ABSTRACT:
In October 2001, load tests on a full-scale model of a hollow core floor assembly at the University of Canterbury indicated potentially serious gaps between assumed and actual behaviour of hollow core floor systems in ductile frame buildings during strong earthquake shaking.

In July 2003, the Department of Building and Housing (then the Building Industry Authority) commenced a review of the use of hollow core floor systems in New Zealand. The objective was to determine the extent and nature of usage of these systems nationally, and to advise the industry of any concerns.

Building consent drawings were surveyed in Christchurch and Wellington to obtain a profile of size, span, depth, building type and support details used. In addition, an assessment was made of the likely displacements of buildings designed in Auckland, Wellington and Christchurch.

A report was compiled, summarising the findings and implications. Recommended actions included advice to owners to have their building checked if they had concerns, and to territorial authorities (TAs) to ask for a report on the hollowcore floor performance when an existing building was significantly altered. A need for guidelines for the assessment of existing buildings and the design of new buildings was identified.

1 INTRODUCTION AND BACKGROUND

Over the last thirty 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 in-situ concrete. Early forms of precast floors consisted of reinforced or prestressed solid slabs about 100mm thick with 50 to 70mm of in-situ concrete topping. Many variations were developed to meet market demand, one of which was the replacement of solid slabs with hollowcore units.

Hollowcore units are produced by an extrusion process and generally have no transverse or shear steel. Typically the units have no reinforcement protruding from the ends to provide positive connections with their supporting beams. The thickness of units has increased from 150mm to 300mm and even 400mm and more, with corresponding increases in spans.

Questions were raised about the integrity of hollow core 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 amongst structural designers, manufacturers, territorial authority officials and regulators.

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 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% 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 BIA, submitted in November 2003 [4] and prepared in response to the Scarry Open Letter, 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’.

2 SURVEYS AND INVESTIGATIONS

In July 2003 the Building Industry Authority (BIA) (now the Building Controls Group of the Department of Building and Housing, and referred to in this paper as the Department) commenced a review of the use of hollowcore floor systems in New Zealand. The objective was to determine the extent and nature of usage of these systems nationally, to relate usage to particular concerns raised by the University of Canterbury tests and to advise the industry of any concerns.

As a first step in assessing the risk profile presented by hollowcore floors throughout New Zealand, a pilot study was carried out for Christchurch [5], in which building consent drawings for all significant buildings with hollowcore floors were examined. A report on this was produced in October 2004.

In February 2005 a similar review was reported on for Wellington [6].

A study for Auckland was initially envisaged, but it was considered that the building displacements in an earthquake were unlikely to produce the conditions that were the cause of concern in the Canterbury tests. A report investigating the potential performance of hollowcore floors in Wellington, Christchurch and Auckland was produced for the Department in February 2005 [7].

In June 2005, the Department issued Practice Advisory No. 5 highlighting issues of concern and providing recommendations for designers, builders and TA officials [11].
3 SURVEY FINDINGS

3.1 Hollowcore Use in New Zealand

Enquiries of suppliers were made 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.

3.2 Hollowcore Usage 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 1 shows a summary comparison of the usage of hollowcore floors in Christchurch, Wellington and Auckland, split into buildings categorised as stiff and flexible. For Christchurch and Wellington the splits are based on the Beca reports [5][6][7]. For Auckland the split is that given by Stresscrete, the principal manufacturer there. 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% of storey height).

Auckland has 52% of the total hollowcore for the three centres, Wellington 31% and Christchurch 17%. Overall, the table shows that 66% of hollowcore is assessed to be in the stiff category. However, this proportion varies considerably, being 44% for Wellington, 84% for Christchurch and 73% for Auckland.

The tests that initiated the concern about hollowcore floors were on floors with 300mm deep units. For this reason, two columns have been included in the table showing the areas of hollowcore units that are 300mm or more in depth. The first shows the total areas in the 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% of the total is 300mm or deeper, and 5.4% of the total is in the flexible category. For Wellington, the proportion of hollowcore that is 300mm deep or more is 18%, with that assessed to be in the flexible category 0.4%. For Auckland these proportions are 45% and 9.7% and for Christchurch, 33% and 1.2%.

3.3 Three Cities Study

This study [7] 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 of buildings with hollowcore floors in Christchurch, Wellington and Auckland. A specific objective was to determine the need for/extent of an investigation in Auckland similar to those carried out in Christchurch and Wellington.

A key parameter in this study was the likely lateral displacement of the structure in a major (design) earthquake, particularly the inter-storey drift. 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%) of the storey height, i.e., 30 to 40mm.

The three cities study concluded that:

- For Wellington the implied maximum inter-storey drift allowed in design is almost always greater than 0.012 irrespective of the soil type.
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 NZS 4203:1984 Standard with periods in excess of 1.5 seconds for soil classes B and C, and 2.5 seconds for soil classes D and E, are unlikely to have inter-storey drifts above the critical level. 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 and to the limit of the Standards operating at the time would be unlikely to present a significant life-safety risk.

### Table 1 Hollowcore Usage in Christchurch Wellington and Auckland

<table>
<thead>
<tr>
<th>Area vs Depth - Christchurch</th>
<th>% vs Depth - Christchurch</th>
<th>Units 300mm or more</th>
</tr>
</thead>
<tbody>
<tr>
<td>H150</td>
<td>7,200</td>
<td>9,900</td>
</tr>
<tr>
<td>H200</td>
<td>126,100</td>
<td>162,700</td>
</tr>
<tr>
<td>H250</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H300</td>
<td>60,000</td>
<td>63,100</td>
</tr>
<tr>
<td>H350</td>
<td>5,500</td>
<td>5,500</td>
</tr>
<tr>
<td>H400</td>
<td>18,000</td>
<td>18,000</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>216,800</strong></td>
<td><strong>259,200</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area vs Depth - Wellington</th>
<th>% vs Depth - Wellington</th>
<th>Units 300mm or more</th>
</tr>
</thead>
<tbody>
<tr>
<td>H150</td>
<td>12,100</td>
<td>22,300</td>
</tr>
<tr>
<td>H200</td>
<td>110,000</td>
<td>360,000</td>
</tr>
<tr>
<td>H250</td>
<td>1,900</td>
<td>1,900</td>
</tr>
<tr>
<td>H300</td>
<td>84,000</td>
<td>86,000</td>
</tr>
<tr>
<td>H350</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>H400</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>208,000</strong></td>
<td><strong>470,200</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Area vs Depth - Auckland</th>
<th>% vs Depth - Auckland</th>
<th>Units 300mm or more</th>
</tr>
</thead>
<tbody>
<tr>
<td>H200</td>
<td>285,311</td>
<td>399,019</td>
</tr>
<tr>
<td>H250</td>
<td>9,777</td>
<td>28,867</td>
</tr>
<tr>
<td>H300</td>
<td>249,901</td>
<td>318,792</td>
</tr>
<tr>
<td>H400</td>
<td>28,882</td>
<td>35,904</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>573,871</strong></td>
<td><strong>782,582</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Total All Three Centres</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>998,671</strong></td>
<td><strong>513,311</strong></td>
<td><strong>1,511,982</strong></td>
</tr>
</tbody>
</table>

3.4 Christchurch Study

The investigation of hollowcore use in Christchurch [5] 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 included the dimensions of the seating, the amount and details of reinforcing, and the likely lateral stiffness of the structural framing. These drawings were those submitted for building consent, and it was recognised that these may not represent the as-built situation.

The conclusions from the Christchurch pilot study were:

- When the combination of building stiffness and connection detailing was considered, 13% of the hollowcore used in Christchurch was judged to fall within a category for which further
investigation would be prudent. When the intermediate stiffness buildings were included the proportion was 16%.

- No instances of building configuration that matched the Canterbury University tests (i.e., hollowcore spanning past a perimeter column) were identified in the Christchurch data.

3.5 Wellington Study

The study of the Wellington Central City region [6] followed completion of the study of the Christchurch area and was done on the same basis as the Christchurch study – using drawings submitted for building consent.

Key conclusions from the Wellington study were:

- When the combination of building stiffness and connection detailing is considered about 9% of the hollowcore used in Wellington was estimated to fall within a category for which further investigation was considered to be prudent.
- Nine buildings were found to match the circumstances of the University of Canterbury test.

The investigations did not include detailed assessment of performance. When subjected to more detailed investigation a number of structures within the potentially at-risk categories may be shown to have an adequate level of performance.

3.6 Further Research on Hollowcore Floors

Since the first test at University of Canterbury by Matthews [1] that gave rise to the concerns, two further full-scale tests have been performed. Both of these used details similar to those recommended in the Amendment to NZS 3101. The first of these [8] incorporated a flexible bearing strip and a backing strip, while the second [9] 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 test by Matthews.

4 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.

The Matthews test [1] was performed using 300mm deep hollowcore units which comprise less than 35% 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 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. Thus it is likely that shallower floors, which comprise 65% of all hollowcore in the three centres, would show improved performance in relation to the Matthews test.

Furthermore, the Matthews test related to 300mm thick floor units spanning past an intermediate column. This is a relatively uncommon detail used for units of 300mm 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 of parallel beams. These were undoubtedly detrimental to the structural performance of the test 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 [8] 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 [9] 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. Thus, 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 represent a significant risk.

It is possible that the inadequacies identified on the drawings were rectified during construction. It is also possible that changes since submittal of the drawings to the TA made things worse. This argument could apply to any aspect of any building, and is thus a building-specific issue rather than a generic one. Nevertheless, the integrity of hollowcore floor systems is very sensitive to the variations in the design and construction of support joint details.

Identification of specific buildings was not the prime intention of the surveys. Identification of concerns about any specific building is a matter for the relevant territorial authority.

5 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, the conclusions relate only to buildings with hollowcore floors.

Hollowcore generally
Table 2 summarises the findings of the surveys carried out.

Table 2 Summary of Findings for Wellington, Christchurch and Auckland

<table>
<thead>
<tr>
<th></th>
<th>Wellington</th>
<th>Christchurch</th>
<th>Auckland</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible (Frame buildings)</td>
<td>56%</td>
<td>44%</td>
<td></td>
</tr>
<tr>
<td>Stiff (Shear wall bldgs)</td>
<td>16%</td>
<td>84%</td>
<td>27%</td>
</tr>
<tr>
<td>Stiff (Shear wall bldgs)</td>
<td>16%</td>
<td>32%</td>
<td>10%</td>
</tr>
<tr>
<td>Investigation prudent:</td>
<td>9%</td>
<td>16%</td>
<td>Not surveyed *</td>
</tr>
</tbody>
</table>

* Displacements not considered to represent significant concern

It has been assessed that 9% of floors in Wellington and 16% in Christchurch are in a category for which further investigation of their performance in earthquake is considered prudent. Auckland was not surveyed, but was assessed to have an insignificant proportion in this category. Taken over all three centres, approximately 6% 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.
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 earthquake, 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 vital that designers, builders and territorial authority officials are up-to-date on the test results, the concerns and the new design requirements.

There is a need to alert building owners in all centres of the possibility of inadequate support structure for 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 300mm or more and with units spanning past intermediate columns.)

In relation to the performance of hollowcore floors, especially earthquake performance, there is a need for guidance documentation covering:

- 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, particular cases of concern due to possible inadequate support/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, notably Auckland. The discovery of buildings of specific 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.

6 PROPOSED ACTIONS

The Department intends to:

- release the results of its investigations
- recommend that owners with concerns seek professional advice
- recommend that TAs 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 TAs
- support Standards NZ amending NZS 3101 as appropriate in the light of research and investigations completed since March 2004
- continue to support and encourage TAs in their working with owners and designers on buildings they identify as being at risk.

7 CONCLUDING REMARKS

From a regulator’s perspective, resolving concerns on structural performance is not a simple matter. For hollowcore floors it is particularly difficult because of the complex three-dimensional interactions between the units, the topping, the supporting corbels and the beams parallel to the units.

The regulator has to decide on the safety of existing and new installations, and has the option to issue warnings about a product or practice. In extreme cases, a formal ban may be issued. The issue of a warning or ban has serious implications for building owners and for manufacturers. Conclusive
evidence is required to demonstrate safety, or the lack of it. In the case of hollowcore floors, it was concluded that a warning or ban was not warranted, but that the product must be used with careful attention to its limitations.

Special care is needed to:

- limit inter-storey drift or avoid using hollowcore floors when drifts are large.
- take account of the brittle nature of the units because of the lack of shear reinforcement.
- limit the depth and span of units. The performance of units more than 300 deep in earthquake has not been tested in a three-dimensional context.
- allow for the sensitivity of floor performance to support details and construction tolerances.

The Department relies on outside professional input for help to resolve concerns about the safety of structures and appreciates the efforts of those involved in this instance.

References


