURE?

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SUMMARY

Innovation is a common buzzword that is used to describe new design solutions or technologies. Although intended to have positive connotations, the reality is that the term innovation is often used to describe new ideas that are untested or under development. These innovative solutions do not always succeed, and examples of notable failures are presented for both radical and incremental innovation. The root causes for these failures are summarised and recommendations are provided regarding the evidence and testing required to prove or validate the solution prior to widespread implementation. The incremental development of seismic design procedures and structural systems has played a critical role in improving the performance of structures during earthquakes. These tried and tested solutions should not be tossed out in favour of underdeveloped ideas being promoted as the next big thing, when in fact that such ideas may instead turn out to be the next big failure.

INTRODUCTION

Engineers often look to develop new solutions to improve designs and performance. In a bid to promote these new solutions buzzwords such as “innovative” and “resilient” are used without consistent definitions of what these terms mean. In the field of earthquake engineering much of our design practice and standards have been developed from observing the performance of structures in past earthquakes. By learning from what did and didn’t work we can incrementally improve structural design practice, improving safety and reducing the economic and societal impacts. Do radical innovative solutions have a place in this incremental improvement cycle? If so, what evidence is required prior to widespread adoption of such new solutions?

Although innovation is a commonly used term there are a large number of interpretations as to what it means. Research has found 60 different definitions of innovation in published papers (Baregheh et al. 2009). A generic definition can be found in the Oxford English Dictionary:

Innovation (Oxford definition): a new method, idea, or product

Frameworks for describing different types of innovation include the distinction between “Radical innovation” being the establishment of a new design or new set of core concepts and “Incremental innovation” being a refinement and extension of established designs (Henderson, and Clark, 1990). Both types of innovation occur in structural engineering and both have potential pitfalls, as will be explored later in the paper. Anecdotally engineers often use innovation as a buzzword to promote new ideas and products that are not fully developed or tested. As a result, an alternative definition of innovation is suggested:

Innovation (alternative definition): an ***untested*** *new method, idea, or product*

There are many examples of failed innovation, examples of which are explored within this paper. Lessons from these past failed innovations are used to define how we should approach new innovative solutions. Rather than treating innovation as a promotional buzzword, a robust process of development of new systems should exist where sufficient research is conducted and evidence gathered prior to implementation.

INNOVATION FAILURES

Although examples of failed innovations are numerous, several notable examples include the clip-on lanes of the Auckland harbour bridge, the use of hollowcore precast concrete floor units, and shear yielding connections in precast concrete beams.

Auckland Harbour Bridge:

The original structure for the Auckland Harbour bridge was completed in 1959 and soon reached capacity, resulting in extensions (commonly referred to as the “clip-on” lanes) being added in 1969, as shown in Figure 1. The clip-on box girder structures have a main span of 244 m, with a section depth that varied from 3.5 m at mid-span to 9.2 m at the supports (Pank 2011). The extremely slender and flexible box girder design were described as an “innovative” and “pioneering” design for that era, with a longer span and more slender profile than other similar bridges (Pank 2011). The sustainability of such a design approach for a major infrastructure project was later questioned, with the 100 year design life of the clip-on box girders unlikely to be achieved and retrofits having been continually required, including in 1973, 1987, 1999, 2010 (Pank 2012). The slender spans pushed the limit of design at the time, but their flexibility has resulted in fatigue issues that have increased the costs of maintenance, reduced the operational capacity, and ultimately reduced the design life of the structure.

Figure 1 – Auckland Harbour Bridge (Pank, 2012)

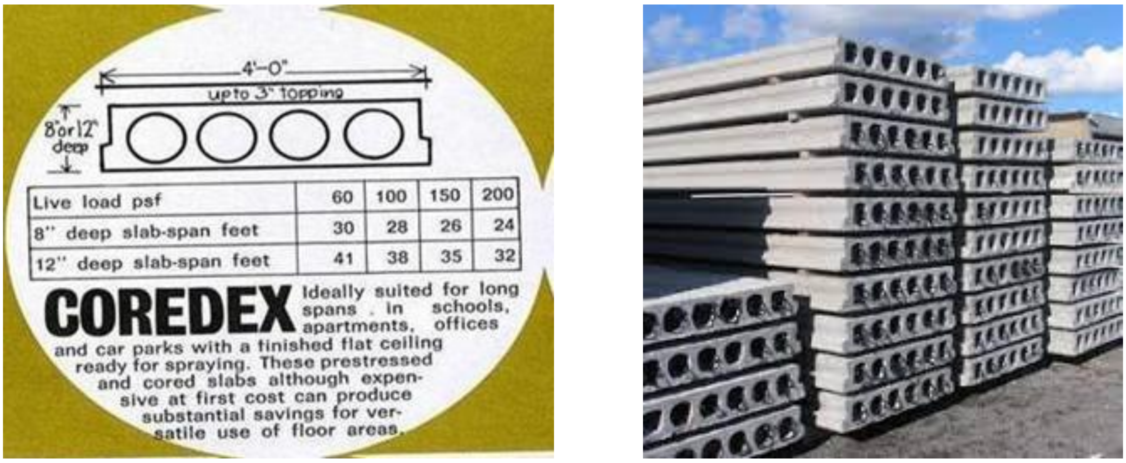
Hollowcore:

Precast concrete floor units were first introduced into New Zealand in the 1960s and quickly because the preferred construction method for suspended floors. Adoption was rapid and the use of traditional insitu concrete floor construction soon become uncommon with precast concrete floors dominating the market for many years to come. Hollowcore floor units (Figure 2) were likely considered a radical innovation at the time of introduction, providing a fast and economical solution to construct suspended floors. The rapid adoption of precast concrete resulted in implementation proceeding ahead of seismic research, a point that is noted in the following quotes from Professor Park and in the CAE Precast Concrete Handbook:

> “*the increase in use of precast concrete in the 1980s required considerable **innovation** because of New Zealand’s location in an active seismic zone*.” (Park 1995)

*"With the increase in **innovative** use of precast concrete elements in buildings in New Zealand came an increasing concern that some of the design solutions should be more researched. Even if there were no reason to doubt the validity of **extrapolating** the results of design and construction procedures that were originally developed for cast-in-plane concrete, the large number of important buildings employing precast concrete for seismic resistance **demanded that more research and testing be done** to justify confidence in the structural systems."* (Park 1995)

*"…significant developments in the use of precast concrete have been made in spite of the fact that some aspects of the seismic design of precast concrete building structures have not yet been formally codified. This reflects an on-going **innovation** by New Zealand practitioners that will no doubt continue."* (CAE 1999)



(a) Coredex profile from 1970s (PCFOG) (b) Stored units (https://stahlton.co.nz)

Figure 2 – Hollowcore floor units

Concerns of the rapid adoption of precast concrete systems led to substantial research programmes during the 1990s that included investigation of support connections in hollowcore floors. Major concerns were raised regarding the seismic performance of hollowcore floors following loss of seating to hollowcore units during the Northridge earthquake. Further testing of hollowcore floors at the University of Canterbury followed, including the notable "Mathews" sub-assembly test that confirmed the vulnerability of hollowcore floors to damage and collapse when subjected to seismic induced deformation demands, as shown in Figure 3a. Subsequent research resulted in multiple amendments to the design standards to address the collapse risk of hollowcore floors.

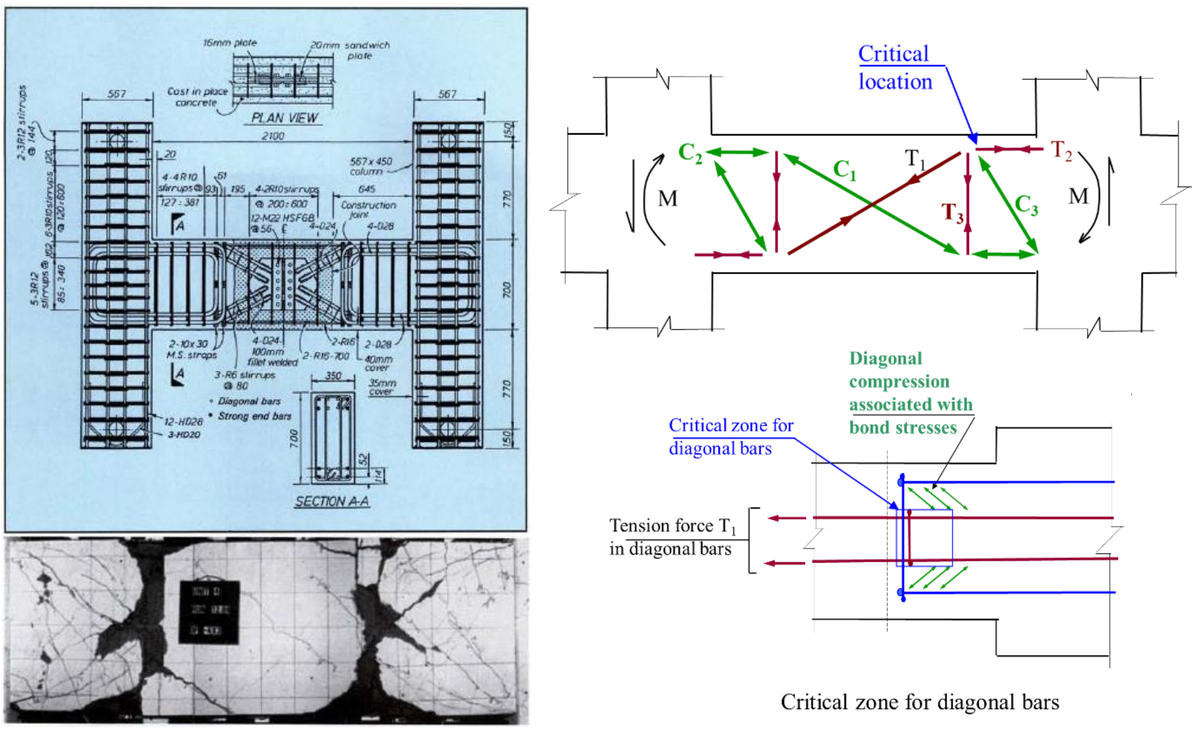
(a) Unit failure during "system" test (Mathews, 2004) (b) Unit damage following Kaikoura earthquake (Credit: Mohamed Mostafa)

Figure 3 – Hollowcore unit damage

Further damage to hollowcore floors was observed during both the Canterbury and Kaikoura earthquakes (Corney et al. 2014, Henry et al. 2017). Subsequent research has focused on the development of assessment and retrofit guidance to address the vulnerabilities observed (Fenwick et al. 2010, MBIE 2018, Brooke et al. 2019). Some 50 years since the first introduction of hollowcore floors in New Zealand, it is now clear that their susceptibility to damage during earthquakes makes them a poor solution for buildings in New Zealand. While new buildings have shifted to alternative more robust floor systems, a large stock of existing buildings with hollowcore floors must be retrofitted or demolished at significant cost.

<u>Shear yielding beams:</u>

Another example of implementation of precast concrete systems proceeding research occurred with the shear-yielding detail for precast concrete frames. A range of alternative configuration and connection detailed were originally developed for precast concrete frames, with the intent on emulating cast-in-place construction and allowing plastic hinges to form in the beams (CAE 1999, Park 1995). Short span beams in seismic frames posed a challenge to fit mid-span stich connections and had a high shear to moment ratio. An alternative detail was proposed using diagonal reinforcement at the mid-span connection and strengthening the ends of the beams to create a shear yielding mechanism similar to diagonally reinforced coupling beams, as shown in Figure 4a. The proposed detail worked in theory and was implemented in at least two buildings in the 1980s.



(a) Shear yielding detail (Restrepo et al. 1995)

(b) Strut and tie model for the shear yielding detail (Credit: Richard Fenwick)

Figure 4 – Shear yiedling precast beam detail

As part of the precast concrete research programme conducted at the University of Canterbury in the 1990s, the shear-yielding beam detail was tested along with other connection details (Restrepo et al. 1995). Unfortunately, the tests demonstrated that the shear-yielding mechanisms did not work as intended, with damage concentrating at the start of the diagonal reinforcement resulting in only limited ductility (Figure 4a). As shown by the strut and tie models for the detail in Figure 4b, analysis of the connection load path in 2D did not reveal an offset in the transfer of force from the diagonals to the outer layer of beam reinforcement, which resulted in a critical section for yielding at the ends of the diagonals prior to the intended design capacity being achieved. An improved reinforcement detail was proposed by Restrepo et al. (1995), but this was too late for the buildings already constructed. It does not appear than many (or any) buildings adopted this connection detail beyond the date of the published tests.

One of the constructed buildings that used the shear-yielding beam detail was the Clarendon Tower in Christchurch that was heavily damaged during the Canterbury earthquake sequence and subsequently demolished. Researchers were fortunate to be able to test frame assemblies that were extracted from the Clarendon Tower to assess their residual capacity and potential impact of repairs (Walsh et al. 2015). These tests again confirmed that the shear-yielding beams did not form the intended yielding mechanisms, with concentrations of damage at the start of the diagonal reinforcement section.

SUBSTANTIALLY SIMILAR DESIGN

The previous examples illustrated radical innovations that were a departure from established design practice or detailing, whereas much of our structural design practice relies on more incremental improvements or changes. Such incremental changes often rely on extrapolation of previously tested or proven designs where we rely on the new design being substantially similar for existing design methods and provisions to be confident in their capacity or performance. Such incremental changes or innovations are not always as straightforward as expected and examples of knowledge gaps identified include:

- Shear strength provisions for reinforced concrete beams that were originally developed empirically based on tests of small beams. Later testing of more realistic beam sizes demonstrated that there was a significant size effect in reinforced concrete members with no shear reinforcement, with the concrete shear strength dropping sharply as the depth increased (Collins et al. 2008).
- Poor ductility in lightly reinforced concrete walls where there was insufficient vertical reinforcement to generate the distributed cracking required to achieve a plastic hinge length comparable to expressions developed for well reinforced sections (Sritharan et al. 2014).
- Premature failures of full-scale energy dissipating devices when tested that were partially attributed to reliance on design methods developed from small-scale devices tested in the lab (Cattanach and Clarke 2020).
- Concerns over the detailing of unstiffened gusset plates for BRBs, where some implemented designs used gusset plate design procedures for conventional braced frames despite being based on a different brace deformation mechanism (MacRae and Clifton 2017).
- Post-tensioned anchors used in rocking walls where the barrel and wedge anchor designs were developed for static loads and failed premature when subjected to cyclic load increases during building tests (Schoettler et al 2009).

RECOMMENDATIONS

With the benefit of hindsight, it is easy to criticise past failures as being an obvious mistake. However, the causes of such failures can be attributed to a number of factors and complex circumstance. Based on the examples presented, some common root causes of structural engineering innovation failures could include:

- Inadequate consideration of critical loading cases (e.g. fatigue, seismic actions).
- Design flaw due to inadequate design procedures and a lack of testing to validate prior to implementation.
- Reliance on lab testing of specimen that do not accurately replicate implemented designs or demands (e.g. reduced scale, regular geometry, simplified boundary conditions and loading protocols).

- Reliance on testing and analysis of components that neglect the complex interactions that occur at the system level.

Some of these failures may have been avoidable if a more rigorous approach was taken to research and development, whereas other failures can be primarily attributed to genuine advancements in knowledge over time. In all cases there is plenty that we can learned in order to improve our process for developing and implementing innovative solutions and avoid falling into some of the same traps.

The importance of both physical testing and earthquake observations have historically been critical to the development of new solutions as both can reveal behaviour that was unexpected. In hindsight these observatories can appear obvious but did not appear so when purely considering theory or numerical analysis. Numerical modelling is often promoted as a replacement for physical testing but its application in the development of innovative solutions needs to be carefully considered. Models are biased towards our preconceived theories and assumptions and the results reflect the inputs provided. Numerical models are best used once the techniques have been comprehensively validated with data from physical testing and again the limits on "similarity" and extrapolation of models beyond the validation data needs to be carefully considered.

When considering the evidence that is required to validate an innovative design solution the difference between the type of innovation is relevant. **Incremental innovation** describes only a small extension of a known system and so evidence from testing may only be required to explore the **known unknowns** (e.g. does a size effect exist?). **Radial innovation** involves a departure from well understood principles and so needs to be more extensively researched and tested in order to identify the potential **unknown knowns** or **unknown unknowns**. For example, when developing new structural systems (e.g. low-damage solutions) we should follow a comprehensive research and development process when the complexity is slowly increased from concept, to component level testing and analysis, sub-assembly testing to investigate interaction between components, and potentially to the system level where an entire structural system is tested, as is shown in Figure 5. This staged approach to developing radical innovation allows for the bugs to be ironed out along the way. For example, during the development of the concrete slotted beam detail, researchers observed during sub-assembly tests (see Figure 5) that the beams rotated due to the increased torsional demands as a result of flexural strength at the floor slab-beam connection when subjected to lateral deformations. This phenomenon did not occur during earlier component testing as it related to an interaction that was only activated when testing at the sub-assembly scale. The design method for the slotted beams was revised to include this additional torsional action and subsequent testing of the detail during a shake table test of the entire building structure verified the success of this improvement.

When considering the evidence required prior to adopting new innovations we should question the speed at which changes to typically design practice occur. In Christchurch the earthquake damaged multi-storey concrete buildings were predominantly demolished and replaced with a range of innovative new structural designs. One could argue that despite their imperfections, the earthquakes (and associated research) taught us considerable lessons regarding the expected performance of these concrete buildings, to the extent that we understand their likely performance better than any alternative system. Are the innovative designs that have replaced these buildings with as well understood? Or have we potentially adopted the "next hollowcore" of innovations that will rear its ugly head in the next major earthquake? Better the devil you know than the devil you don't.

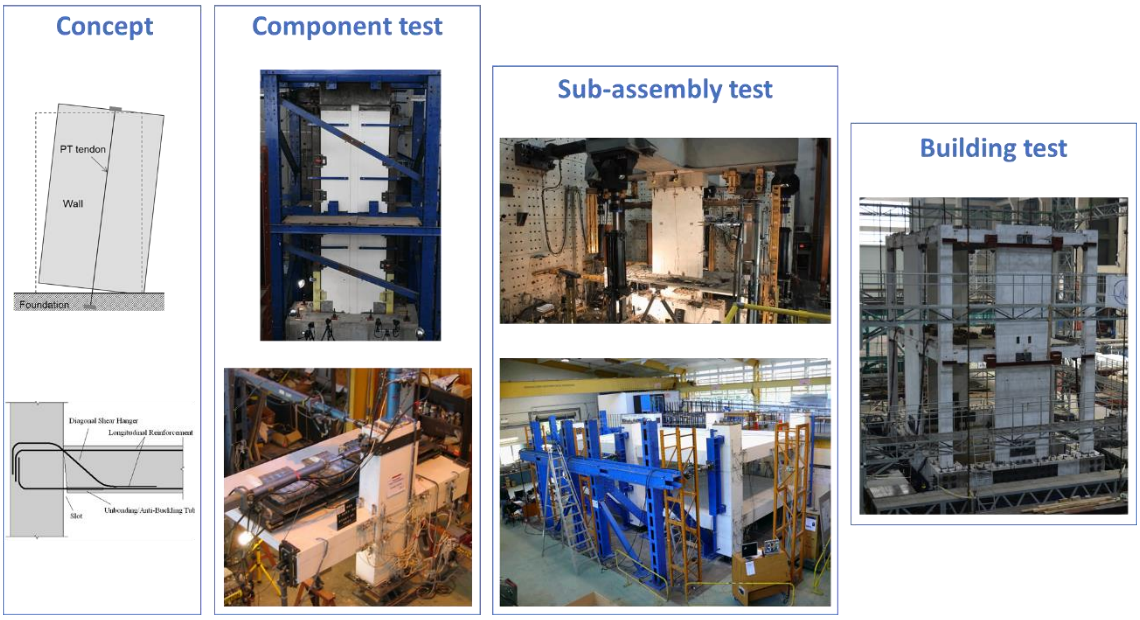


Figure 5 – Research and development of low-damage concrete structural systems

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