Department of
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Te Tari Kaupapa Whare

Hollowcore Floor Overview Report

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Summary

Over the last 30 years, considerable use of precast concrete has been made in the construction of buildings in New Zealand for floors, beams and columns. The use of precast concrete has been particularly common in flooring systems, replacing the traditional and more labour-intensive cast in situ concrete. Units incorporating hollow cores to reduce weight without significant loss of strength or stiffness are structurally efficient and competitive in cost. They became popular for a wide range of buildings in New Zealand and overseas. Reliance for overall continuity and integrity of the floor system is on reinforcement placed in the cast in situ topping slab 50 to 65 mm thick. Over the years, the thickness of hollowcore units increased from 150 mm to 300 mm and more recently even 400 mm, with corresponding increases in spans.

Questions were raised about the integrity of hollowcore floors, particularly after some failures in the Northridge earthquake in California in 1994. In October 2001, load tests on a full-scale model of a hollowcore floor assembly at the University of Canterbury [1] indicated potentially serious gaps between assumed and actual behaviour of hollowcore floor systems in strong earthquake shaking. The hollowcore units collapsed on to the test floor at lower levels of load than expected, and exhibited brittle failure mechanisms in some elements. The results caused considerable concern among structural designers, territorial authority officials and manufacturers. However, importantly, the intermediate column did not have the required reinforcement tying it back to the floor and to other columns. Had the test been done on a floor with the same support details, but with the requisite intermediate column tie-back in place, it is highly likely that the performance of the hollowcore floor would have been significantly improved. Subsequent tests incorporating the requisite tie-back, and revisions to support and perimeter detailing, showed a marked improvement. A further test incorporating reinforced ties in the voids at the ends of the units showed even better performance.

In April 2002, the Cement and Concrete Association of New Zealand and the New Zealand Society for Earthquake Engineering set up a Technical Advisory Group representing industry, research, consulting engineering and local authority interests. The Group's role was to interpret the outcome of the University of Canterbury tests, disseminate information and indicate necessary directions of future research and design practice. In August 2002 and October 2003, this Group reported on the test and recommended changes in design approaches. They recommended changes to hollowcore seating and connection details. Changes to the Concrete Design Standard, NZS 3101 [2], were made effective in March 2004, and cited as a means of compliance with Clause B1 Structure of the Building Code in March 2005.

A report by Sinclair Knight Merz to the Building Industry Authority, submitted in November 2003 [3] and prepared in response to the Scarry Open Letter [4], had as one of its recommendations that a survey be conducted 'to determine the extent of the hollowcore deficiency that may lead to building failure in a major earthquake event'.

In July 2003, the Building Industry Authority started a review of the use of hollowcore floor systems in New Zealand. The objective was to determine the extent and nature of the use of these systems nationally, to relate that use to particular concerns raised by the University of Canterbury tests and to advise the industry of any concerns. This work has been continued by the Department of Building and Housing.

In May 2004, a report entitled *Review of Hollowcore Flooring Performance in Recent Earthquakes* was produced for the Building Industry Authority [5]. This reviewed the design details and performance of hollowcore floors in overseas earthquakes and related the information to New Zealand conditions. Relevant information was limited, but the report commented that hollowcore floor systems in low-rise structures similar to New Zealand buildings performed well in at least one severe earthquake.

A report on a pilot survey in Christchurch was produced in October 2004 [6]. This survey reviewed building consent documents and indicated that 16 percent of hollowcore flooring in Christchurch was in a category for which further investigation was considered prudent. Two buildings were identified as being of potential concern, and these were referred to Christchurch City Council with a request that the owners be advised to make more detailed checks.

In February 2005, a similar review was reported on for Wellington [7] where, by reviewing building consent documents, 9 percent of hollowcore floors were assessed to be in a category for which further investigation was considered prudent. Thirteen buildings were brought to the attention of Wellington City Council with a recommendation that the owners be advised to check them in more detail.

A report investigating the potential performance of hollowcore floors in Wellington, Christchurch and Auckland was produced for the Department in February 2005 [8]. The report examined the likely displacements of buildings designed to the limits of the current Standards and compared them to those considered acceptable in the light of the Canterbury tests. The conclusion was that, for a design earthquake in Wellington, displacements of flexible (frame) buildings designed to the limits permitted by the loading Standard could exceed the lateral displacement limits for buildings with hollowcore floors now in the concrete design Standard as amended in March 2004. In Christchurch, it was found that a significant number of such buildings could exceed the maximum displacement level now considered advisable. For Auckland, the report concluded that the displacements of such buildings would generally be less than the limits now considered advisable, and that a detailed survey of Auckland hollowcore use was not warranted.

Since the initial test at the University of Canterbury, two further full-scale tests were performed [10, 11]. Each used details recommended in the revisions to NZS 3101 [2]. Both tests showed markedly improved performance from the original detail.

In June 2005, the Department issued *Practice Advisory 5* highlighting issues of concern and providing recommendations for designers, builders and territorial authority officials.

As a result of its investigations, the Department will:

- release the results of its investigations
- recommend that owners with concerns seek professional advice
- recommend that territorial authorities require a report from a qualified structural engineer when buildings with hollowcore floors are subject to significant alteration
- support the development of guidance material for designers and territorial authorities
- support Standards New Zealand in making any necessary amendments to NZS 3101 in the light of research and investigations completed since March 2004

- continue to support and encourage territorial authorities in their interaction with owners and designers on buildings they identify as requiring further investigation.

Introduction and background

Over the last 30 years considerable use of precast concrete has been made in the construction of buildings in New Zealand for floors, beams and columns. The use of precast concrete has been particularly common in flooring systems, replacing the traditional and more labour-intensive cast in situ concrete. Early forms of precast floors consisted of reinforced or prestressed solid slabs about 100 mm thick with 50 to 70 mm of cast in situ concrete topping. Many variations were developed to meet market demand.

Units incorporating hollow cores to reduce weight without significant loss of strength or stiffness are structurally efficient and competitive in cost. They became popular for a wide range of buildings in New Zealand and overseas. Reliance for overall continuity and integrity of the floor system is on reinforcement placed in the cast in situ topping slab 50 to 70 mm thick. Over the years, the thickness of hollowcore units has increased from 150 mm to 300 mm and more recently even 400 mm and more, with corresponding increases in spans.

Typically, the units have no reinforcement protruding from the ends to provide positive connections with their supporting beams. The units are produced by an extrusion process and have no transverse or shear steel.

Questions were raised about the integrity of hollowcore floors, particularly after some failures in the Northridge earthquake in California in 1994. There was a concern that strong earthquake shaking could cause loss of support to the ends of the precast units in ductile frame structures due to elongation of beams parallel to the floor units. This concern led to a test programme being undertaken at the University of Canterbury in Christchurch.

In October 2001, load tests on a full-scale model of a hollowcore floor assembly at the University of Canterbury indicated potentially serious gaps between assumed and actual behaviour of hollowcore floor systems (precast units and in situ topping, together with the surrounding and supporting beams) in strong earthquake shaking [1]. The hollowcore units collapsed on to the test floor at lower levels of load than expected, and exhibited brittle failure mechanisms in some elements. In view of the amount of hollowcore floor in existing buildings, and its ongoing common use, the test results caused considerable concern among structural designers, territorial authority officials and manufacturers. Importantly in this test, the intermediate column did not have the required reinforcement tying it back to the floor and to other columns. The absence of this steel resulted in very significant sideways displacements that were detrimental to the structural performance of the floor. Had the test been done on a floor with the same support details, but with the requisite column tie-back in place, it is highly likely that the performance of the hollowcore would have been significantly improved.

In April 2002, the Cement and Concrete Association of New Zealand and the New Zealand Society for Earthquake Engineering set up a Technical Advisory Group representing industry, research, consulting engineering and local authority interests. The Group's role was to interpret the outcome of the tests, disseminate information and indicate necessary directions of future research and design practice. In August 2002 and October 2003, this Group reported on the University of Canterbury test and recommended changes in design approaches. They recommended changes to hollowcore seating/connection details for structures where the inter-storey displacement was expected to be greater than 1.2 percent of the storey height. Changes to the concrete design standard, NZS 3101, were initiated to reflect these recommendations and amendments were made effective in March 2004 [2]. They were cited as a means of compliance with the Building Code in March 2005.

Concerns regarding the University of Canterbury tests coincided with the issue, in December 2002, of an Open Letter by structural engineer John Scarry [3] expressing concerns on the state of the structural engineering industry in New Zealand. A report by Sinclair Knight Merz to the Building Industry Authority, submitted in November 2003 [4], was prepared in response to the Scarry Open Letter. One of its recommendations was that a survey be conducted ‘to determine the extent of the hollowcore deficiency that may lead to building failure in a major earthquake event’.

Surveys and investigations

In July 2003, the Building Industry Authority started a review of the use of hollowcore floor systems in New Zealand. This work was continued by the Building Controls Group of the Department of Building and Housing after the disestablishment of the Building Industry Authority in November 2004. The objective was to determine the extent and nature of the use of these systems nationally, to relate that use to particular concerns raised by the University of Canterbury tests and to advise the sector of any concerns.

A review of hollowcore flooring performance in recent overseas earthquakes was commissioned by the Building Industry Authority and reported on in May 2004 [5]. Failures of hollowcore floors in Northridge, Califiornia (1994) and Armenia (1988) were described and their details and performance were related to New Zealand conditions. Only the Northridge event was considered relevant to New Zealand, and most of the buildings were low-rise (two or three storey). A manufacturer reported having provided over 200,000 m^2 of hollowcore flooring to 55 buildings that were within 16 km of the epicentre of the earthquake. Damage to hollowcore floors had been minor and hollowcore did not adversely affect other elements of the structure. A car park ramp and one apartment block collapsed, but the influence of the hollowcore on the collapse was not clear. Overall, the report concluded that hollowcore floors in low-rise buildings had performed well in at least one severe earthquake.

As a first step in assessing the risk profile presented by hollowcore floors throughout New Zealand, a pilot survey was carried out in Christchurch. Building consent drawings of all significant buildings with hollowcore floors were examined. A report on this was produced in October 2004 [6].

In February 2005, a similar review was reported on for Wellington [7].

A survey for Auckland was initially envisaged, but it was considered that the building displacements in design-level earthquakes were unlikely to produce the conditions that were the cause of concern in the first University of Canterbury test by Matthews. A report investigating the potential performance of hollowcore floors in Wellington, Christchurch and Auckland was produced for the Department in February 2005 [8].

In June 2005, the Department issued *Practice Advisory 5* highlighting issues of concern and providing recommendations for designers, builders and territorial authority officials. Refer to www.dbh.govt.nz/guidance-information#pa5.

Survey findings

Hollowcore use in New Zealand

Enquiries were made of suppliers to determine the nature and scope of application of hollowcore floors in New Zealand and particularly in the main centres. Manufacture under licence has been restricted to the Auckland, Wellington and Christchurch regions, and almost all of the buildings with hollowcore are in these regions.

Use of hollowcore floors outside these centres was limited, and the findings of the investigations may be taken to apply to other areas.

Auckland hollowcore data

Data on the supply of hollowcore units in the Auckland region was provided by the major supplier of hollowcore in that region. This covered a period from 1981 until 2003. The assessments of building flexibility were made by the supplier, so may be open to question. In broad terms they indicate that 73 percent of the hollowcore (by floor area) is in stiff buildings and therefore unlikely to be of concern in strong earthquake shaking. The tests at the University of Canterbury deliberately set out to test hollowcore floors under extreme displacements in flexible buildings.

Table 1 shows the distribution in square metres made and expressed as a percentage of the total within each size category and age group. The size of the unit is indicated (eg, H200 means units that are 200 mm deep).   ‘Shear Wall’ denotes that the units were judged to be in shear wall buildings and therefore stiff. ‘Frame’ indicates that the buildings were judged to be frame buildings and therefore flexible.

Size	Date	Shear Wall		Frame		Shear Wall + Frame
		m2	%	m2	%	m2
H200	81-85	2,380	61%	1,508	39%	3,888
H200	86-90	7,232	26%	20,181	74%	27,413
H200	91-95	45,371	73%	16,918	27%	62,289
H200	96-00	147,620	73%	53,853	27%	201,473
H200	01-05	82,709	80%	21,248	20%	103,957
	H200 All years	**285,311**	**72%**	**113,708**	**28%**	**399,019**
Size	**Date**	**Shear Wall**		**Frame**		**Shear Wall + Frame**
H250	81-85	0		0		0
H250	86-90	9,195	34%	17,890	66%	27,085
H250	91-95	582	55%	480	45%	1,062
H250	96-00	0	0%	720	100%	720
H250	01-05	0		0		0
	H250 All years	**9,777**	**34%**	**19,090**	**66%**	**28,867**
Size	**Date**	**Shear Wall**		**Frame**		**Shear Wall + Frame**
H300	81-85	311	100%	0	0%	311
H300	86-90	3,943	58%	2,830	42%	6,773
H300	91-95	83,955	77%	24,713	23%	108,668
H300	96-00	87,727	82%	19,389	18%	107,116
H300	01-05	73,965	77%	21,959	23%	95,924
	H300 All years	**249,901**	**78%**	**68,891**	**22%**	**318,792**
Size	**Date**	**Shear Wall**		**Frame**		**Shear Wall + Frame**
H400	81-85	0		0		0
H400	86-90	0		0		0
H400	91-95	0	0%	127	100%	127
H400	96-00	15,138	72%	5,767	28%	20,905
H400	01-05	13,744	92%	1,128	8%	14,872
	H400 All years	**28,882**	**80%**	**7,022**	**20%**	**35,904**
	Total All	**573,871**	**73%**	**208,711**	**27%**	**782,582**

Table 1: Hollowcore use in Auckland: 1981 to 2003

Hollowcore use in Christchurch, Wellington and Auckland

Data from suppliers and the surveys made were combined to provide a profile of use in Christchurch, Wellington and Auckland.

Table 2 shows a summary comparison of the use of hollowcore floors in Christchurch, Wellington and Auckland, split into buildings categorised as stiff and flexible. The splits are based on the Beca reports for Christchurch and Wellington. For Auckland, the split is that given by the major supplier as given in Table 1. The term ‘stiff’ is used when the buildings are considered to be stiff enough to control displacements sufficient to render the risk of collapse low (provided there are no significant detailing deficiencies). The term ‘flexible’ is used when the buildings are expected to have lateral displacements of the same order as those experienced in the University of Canterbury tests (generally greater than 1.0 percent of storey height).

Auckland has 52 percent of the total hollowcore floor area for the three centres, Wellington 31 percent and Christchurch 17 percent. Overall, the table shows that 66 percent of hollowcore is assessed to be in stiff buildings and therefore not subject to displacements similar to those in the Matthews test. The proportion of hollowcore in stiff buildings was assessed to be 44 percent for Wellington, 84 percent for Christchurch and 73 percent for Auckland.

The tests that initiated the concern about hollowcore floors were on floors with 300 mm deep units. For this reason, two columns have been included in the table showing the areas of hollowcore units that are 300 mm or more in depth. The first shows the total of flexible and stiff categories, while the second shows areas in the flexible category only. This gives an indication of the proportion of the total area of hollowcore that these deeper, long-span units represent. Overall, 35 percent of the total is 300 mm or deeper, and 5.4 percent of the total is in the flexible category. For Wellington, the total proportion of hollowcore that has a depth of 300 mm or more is 18 percent. The percentage that is 300 mm or more in depth and assessed as being in the flexible category is 0.4 percent. For Auckland these proportions are 45 percent and 9.7 percent and for Christchurch, 33 percent and 1.2 percent.

Summary Table of Hollowcore Usage in Christchurch Wellington and Auckland										
Area vs Depth - Christchurch				**% vs Depth - Christchurch**					**Units 300mm or more**	
HC Unit	**m2**	**m2**	**m2**	**Size**	**%**	**%**	**% CHC total**		**m2**	**m2**
(see note)	**Stiff**	**Flexible**	**Total**		**Stiff**	**Flexible**			**Total**	**Flexible**
H150	7,200	2,700	9,900	H150	73	27	4			
H200	126,100	36,600	162,700	H200	78	22	63			
H250	0	0	0	H250			0			
H300	60,000	3,100	63,100	H300	95	5	24		63100	3100
H350	5,500	0	5,500	H350	100	0	2		5500	0
H400	18,000	0	18,000	H400	100	0	7		18000	0
	216,800	**42,400**	***259,200***				*100*		***86,600***	***3,100***
	84%	***16%***	***100%***			***Christchurch is***	***17%***			
							of NZ total		***33%***	***1.2%***
Unit mark is H followed by depth in millimetres									***of total for Christchurch***	
Area vs Depth - Wellington				**% vs Depth - Wellington**						
HC Unit	**m2**	**m2**	**m2**	**Size**	**%**	**%**	**% WGN total**		**m2**	**m2**
(see note)	**Stiff**	**Flexible**	**Total**		**Stiff**	**Flexible**			**Total**	**Flexible**
H150	12,100	10,200	22,300	H150	54	46	5			
H200	110,000	250,000	360,000	H200	31	69	77			
H250	1,900	0	1,900	H250			0			
H300	84,000	2,000	86,000	H300	98	2	18		86000	2000
H350	0	0	0	H350			0		0	0
H400	0	0	0	H400			0		0	0
	208,000	**262,200**	***470,200***				*100*		***86,000***	***2,000***
	44%	***56%***	***100%***			***Wellington is***	***31%***			
							of NZ total		***18%***	***0.4%***
Unit mark is H followed by depth in millimetres									***of total for Wellington***	
Area vs Depth - Auckland				**% vs Depth - Auckland**						
HC Unit	**m2**	**m2**	**m2**	**Size**	**%**	**%**	**% AKL total**		**m2**	**m2**
(see note)	**Stiff**	**Flexible**	**Total**		**Stiff**	**Flexible**			**Total**	**Flexible**
							0			
H200	285,311	113,708	399,019	H200	72	28	51			
H250	9,777	19,090	28,867	H250	34	66	4			
H300	249,901	68,891	318,792	H300	78	22	41		318792	68891
H400	28,882	7,022	35,904	H400	80	20	5		35904	7022
							0		0	0
	573,871	**208,711**	***782,582***						***354,696***	***75,913***
	73%	***27%***	***100%***			***Auckland is***	***52%***			
							of NZ total		***45%***	***9.7%***
Unit mark is H followed by depth in millimetres									***of total for Auckland***	
Total All Three Centres										
	998,671	**513,311**	**1,511,982**						527,296	81,013
	66%	***34%***	***100%***						**35%**	**5.4%**
									Total	**Flexible**
									of total for NZ.	
Stiff - denotes hollow core in buildings where assessed inter-storey deflection in a major earthquake would be **less** than 1% of storey height										
Flexible - denotes hollow core in buildings where assessed inter-storey deflection in a major earthquake would be **more** than 1% of storey height										

Table 2: Hollowcore use in Christchurch, Wellington and Auckland

Three cities study

This study reviewed the effect of the variation of seismicity, design load levels and deflection constraints on aspects of structural performance likely to be of particular interest in assessing the performance buildings with hollowcore floors in Christchurch, Wellington and Auckland. A specific objective was to determine the need for an investigation in Auckland similar to those carried out in Christchurch and Wellington.

An important parameter in this study was the likely lateral displacement of the structure in a major (design) earthquake, particularly the displacement between one floor and the next (termed inter-storey displacement). Conclusions drawn from the Canterbury tests were that satisfactory performance of hollowcore floors could be expected, provided that the inter-storey displacements were limited to 0.012 (1.2 percent) of the storey height, in other words 30 to 40 mm.

Conclusions

The conclusions of this review were as follows.

- For Wellington, the implied maximum inter-storey drift allowed in design is almost always greater than 0.012, irrespective of the soil type. A more detailed survey of Wellington buildings is warranted.
- For Christchurch, the implied maximum inter-storey drifts allowed in design are generally greater than 0.012. However, buildings designed to the allowable limit of the loadings Standard, NZS 4203: 1984, with periods in excess of 1.5 sec for soil classes B and C and 2.5 sec for soil classes D and E are unlikely to have inter-storey drifts above the critical level. The overall conclusion was that a detailed survey of Christchurch buildings was warranted, but that taller buildings designed strictly in accordance with NZS 4203: 1984 are unlikely to be a significant concern.
- For soil classes B and C in Auckland, the implied maximum inter-storey drifts allowed in design are generally less than 0.012 and therefore were not considered to be of concern. For other soil classes, there were some exceptions to this, but these were not considered significant.

Overall, the conclusion was that Auckland buildings designed strictly in accordance with the Standards operating at the time would be unlikely to present a significant life-safety risk, and that a detailed survey of the building stock containing hollowcore was not warranted.

It was noted that it was possible in some buildings that there could be a lack of starters between floor systems and the primary structure, as had been observed in Christchurch and Wellington.

Christchurch City survey

The investigation of hollowcore use in Christchurch was a first step in assessing the risk profile presented by hollowcore throughout New Zealand. Drawings held by Christchurch City Council were examined and details of hollowcore floor support recorded. These drawings included the dimensions of the seating, the amount and details of reinforcing, and the likely lateral stiffness of the structural framing. The drawings were those submitted for building consent, and it was recognised that these may not be wholly representative of the as-built situation.

Conclusions

The conclusions from the Christchurch pilot survey were as follows,

- A significant number of the buildings (85 percent) were found to be in a stiffness range that were considered of minimal risk without further investigation or assessment.

- When the combination of building stiffness and connection detailing was considered, 13 percent of the hollowcore used in Christchurch was judged to fall within a category for which further investigation would be prudent. If the buildings of intermediate stiffness are included, the proportion rises to 16 percent.
- No instances of building configuration that matched the University of Canterbury tests (ie, hollowcore spanning past a perimeter column) were identified in the Christchurch data.
- The pilot survey indicated that this desktop approach would yield useful results in other main centres, provided that access was available to building consent records and that good records could be obtained from the manufacturers of precast concrete.
- Based on the experience of the pilot survey, there appeared to be little benefit in applying the methodology to other South Island cities or to other provincial centres. Almost all South Island hollowcore production and use was in Christchurch.
- Similar assessments of the use of hollowcore in Wellington, and possibly Auckland, were considered desirable.

Two buildings were identified as being of potential concern. In October 2004, these were referred to Christchurch City Council who advised the owners of the potential concerns. In February 2005, representatives of the Council and the Department met with the owners to explain the context of the Department's investigations and to outline the potential concerns.

The investigation did not include detailed assessment of performance. When subjected to more detailed investigation, a number of structures that potentially require further review may be shown to have an adequate level of performance.

Wellington City survey

The survey of the Wellington Central City followed completion of the survey of the Christchurch area and was done on the same basis as the Christchurch survey by using drawings submitted for building consent.

Conclusions

Key conclusions from the Wellington City survey were as follows.

- Sixty-four percent of the buildings (by number) were found to be in a stiffness range that was considered of minimal risk without further investigation or assessment. The majority of the remainder (36 percent by number, 49 percent by area) were considered to potentially require further investigation on the basis of the University of Canterbury tests, but a large proportion of these buildings had at least some reinforcement (other than topping mesh) between the precast floor units and the building structure.
- When the combination of building stiffness and connection detailing is considered, about 9 percent of the hollowcore floor area (in 13 buildings) used in Wellington was estimated to fall within a category for which further investigation was considered to be prudent.
- Ten of the 13 buildings were assessed as having mitigating factors that would enhance their performance in relation to the University of Canterbury tests.

- Nine buildings were found to match the circumstances of the University of Canterbury test and five additional flexible buildings were identified as having floors showing no reinforcement between the precast floor system and the primary structure, other than the topping mesh.

In May 2005, 13 buildings were brought to the attention of Wellington City Council. The Council wrote to all those with a registered interest in each building, advising of potential concerns with hollowcore floors. Through the Council, the Department offered to meet with building owners to explain the context of the Department's investigations and to outline the potential concerns. No requests for meetings have been received. The Council has included the buildings in its list of those that are potentially earthquake-prone under section 122 of the Building Act 2004.

The survey did not include a detailed assessment of performance. When subjected to more detailed investigation, a number of structures that were identified as requiring further review may be shown to have an adequate level of performance.

Study of floor support mechanisms

The Department engaged Dr Richard Fenwick of the University of Canterbury to examine the effect of the variables on the failure mode of hollowcore flooring units. The objective was to determine stresses under different actions that could lead to failure of a hollowcore unit under seismic actions.

A paper summarising the situation was prepared and published in the *Journal of the Structural Engineering Society* (SESOC) [9]. This provided useful information to designers about the mechanisms and interactions that are involved in providing effective support to hollowcore floor units in strong earthquake shaking.

Further research on hollowcore floors

Since the first test at the University of Canterbury (Matthews test) in 2003 that gave rise to concerns about the performance of hollowcore floors, two further full-scale tests have been performed. Both of these used details similar to those recommended in the March 2004 amendment to NZS 3101. The first of these (Lindsay test) [10] incorporated a flexible bearing strip and a backing strip, while the second (MacPherson test) [11] used details incorporating reinforcing steel connecting the ends of the cores to the supporting beams. Both tests showed markedly improved performance when compared with the Matthews test.

Discussion

The surveys of hollowcore use indicate that there is a wide variety of sizes and situations in the three centres studied. The extent of the risks from earthquake performance of hollowcore floors in buildings can be assessed by examining the results of the surveys in Christchurch and Wellington, and the data for Auckland.

In Christchurch, it was found that 85 percent of buildings with hollowcore floors were in a stiffness range considered to be of minimal risk in relation to hollowcore floor performance. For Wellington, the corresponding figure was 64 percent.

When both building stiffness and detailing were considered for Wellington, 9 percent of hollowcore flooring was in a category for which further investigation was considered prudent. For Christchurch, the figure was 16 percent. Lower proportions are likely to apply to Auckland because of the reduced inter-storey drifts expected.

It should be noted that the Matthews test was performed using 300 mm deep hollowcore units, which comprise less than 35 percent of the total for the three centres. Three-dimensional tests have not been performed on structures with shallower hollowcore units that have shorter spans than those used in the Matthews test. For the shallower units, the cast in situ topping thickness is a higher proportion of the overall floor depth. The shorter spans mean lower bearing pressures and smaller differential displacements between the floor units and surrounding structure. It is likely that shallower floors, which comprise 65 percent of all hollowcore floors in the three centres, would show improved performance from the Matthews test.

A further point that needs to be considered in assessing the overall risk of New Zealand's hollowcore floors is that the Matthews test related to 300 mm thick floor units spanning past an intermediate column. This is a relatively uncommon detail used for units of 300 mm depth or greater. Importantly, in the Matthews test the intermediate column did not have the required reinforcement tying it back to the floor and to other columns. The absence of this steel resulted in very significant sideways displacements that were detrimental to the structural performance of the floor. Had the test been done on a floor with the same support details, but with the requisite column tie-back in place, it is highly likely that the performance of the hollowcore floor would have been significantly improved.

The subsequent Lindsay tests [10] showed a marked improvement of performance over the Matthews tests due to both the insertion of the requisite tie-back, and revisions to support and perimeter detailing. A further test by MacPherson [11] incorporating reinforced ties in the voids at the ends of the units showed even better performance.

From these overall considerations, it can be seen that there is a relatively low proportion of hollowcore flooring for which further investigation is considered to be prudent. This helps to set in context the concerns resulting from the Matthews test, but it does not alter the severity of the consequences in the event of circumstances in practice that could lead to severe damage or collapse of a particular hollowcore floor. It is possible that collapse of one floor or part of a floor could cause progressive collapse of floors below.

Both the Christchurch and Wellington surveys resulted in recommendations to look at particular buildings because of possible inadequacies of the detailing of support and/or connection to the surrounding structure. Therefore, even though the general concerns are confined to a small percentage of overall floors in place, the surveys have shown that it is possible that some buildings may have inadequate (non-conforming) details that require further investigation.

It is of course possible that the inadequacies identified on the drawings were addressed during construction, but it is also possible that changes since the drawings were submitted to the territorial authority were detrimental to structural performance. This argument could apply to any aspect of any building, and is therefore a building-specific issue rather than a generic hollowcore one. Overall, it is important to note that the integrity of hollowcore floor systems is sensitive to the variations in the design and construction of support joint details.

In summary, up to 16 percent of hollowcore floors in any one city are seen to warrant further investigation in the context of a major earthquake (16 percent for Christchurch, 9 percent for Wellington, with Auckland not surveyed). Not all of these floors will have circumstances (support details, units 300 mm deep or more, units spanning past columns) that match the Matthews tests, but they may still warrant further investigation. The report comparing the three centres showed that for Auckland displacements of buildings in a design earthquake were unlikely to be greater than the 1.2 percent. This was considered to be the limit to which floors with detailing similar to the Matthews test could reliably sustain. In Auckland, the proportion of hollowcore floors shown to be in stiff buildings was generally in line with the more detailed surveys in Christchurch and Wellington.

A survey of Auckland buildings was initially intended, but the low risk of large displacements, together with the information gained from the other two studies in Wellington and Christchurch, mean that such a survey would add little, if any, information to the generic concerns.

Conclusions

The following conclusions have been drawn from the investigations into buildings with hollowcore floors. While there may be similar considerations for other types of precast floor, this report and its conclusions relate only to buildings with hollowcore floors.

Hollowcore generally

The following table summarises the findings of the surveys carried out.

	Proportion of total Hollowcore Floors in each city					
	Wellington		**Christchurch**		**Auckland**	
	Flexible (Frame buildings)	Stiff (Shear wall bldgs)	Flexible (Frame buildings)	Stiff (Shear wall bldgs)	Flexible (Frame buildings)	Stiff (Shear wall bldgs)
All Hollow Core:	56%	44%	16%	84%	27%	73%
300mm or greater:	< 1%	18%	1%	32%	10%	35%
Investigation prudent:	9%		16%		Not surveyed *	
	14 buildings identified for follow-up by Wellington City Council		*2 buildings identified for follow-up by Christchurch City Council*		** Displacements not considered to represent significant concern*	

Table 3: Summary of findings for Wellington, Christchurch and Auckland

The Wellington survey indicates that, when the combination of stiffness and connection detailing is considered, 9 percent of its hollowcore floors are in situations 'for which further investigation would be prudent'. Wellington has 31 percent of the total area of hollowcore floors over the three centres. The Christchurch survey indicates that, when the combination of stiffness and connection detailing is considered, 16 percent of its hollowcore floors are in situations 'for which further investigation would be prudent'. Christchurch has 17 percent of the total area of hollowcore floors over the three centres. For Auckland, the proportion requiring further investigation would be lower than for Christchurch or Wellington because the implied maximum inter-storey drifts were not considered to be of concern.

Auckland was not surveyed, but was assessed to have an insignificant proportion in this category. Taken over all three centres, approximately 6 percent of all hollowcore floors could require further investigation. The floors referred to in this category are those in flexible buildings and/or without adequate support details, as determined from building consent drawings. In making this overall assessment, it must be remembered that for all hollowcore floors, careful attention to detail is required throughout the design and construction process. The structural performance of all hollowcore floors, particularly in earthquakes, will depend on the exact details used in construction.

The tests at University of Canterbury raised concerns that the behaviour of hollowcore floors under earthquake actions was not adequately understood. Revisions to design recommendations have been made and more may be required. It is important that designers, builders, manufacturers and territorial authority officials are up to date on the test results, the concerns and on the new design requirements.

There is a need to inform building owners in all centres of the possibility of inadequate support structure to hollowcore floor systems and/or of insufficient structural integrity with the surrounding structure (beams). Checking by a suitably qualified structural engineer should be encouraged, especially of those floors in flexible buildings and/or having similar details to the Matthews test (hollowcore depth of 300 mm or more and with units spanning past intermediate columns.)

There is a need for guidance documentation on the performance of hollowcore floors, especially their earthquake performance. It should cover:

- assessment and retrofit of hollowcore floors in existing buildings
- updated design and detailing requirements for new buildings in the light of recent research.

Specific installations

In both Christchurch and Wellington, potential cases of concern due to possible inadequate support and connection were noted. These have been notified to the relevant councils, requesting that they advise the owners to make specific checks. Similar cases could exist in other centres. The discovery of buildings of potential concern, together with the results of the Matthews test, is a reminder of the sensitivity of the integrity of these floor systems to variations in detailing of the supports and relative movement of the surrounding structure. Such variations can occur in design or construction.

Auckland City survey

A survey of the drawings of hollowcore buildings in Auckland City by the Department is not warranted. Sufficient information has been gained on hollowcore installations generally from the other studies to give an overall indication of the risk profile for hollowcore floors. Whether further studies are undertaken in Auckland is a matter for the relevant territorial authorities.

Recommendations

- The extent, nature and results of these investigations are widely distributed to designers, constructors, manufacturers, territorial authorities and building owners. If owners have concerns about buildings containing hollowcore floor units, they should seek advice from a suitably qualified engineer (chartered professional engineer experienced in structural engineering).
- Territorial authorities are advised to require a special check on any existing building containing hollowcore floors when the building is the subject of significant alteration, upgrade or change of use.
- The Department continues to support and encourage territorial authorities in their interactions with owners and designers on buildings identified as requiring further investigation.
- A special study group be set up by the Department to develop a guidance document for the evaluation and strengthening of existing hollowcore floors and the design of new installations. The group, which would comprise selected members of the New Zealand Structural Engineering Society (SESOC), New Zealand Society for Earthquake Engineering (NZSEE), and New Zealand Concrete Society, should make recommendations for future research.
- Deliberations of the special study group be incorporated in future development of NZS 3101. Amendments to the Standard would include the results of new research.

Actions to date

The Department issued a practice advisory in June 2005 highlighting issues of concern and emphasising recommended good practice. It urged designers and building officials to keep themselves informed of the latest recommendations from researchers and reminded them of the need to follow NZS 3101 Amendment No 3. The design details in this amendment were incorporated in further tests at the University of Canterbury and performed satisfactorily.

For the buildings identified to be of potential concern in Christchurch and Wellington, the Department supported the territorial authorities in following up with owners. Through the respective councils, the Department offered to meet with building owners to explain the context of the Department's investigations and the potential concerns about their buildings.

For the two buildings in Christchurch, the Department advised the Council in October 2004 and owners were advised by the Council. In February 2005, a Department representative, Council representatives and the survey consultant met the owners. Both owners have since reviewed the hollowcore floors in their buildings.

In Wellington, 13 buildings were brought to the attention of Wellington City Council in May 2005. The Council wrote to all those with a registered interest in each building advising of potential concerns with hollowcore floors. No requests for meetings were received. The Council has included the buildings in its list of those that are potentially earthquake-prone under section 122 of the Building Act.

In October 2006, the Department brought together a special study group to prepare guidance material for designers and building officials on assessing existing buildings and designing remedial measures. Recommendations from the group are expected to be published in 2007. Guidance material will then be prepared for new buildings, and recommendations made for any necessary changes to NZS 3101, the concrete design Standard.

A paper has been prepared summarising the Department's investigations and promoting good practice. This will be presented to the annual conference of the New Zealand Society for Earthquake Engineering in Palmerston North in March 2007 [12].

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