PRECAST DOUBLE TEE SUPPORT SYSTEMS – 10 YEARS ON

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SUMMARY

Ten years ago, the findings of a SESOC working group investigating the performance of double tee support systems were published (Hare et al. 2009). Significantly, the working group identified the non-compliance of the ‘pigtail’ detail with the performance requirements of the New Zealand Building Code, and strongly recommended that structural engineers not utilise the detail. Recently, consequential to the failure of double tee units during the Kaikoura earthquake (MBIE 2017, 2018a), MBIE issued a formal warning confirming that the pigtail detail is unlikely to comply with the Building Code (MBIE 2018b).

This paper revisits the findings of the SESOC working group in light of developments in the intervening period and reiterates why the pigtail detail is not compliant with the Building Code. Significant issues that have arisen since the original publication that are addressed include:

1. Revelation of a new failure mechanism for flange hung double tees related to support rotation that was identified during post-earthquake evaluations, primarily on Statistics House.
2. Consideration of tolerances, noting that there are three major factors, and that the timing of these manifesting is not necessarily favourable:
   a. The distance between the supports
   b. The length of the precast unit, itself bifurcated between the length of the ribs and the outstand of the nibs
   c. The location of the loop bars within the tee.
3. Safety in design – noting that there is a requirement to consider this all the way through to safe demolition and that there have been several premature failures which are arguably either due to inappropriate (but ‘industry standard’) demolition techniques (nibbling onto the floor below before sweeping off) or a failure of the floor/tees to consistently provide support.
4. Whether it is appropriate to use double tees on steel composite beams, and what form of support is required during construction and in service.

INTRODUCTION

Nearly ten years ago, a SESOC subcommittee comprising John Hare, Richard Fenwick, Des Bull, Richard Built and Rod Fulford published their paper, Precast Double Tee Support Systems (Hare et al. 2009). The subcommittee was assembled to address concerns expressed by some members of the society over the use of the loop bar or ‘pigtail’ in flange supported double tee
systems (see Figure 1). For some time prior, a number of members of industry had expressed concerns over the lack of robustness of the detail and its widespread use.

![Figure 1: 'Pigtail' hanger detail (Hare et al. 2009)](image)

At that time, the loop bar detail had been in widespread use for approximately thirty years. As a proprietary detail, it was not subjected to the same degree of design validation that specifically designed details would be and its use was largely supported by limited testing. Originally, its use was somewhat restricted as it was under patent and the original users had apparently placed some restrictions on its application. However, by the time the subcommittee was convened, its use was widespread and there were no significant restrictions on its use that the authors are aware of.

**Precast double tee support systems – a brief recap**

The SESOC subcommittee exhaustively investigated the full range of double tee supports, including the loop bar. In particular, it reviewed the structural mechanism of the loop bar and concluded that it has significant shortcomings.

It was noted that conventional flexural and shear theory could not apply to the disturbed zones at the loop bar support. However, a review of possible strut and tie models could determine no mechanism that would fit the reinforcement details. Amongst numerous potential failure mechanisms (see Figure 2), the most significant concern was with the tension field that would develop behind the loop bar, across the interface with the topping slab. This is shown in more detail below in Figure 3.

The following extract from the SESOC sub-committee summarises the findings:

*The pigtail detail undoubtedly has some capacity, based on observations of testing and performance to date. However the available published test data and the original design methodology cannot now be validated in light of current code practices. The argument that 30 years of use and acceptance by industry should be sufficient evidence for acceptance does not stand scrutiny. Although there have been no recorded failures and the tests completed to date have indicated failure loads in excess of design loads, the margins are not statistically sufficient. It is concluded that the inherent factors of safety provided by the NZS3101 for other members (floors, beams etc) are not therefore being met by the floor supports, which are the least desirable location for a failure.*

The report concluded that the Cazaly hanger would be a more appropriate detail to use for flange supported double tees.
Subsequent events

Since the publication of the report in 2009, there have been a number of further events that warrant revisiting that study, including, more or less chronologically:

1. The Canterbury earthquakes
2. The publication of the SESOC Interim Design Guidance (SESOC Management Committee 2012)
3. Introduction of new, more stringent and more encompassing, health and safety legislation (New Zealand Government 2015)
4. The Kaikōura earthquake and the failure of double tee beams in Statistics House
5. The publication of amendment 3 of NZS3101:2006 (NZS 3101 2017)
6. The MBIE warning on the use of the loop bar detail (MBIE 2018b)
7. The publication of report and addendum describing the investigation into the performance of Statistics House failure (MBIE 2017, 2018a)

These will be discussed briefly in the sections that follow.

**Canterbury earthquakes**

In the interests of brevity, the full detail of the earthquakes will not be presented here, but there are numerous accounts of building performance that have already been published (e.g. Cooper et al. 2012; Corney et al. 2014; Galloway et al. 2011; Kam et al. 2010, 2011). However, it is of significance that this series of events, commencing on September 4th 2010, was the first major seismic test of modern buildings in New Zealand. Although the more destructive February 22nd 2011 earthquake (Geonet 2013) was of relatively low Magnitude (Mw 6.2), its shallow depth and close proximity produced very intense seismic actions, well in excess of current design levels, for much of Christchurch including the CBD.

While Christchurch had not been as heavily redeveloped as either Wellington or Auckland in the 1980s, and adoption of hollowcore flooring had been slower than in the North Island due to the lack of full local production facilities until circa 1987 (PCFOG 2009), double tees were relatively common in pre-earthquake Christchurch. It is not known with any accuracy what proportion of buildings had double tee flooring and of those, what proportion may have used the loop bar detail. Nevertheless, there were a number of significant structures with double tee flooring systems, including:

- The PWC tower
- Clarendon Tower
- The Crowne Plaza hotel

All of the buildings noted above were demolished after being deemed uneconomic to repair. The most heavily damaged building of those known to contain flange hung double tees was probably the Clarendon Tower. No flooring units fell in the Clarendon (Cattanach and Thompson 2013; Cooper et al. 2012), but there were a number of locations where up to 20 mm vertical dislocation of the floor at seatings was recorded, in conjunction with significant (> 10mm) cracking of the floor topping at the junction of the tees to the supporting beams (Zimmerman and Holmes 2012).

**SESOC Interim Design Guidance**

Following the Canterbury Earthquakes, SESOC took the step of publishing Interim Design Recommendations (SESOC Management Committee 2013). The intent of this document was to enable the profession to react and learn quickly to the lessons of the earthquakes, without having to wait for a full cycle of code revisions. It provided three levels of guidance:

1. To highlight or clarify elements of the Verification Methods (MBIE 2014) that were observed to have been misapplied in practical use,
2. To offer proposed amendments to the Verification Methods in anticipation of likely updates to the underpinning Standards where it had been observed that they may not have achieved the performance requirements of the NZ Building Code, and
3. To offer suggestions to achieve improved performance, over and above the minimum performance requirements of the Building Code.

After some consultation and review, this Interim Guidance was published in the SESOC Journal and is still available on the SEOC website (SESOC Management Committee 2013),
although it is expected to be withdrawn or substantially revised in the near future because the Building Code and Standards have been updated to incorporate learnings from the earthquakes.

The interim design guidance made only brief specific reference to double tee flooring as it referenced the earlier subcommittee publication (Hare et al. 2009). The most significant advice pertinent to double tees was a clarification that support systems should be designed to accommodate the peak deformation demands expected to occur during the ‘maximum considered’ earthquake (MCE), i.e. 1.5/$S_p$ times the ultimate limit state (ULS) deformation, including effects such as frame elongation as had been previously identified as necessary for hollowcore floors (Fenwick et al. 2010). This recommendation has since been adopted in the Concrete Structures Standard (NZS 3101 2017).

Health and Safety at Work Act 2015

Far reaching changes to New Zealand’s approach to workplace health and safety were introduced by the Health and Safety at Work Act 2015 (New Zealand Government 2015). Duties under the Act cannot be contracted out of, and (onerous) fines imposed for breaches may not be insured against. A key aspect of the Act is that responsibility for health and safety is spread across a wider range of individuals. Notably this includes specific duties for designers of structures, who are required to:

“so far as is reasonably practicable, ensure that the…structure is designed to be without risks to the health and safety of persons—

“(a) who, at a workplace, use the … structure for a purpose for which it was designed; or …

“(d) who construct the structure at a workplace; or

“(e) who carry out any reasonably foreseeable activity (such as inspection, cleaning, maintenance, or repair) at a workplace in relation to—

“(iii) the manufacture, assembly, or use of the structure for a purpose for which it was designed, or the proper demolition or disposal of the structure”

Generally, these duties are responsibilities structural engineers (should) have been considering irrespective of the Act. However, the nebulous requirement to judge what is “reasonably practicable” can have broad implications such as precluding full investigation of damaged buildings. Consequently the Act has significant implications for many aspects of structural engineering practice, including some with specific relevance to double tee floors.

The Kaikōura Earthquake

The Mw 7.8 Kaikōura earthquake of November 14th 2016 (Geonet 2016) involved a complex series of fault ruptures commencing in the Culverden region and ending relatively close to Wellington. Although closer at its source to Christchurch, the rupture mechanisms and local geology produced significantly greater impact in Wellington. Again, there are many authoritative sources of information on this event (e.g. Brunsdon et al. 2017; Henry et al. 2017) so a full discussion will not be represented here. However, it is of note that there was widespread shaking at close to design levels in pockets of the CBD. This was in many cases considered to be a combination of basin edge effects and the natural ground periods; and had greatest impact on buildings with fundamental periods in the range of 1.0-1.5 seconds, typically corresponding to heights in the range of 6-15 stories.
There were a number of building failures, the most significant of which for this paper was Statistics House, which is addressed separately below. One of the most significant general observations from this event was the duration of the shaking leading to extensive frame elongation in some buildings, resulting in many cases in significant damage to precast flooring systems (Henry et al. 2017). However, most (65%) of the affected buildings in Wellington used hollowcore flooring, with about 5% using flange supported double tees (Brunsdon et al. 2017).

A Targeted Damage Evaluation process was developed by Wellington City Council, SESOC, and the NZSEE in the aftermath of the Kaikōura earthquake in order to ensure to the potentially damaged buildings were evaluated sufficiently. Approximately 70 buildings were evaluated under this scheme, with approximately 50% shown to have potentially significant distributed or localised damage to frames and floors (Brunsdon et al. 2017).

Since the Kaikōura earthquake, a significant body of research into the behaviour of precast floors has commenced with support from the Natural Hazards Research Platform, the Building Research Levy (BRANZ), EQC, and QuakeCoRE. Although hollowcore floors are the primary focus of this work, the assessment and retrofit of double tees forms a significant part of the work planned as part of a major multi-agency research programme recently funded by BRANZ, EQC, Concrete New Zealand Learned Society, and others (Brooke et al. 2018).

The results of post-Kaikōura research are already being disseminated, for example by inclusion in proposed updates to the assessment guidelines (Brooke and Elwood 2018; NZSEE et al. 2017). One important conclusion that has been arrived at through this process is that most potentially affected buildings are not considered to be earthquake prone, although this may need further consideration with regard to flange suspended double tees with loop bar supports.

Amendment 3 to NZS3101:2006

Amendment 3 of NZS3101:2006 was published in mid-2017, and cited in the April 2018 amendment to Verification Method B1/VM1 (MBIE 2018c). The amendment introduced a number of new provisions based on the lessons from the Canterbury earthquakes (Cooper et al. 2012; SESOC Management Committee 2013) as well as significant new research on precast floors. The foreword describes aspects that were amended in some detail, but the most significant aspects (for this paper) include:

- Provisions requiring explicit consideration of plastic hinge elongation,
- Precast seating details were amended to be considerably more stringent, and
- Clarification of the seismic displacements to be used in seating design for flooring

The revised Standard also now makes explicit the requirements that the tensile strength of concrete should not generally be relied on as a load path, and that:

“every load or force acting on a structure shall have one or more dependable load paths that can transfer the force to the foundation soils. Each load path shall satisfy the fundamental structural design requirements of equilibrium and displacement compatibility.”

The consequence of these provisions was to significantly increase the required seating for precast flooring systems, reflecting increased awareness of the potential for elongation and more prescriptive requirements for spalling and other factors that can reduce available seating. For example, the estimated seating length required for the double tees in the Statistics House building in accordance with the new provisions is approximately three times the seating required by the Standard at the time. For double tees the large seating lengths required by the new provisions are likely to increase the use of armoured support details to reduce spalling lengths.
The MBIE warning

On 3 April 2018, the Ministry of Building Innovation and Employment published a Warning (under S26 of the Building Act) on the use of the loop bar (MBIE 2018a). It noted that the loop bar details do not comply with NZS3101 and are unlikely to comply with clause B1 of the NZ Building Code.

This followed a period of consultation in which there was a level of disagreement amongst engineers, including between technical societies, over whether a ban should be imposed. Some engineers were concerned that a ban could have disproportionate impact on the value of existing buildings using loop bars. Others (including the authors) felt that a ban would finally eradicate use of the loop bar in new buildings, noting that some designers or builders may try to justify its use under alternative design provisions.

The warning notice highlighted a point that was perhaps not widely known – that despite the SESOC subcommittee report of 2009 warning against use of the loop bar, it had continued to be used sporadically ever since. The authors are aware of at least one case since the Christchurch earthquakes where the design engineer, having specified another form of hanger, was actively undermined by a precast supplier promoting the alternative use of the loop bar.

Statistics House

Statistics House was a six-storey reinforced concrete office building with a lightweight roof structure, built in the Centre Port Harbour Quays business park in 2005. As a result of the Mw 7.8 Kaikōura earthquake on 14 November 2016, the building suffered the partial collapse of two floors. Three precast double tee units fell, having delaminated from the topping which was left suspended intact.

Soon after the collapse, MBIE appointed an expert panel to investigate the failure. The investigation report was published in March 2017 (MBIE 2017). It concluded that:

“the partial floor collapses of Statistics House were caused by a combination of:

- “a highly flexible ductile frame with two bays of frame per precast floor span, which effectively doubled the impact of beam elongation due to plastic hinging; and
- “shortening of the precast double-tee flooring units as the ends spalled during the earthquake; and
- “amplification of ground shaking, primarily due to basin-edge effects in the Thorndon basin area; and
- “the duration of the earthquake.“

Among the findings of the report, was a key observation on the form of failure of the nib of the doubletees. It was noted that the nib appeared to have failed progressively due to the cyclic rotation of the supporting beams under reversing load. This form of failure was not considered by the SESOC sub-committee, which largely considered seismic demands as idealised static loads.

Subsequently, Statistics House was demolished over the period December 2017 to February 2018. The engineer to the demolition noted several apparent anomalies during the demolition process. These were notified to MBIE, who then re-convened the investigating panel. The primary issues being investigated were the double tee seatings and apparent fragility of the double tee supports.

An addendum report was published in June 2018 (MBIE 2018b). The panel concluded that the seatings of the double tees were short in a number of locations, but that this did not change
the findings of the original study. However, a number of further recommendations were made in respect of double tees, including:

- that engineers and contractors involved with the demolition of such buildings should be aware of and allow for, the propensity of flange supported double tees to fail suddenly under shock loading.
- the industry approach to construction tolerances requires review, taking into account the sequence of casting and erection of precast concrete elements

Discussion

There are several key issues that have emerged since the 2009 paper that warrant discussion in more detail, following.

Alternative mechanism of failure

As noted above, the Statistics House floor collapse appeared to result from an alternative failure mechanism of the nib to those investigated by the SESOC sub-committee. The sub-committee dealt primarily with vertical static loading under gravity, although recognising the potential impacts of seismic actions, including frame elongation and rotation.

However, the Statistics House investigation provided evidence of fracture of the nib, leading to shortening of the units and exposure of the loop bars. This is shown below in Figure 4, drawn from the MBIE investigation report.

Figure 4: Failure sequence of double tee nib (MBIE 2017)
As the elongation of the parallel beams progressed, the ledge under the loop bars spalled and the units fell, with the loop bars themselves being further crushed and shortened. The topping above the units remained in place.

As part of the MBIE investigation, the surface roughening of the units during construction was considered. Photographs from construction were located, indicating that surface of the units was adequately roughened. Hence it appears that the delamination was as a consequence of the progressive elongation actions in the topping causing progressive elongation. It is emphasised that while appropriate roughening of the interface between a precast unit and the topping can provide adequate in-plane shear transfer, no reliable load path for vertical tension forces exists between the topping and precast unit. Consequently, there should be no expectation that an unseated precast unit will ‘hang’ from the topping concrete.

Figure 5: View of end of fallen double tee. Note broken off concrete nib and exposed loop bar.

Tolerances

Among other things, the MBIE addendum report considered in detail the impact of construction tolerances on the seatings of the double tees, with regard to the sequence of casting and erection of the floor units; and the position of the supporting members.

Consideration of tolerances is specifically required in NZS3101 when assessing ledge width, with relevant details and tolerances outlined in other documents (Bull 1999; NZS 3109 1997). However, typically calculations are based on an implicit assumption that the supported element is able to carry the load reliably to the end of the unit (in this case, the nib of the double tee). The validity of this assumption must be explicitly checked. In the case of a specifically designed element such as a Cazaly hanger, this is achieved during the design by considering the load at the tip of the hanger. In the case of a proprietary cast-in element such as a loop bar, the precise location of the element within the precast becomes critical, as does the consideration of the loading of the nib beyond the proprietary element.
The conclusion of the addendum in this regard was that the geometry of the loop bar, in combination with normal construction tolerances, means that it is virtually impossible for the centre of the loop bar to be located over the support through all loading circumstances (including elongation effects). This would mean that the continued support of the double tee would be reliant on concrete tension in the nib, which is not a reliable load path.

Steel Support Beams

With the increased use of structural steel, contractors and designers have been challenged to provide economic floor configurations and some have adopted combinations of precast floors and steel composite floor supports. These systems have typically not been subject to the same levels of testing that the combination of steel composite decking and composite beams have been through, and there may be some aspects of the behaviour of these systems that are not yet fully understood.

One such concern is that the concentration of shrinkage, creep and other long-term loading effects may lead to opening of cracks at the ends of the precast units, artificially creating an edge and hence reducing the capacity of the composite studs (which require the confinement of the in-situ concrete to develop their full shear capacity). This concern was addressed in the Interim Design guidance (SESOC Management Committee 2013), which recommended among other things that if using precast flooring with steel beams, designers ensure that the bare steel beam is able to support at least the G&Q load case in the event of loss of composite capacity.

Another consideration with this practice is the load transfer to the web of the steel supporting element. Eccentric loading of the steel beams can cause construction problems with the potential for rolling of the supporting steel beam. It is suspected that this was a contributing factor to a partial floor collapse during construction, which occurred at a construction site in Albany (Stuff 2017). If using a flange supported double tee, a Cazaly hanger or similar that can extend beyond the web of the supporting steel beam may be used. However, this may make achieving composite action more difficult, as a central row of studs may clash with the hangers.

Demolition

The double tee units in Statistics House were found to frequently collapse as the debris from the floors above dropped onto them. While it had been suggested that this was an unusual event and not previously encountered, the demolition contractor observed that this is a common occurrence and that buildings with double tee floors are consequently considered easy to demolish. The corollary is that care must be taken to address safety with this form of failure and for taller buildings, this may not be so controllable. Hence the advisory note in the conclusions of the MBIE addendum report. The need for consideration of this behaviour is particularly pressing in the context of the duties owed under the Health and Safety at Work Act 2015 (New Zealand Government 2015), Where demolition of buildings with even moderately damaged precast floors is required, preference should be given to methods that minimise the need for contractors to work under damaged floors. If ‘cut and carry’ demolition is required, this likely requires employment of ‘from above’ methods such as those used during demolition of Clarendon Tower (Cattanach and Thompson 2013).

Further research

Despite the extent of work undertaken previously to investigate the behaviour of precast concrete floors, many gaps exist in our understanding. This applies particularly to double tee floors that have not been investigated extensively. Additionally, and unacceptably, no comprehensive validation has been undertaken of retrofit approaches for existing precast concrete floors.
To address these gaps, a coordinated research programme (‘ReCast floors’) funded by BRANZ, EQC, and Concrete New Zealand Learned Society has been established address retrofits for precast floor systems (Brooke et al. 2018). This will include tests to further understand the behaviour of both web supported and flange supported double tee units. The testing will be used to confirm assessment guidelines for the capacity of existing double tee support details as well as to validate retrofit solutions that could be implemented in existing buildings.

CONCLUSIONS

Developments since the 2009 SESOC sub-committee report have generally tended to vindicate the findings of that review. Further learnings as a result of the Canterbury and Kaikōura earthquake have highlighted a further form of failure that may form under the combination of elongation and support rotation during earthquakes.

Although Statistics House may represent an extreme combination of site amplification, flexible elongating frame configuration and unfavourable detailing of the support system, it represents a ‘canary in the mine’ of building performance. In other words, it was a pointer to the potential for more similar failures in the event of longer duration earthquakes. Given the scale of some of the buildings that have double tee floors, this represents a significant life safety hazard during severe events, noting that most potentially affected buildings are not considered to be earthquake prone.

The MBIE warning should put considerable weight behind both the conclusions of the 2009 SESOC sub-committee report and the outcomes from the Statistics House report. Although it is acknowledged that there may be specific circumstances (for example over a rigid basement) when the loop bar may provide adequate performance over the full range of possible actions under both frequent and infrequent events, the availability of alternative details should mean that the industry will no longer use the loop bar.

Focus should now shift to the assessment and repair or replacement of these systems. While it is acknowledged that this detail has some capacity, it is very difficult to apply normal quantitative procedures to assess this, given the uncertainty involved in the geometry and behaviour of the supports. As noted above, further research is required.

The authors are of the view that in general, the floors of a structure should be able to survive without collapse the level of shaking that would bring the primary frame to the point of collapse. Current thinking indicates that this is not the case for most existing precast flooring systems, and loop bar supported double tees in particular. How the engineering profession addresses this challenge is a work-in-progress, but with the current state of knowledge, the authors would strongly recommend installation of secondary supports for double tees with loop bars in multi-storey construction.

REFERENCES


MBIE. (2018b). *Warning Against the Use of Loop Bar Details in Flange-Hung Double-Tee Precast Concrete Floor Units that do not Comply with NZS 3101 (Warning 2018/001)*. Ministry of Business, Innovation, and Employment, Wellington, New Zealand, 3p.


