The New Zealand Concrete Industry
Conference2012
Claudelands, Hamilton 11-13 October

PERFORMANCE OF PRECAST CONCRETE FLOOR SYSTEMS DURING THE 2010/2011 CANTERBURY EARTHQUAKES

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SUMMARY

The 2010/2011 Canterbury earthquakes caused significant damage to both traditional and modern reinforced concrete (RC) buildings. There has previously been a significant amount of research into the seismic behaviour of precast concrete floor systems, and the observed damage caused to precast floor systems should be compared against the expected levels of performance. Preliminary results of an investigation into the performance of precast concrete floor systems during the Canterbury earthquakes are presented. In general, only minor damage was observed in precast floor units and the severe damage in several buildings was attributed to displacement incompatibilities in the structure and the lack of robustness of the entire floor diaphragm. Additionally, it is expected that if current best-practice recommendations were followed, the resulting damage to precast floors would have been significantly less than was observed following the earthquakes.

INTRODUCTION

The 2010/2011 Canterbury earthquakes have provided a unique opportunity to investigate the seismic performance of both traditional and modern buildings constructed in New Zealand. It is critical that the observed performance of buildings during the Canterbury earthquakes is examined and compared against the expected levels of performance that are outlined by the New Zealand Building Code and the corresponding material design standards. The observed damage to reinforced concrete (RC) buildings confirmed lessons learned from previous earthquakes and research, as well as highlighting previously unidentified issues that could affect the seismic performance of modern RC buildings (Kam et al. 2011). It has been reported that building floors that used precast concrete units performed poorly during the Canterbury earthquakes when compared to cast-in-place concrete floors (Structural Engineering Society of New Zealand (SESOC) 2011a; Structural Engineering Society of New Zealand (SESOC) 2011b), however little evidence has been published to support this statement. This paper presents the preliminary findings from an investigation into the performance of precast concrete floor systems in Christchurch, and it is anticipated that a detailed database and associated damage statistics will be published following the completion of the data collation process.

BACKGROUND

Precast concrete is commonly used in New Zealand for a range of different structural and non-structural applications. The use of precast floor units is particularly common in buildings, typically consisting of hollow-core, double-tee, rib and timber infill, or flat slab systems. It is estimated that in Christchurch alone there is over 250,000 m^2 of installed hollow-core flooring (PCFOG committee 2009). As summarised by Fenwick et al. (2011), over the last decade there has been extensive research in New Zealand investigating the seismic performance of precast concrete floor units. Following the discovery that beam elongation could have a negative impact on the performance of floor diaphragms (Lau 2007), an extensive research program was initiated at the University of Canterbury (UC) to investigate the seismic performance of floor diaphragms with precast hollow-core floor units (Lindsay 2004; Mathews 2004; MacPherson 2005; Jensen 2006; Fenwick et al. 2010). Recommendations from the UC research regarding the displacement incompatibilities between the floor and frame systems and the robustness of the floor support detail were subsequently included into revisions of NZS 3101:2006 and a draft report prepared by the Precast Floor Overview Group (PCFOG) established by the Department of Building and Housing (PCFOG committee 2009). More recently, the seismic performance of precast flange-supported double-tee units has been questioned (Hare et al. 2009). Due to potential failure mechanisms not having been addressed by previous research, the previously widely used loop-bar hanger detail for flange supported double-tee units is no longer an accepted detail for new construction.

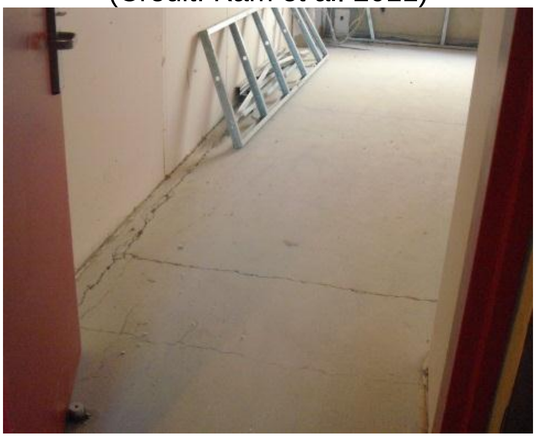
There have been several anecdotal comments that suggest that precast concrete floor units performed poorly during the Canterbury earthquakes, however few detail have been published to substantiate these claims. Kam et al. (2010) reported that following the 4 Sept 2010 earthquake several instances of beam elongation induced cracks were observed in floor diaphragms, but despite previous concerns over the seismic performance of hollow-core floors, damage to hollow-core floor units was only observed for a single building. Kam et al. concluded that the lack of damage to hollow-core units confirmed the low displacement demands on multi-storey RC buildings during the 4 Sept 2010 earthquake. Following the 22 Feb 2011 earthquake, Kam et al. (2011) reported that cracks in floor diaphragms due to beam elongation were further exacerbated in one multi-storey building, and that in another building a poorly detailed ramp structure had led to damage and loss of support to hollow-core units. However, widespread damage to precast floor units was not reported, and Kam et al. suggested that the short duration of the 22 Feb 2011 earthquake contributed to the lack of damage observed in the floor diaphragms of many multi-storey buildings.

DIAPHRAGM PREFORMANCE

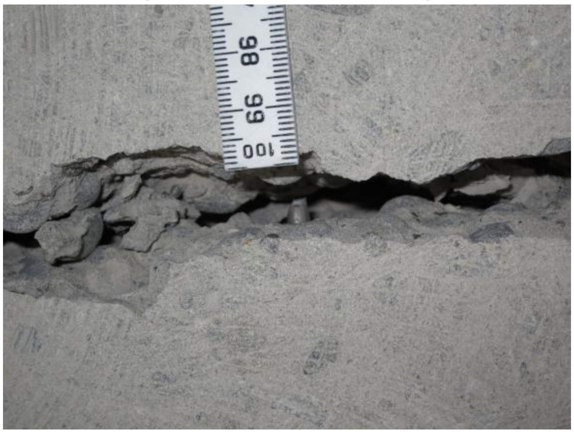
As reported previously by Kam et al. (2010; 2011), cracks were observed in floor diaphragms where beam hinging and elongation had occurred in multi-storey buildings. As shown in Figure 1, cracks were observed in the cast-in-place topping of several floors, both at the joint between the beam and the precast unit, and at the joints between precast units. In many cases wide cracks led to the fracture of non-ductile mesh used in the topping concrete. The lack of robustness of non-ductile mesh has been recognised for several years, and current regulations required that ductile seismic grade reinforcing steel be used in floor diaphragms. In the building shown in Figure 1c and d, cracks were observed in the topping at almost all of the joints between the precast flat slab units. Although this loss of continuity in the topping does not threaten the vertical stability of the floor diaphragm, an increase in the flexibility and noticeable sagging of the floor diaphragm was observed. As noted in the SESOC preliminary observations report (2011b) and by Kam et al. (2011), it is recommended that a more robust and unified design method is required for floor diaphragms, and this design method should be developed with equal consideration to all types of floor system.

(a) Cracking due to beam elongation
(Credit: Kam et al. 2011)

(b) Cracking at joints between precast units
(Credit: John Marshall)



(c) Cracking at joints between precast units
(Credit: John Marshall)



(d) Mesh fracture in topping
(Credit: Rod Fulford)

Figure 1. Damage to floor diagrams in multi-storey buildings with precast floor units

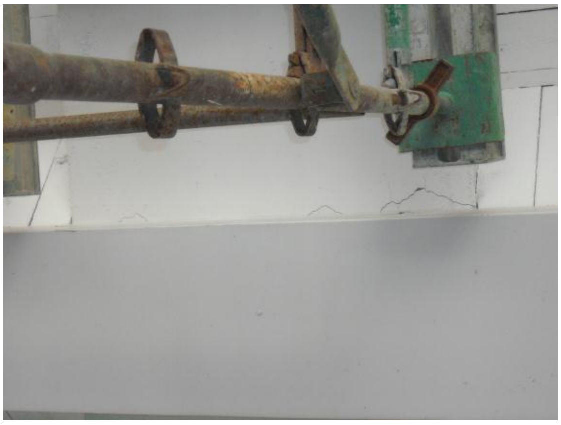
PERFORMANCE OF PRECAST UNITS

In general, the performance of precast concrete floor units was adequate following all of the major earthquakes in the Canterbury sequence. The observed damage to precast units was typically minor, with more severe damage primarily attributed to displacement incompatibilities within the structure. A more detailed description of the notable damage caused to hollow-core, double-tee, rib and timber infill, and flat slab is presented below.

<u>Hollow-core</u>

A single storey carpark structure with spaced hollow-core floor units, shown in Figure 2, suffered minor damage during the 4 Sept 2010 earthquake and was severely damaged during the 22 Feb 2011 earthquake. As shown in Figure 2b, cracks were observed in two hollow-core units oriented parallel to the beam support following the 4 Sept 2010 earthquake. On-site load tests confirmed that these cracks did not compromise the vertical load carrying capacity of the floor. During the 22 Feb 2011 earthquake the connection between the floor diaphragm and the shear walls failed, causing the ramp to act as a strut to resist the lateral forces generated in the structure. As a consequence of this unintended strut action, the hollow-core units in the ramp structure were badly damaged, as shown in Figure 2d. However the ramp structure would have suffered damage irrespective of the type of floor construction due to inadequate design and detailing. Because this structure was only single storey and responded with a column-sway mechanism during the earthquakes, beam elongation and/or large rotations between the hollow-core and support beam did not occur, and so no significant damage occurred to hollow-core units in other sections of the floor.

(a) Overview of the structure



(b) Cracking at unit end following 4 Sept 2010

(c) Damaged ramp structure following 22 Feb 2011

(d) Damaged units in the ramp structure following 22 Feb 2011

Figure 2. Single storey parking structure with hollow-core units (Credit: Rick Henry and John Marshall)

In spaced hollow-core floors, cracking was noted at the corners of the units at the support, as shown in Figure 3. These corner cracks occurred in several different buildings with spaced hollow-core units and are possibly induced by torsion rotation of the hollow-core unit. The corner cracks did not appear in hollow-core units that were placed directly adjacent to one another.

(a) Cracks in the unit corners

(b) Cracks in corner and parallel to unit edge

Figure 3. Examples of cracking on corners of spaced hollow-core units (Credit: John Marshall)

Another observed damage pattern was longitudinal splitting cracks in hollow-core units, as shown in Figure 4. These longitudinal cracks were observed in a couple of buildings where the hollow-core units spanned perpendicular to moment resisting frames and flexural cracks at the ends of the beams elongated the floor diagram. This behaviour was only observed in older buildings where no bearing strip was placed at the hollow-core support, and so the hollow-core units tended to crack directly adjacent to the location of the beam flexural cracks. It is expected that the effect of this displacement incompatibility would be minimised if current recommended hollow-core seating details were used.

(a) Longitudinal cracks at unit support

(b) Longitudinal cracks along entire unit

Figure 4. Longitudinal cracks in hollow-core units (Credit: Rod Fulford and John Marshall)

More recently hollow-core units with depths of 400 mm (400HC) have been manufactured and installed in several buildings in Christchurch. Observations indicated that no significant damage was noted to the 400HC units. However, the location and design of these low-rise parking structures that used 400HC meant that the likely magnitude of lateral displacements developed during the earthquakes was small.

Despite previous research highlighting serious deficiencies in the seismic performance of hollow-core floor units, few instances of severe damage were reported. It is likely that the short duration of the shaking during the major earthquakes, in particular the 22 Feb 2011 event, contributed to the lack of damage observed in hollow-core floors. The beam elongation that occurs in ductile multi-storey buildings would be more severe following an earthquake of longer duration, which would increase the likelihood of severe damage due to the identified deficiencies of traditional hollow-core floors. It should not be assumed that the lack of observed damage implies that the potential issues with hollow-core floors do not exist, and best-practice recommendations for hollow-core floors (PCFOG committee 2009; Fenwick et al. 2010) should always be followed.

Double-Tees

Double-tee floor units in Christchurch incorporated several support details, including being web-supported, having dapped end supports, and being flange-supported. Flange-supported units tend to be preferred by designers due to the minimised inter-storey height and improved geometry for shrinkage and thermal effects when compared to web supported units. The majority of the flange-supported double-tees in Christchurch would have been constructed using the loop-bar hanger detail. In general, no serious failure of the double-tee units or supports were noted. Figure 5 shows existing cracks in the flange-supported double-tees that propagate from the support parallel to the web and then at 45 degrees across the flange. This type of cracking is common in flange-supported double-tees and does not compromise the vertical load carrying capacity of the floor.

(a) Cracks at 45 degrees in the flange

(b) Cracks parallel to the web and at 45 degrees across the flange

Figure 5. Existing cracks in flange-supported double-tee units (Credit: Rick Henry and John Marshall)

The earthquakes appear to have exacerbated existing cracks in flange-supported double-tees. As shown in Figure 6a, a possible existing crack has widened and some spalling has occurred, in this case possibly due to vertical movement at the joint between the two wall panels that the double-tee is seated on. A retrofit strategy to prevent loss-of-support of flange-supported double-tees is shown in Figure 6b.

(a) Cracking in flange

(b) Retrofit technique to prevent loss of support

Figure 6. Flange-supported double-tee units (Credit: Rob Fulford)

Minor damage was observed to older double-tee units with dapped end supports. As shown in Figure 7, unprotected dapped end supports exhibited some spalling of the beam edge and vertical cracking in the double-tee web. In contract, armoured dapped end supports with steel angles on the beam edge and on the underside of the double-tee web performed well with no damage observed, as shown in Figure 7c. The SESOC recommendations that web supported and dapped end supported double-tee units should be armoured with steel angles in order to avoid minor damage appears to be logical (Structural Engineering Society of New Zealand (SESOC) 2011a).

(a) Spalling at unprotected support
(b) Cracking at unprotected support
(c) Undamaged protected support

Figure 7. Dapped end support of double-tee units (Credit: John Marshall)

Rib and Timber Infill

In general rib-and-timber infill floors performed well during the earthquakes. The ability of the flexible infill strips to accommodate movement and distribute cracks reduced the potential for damage to rib-and-timber floors. However, one common damage pattern was the formation of flexural cracks at the ends of the prestressed ribs, as shown in Figure 8. The rib support conditions typically provide a partially fixed restraint and the ribs have little flexural capacity due to the transfer length of the prestressing strands. The SESOC recommendation that stirrups be placed in the ribs over the transfer length is again logical in order to improve the robustness of the support (Structural Engineering Society of New Zealand (SESOC) 2011a). However, it should be noted that the use of stirrups at the ends of the prestressed ribs is already consistent with current practice (Cook 2012).

(a) Side view of cracked rib
(b) Underside of cracked rib

Figure 8. Flexural cracking at rib support (Credit: John Marshall)

Flat Slab

Floors with flat-slab units also performed well during the earthquakes, with only minor damage observed. As explained earlier, cracks in the cast-in-place topping were observed at the joints between flat slab units, as shown in Figure 9a. Additionally, in the same building cracks were observed in the corners of the precast flat slab units, in particular close to the corner of the building, as shown in Figure 9b.

(a) Cracking in topping between precast units

(b) Cracking in the corner of precast unit

Figure 9. Cracking in flat-span units (Credit: John Marshall)

FURTHER DATA COLLATION

As stated earlier, the preliminary finding of an investigation into the performance of precast concrete flooring during the Canterbury earthquakes has been presented. A large number of practicing engineers and researchers have examined and recorded the damage to buildings in Christchurch, and the authors would welcome any comments or evidence to further develop the database of damaged precast floor units. Please feel free to contact either of the authors if you feel that you have information that you can contribute to this data collation process.

CONCLUSIONS

In general, the performance of precast concrete floor units was adequate following all of the major earthquakes in the Canterbury sequence. The most severe damage caused to floor diaphragms was primarily attributed to displacement incompatibilities within the structure, and in particular beam elongation in plastic hinges. However, despite a small number of buildings with damaged floor diaphragms, widespread damage was not observed, which was most likely due to the short duration of each of the earthquakes. The observed damage to precast units was typically minor and did not result in the collapse of any floor diaphragms. Additionally, the use of best-practice recommended details for the supports of precast floor units would have eliminated a large portion of the cases in which minor damage was observed.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of Precast NZ members, in particular Rod Fulford and John Marshall, for providing photos and advice from their own observations in Christchurch.

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