OPAL TOWER INVESTIGATION
FINAL REPORT

Independent Advice to
NSW Minister for Planning and Housing

19 February 2019

Unisearch
Expert Opinion Services

Contents

OPAL TOWER INVESTIGATION – FINAL REPORT

Executive Summary

At the request of the Hon. Anthony Roberts, Minister for Planning and Housing, an investigation was carried out into the cause or causes of structural damage to the Opal Tower at Sydney Olympic Park, which was first observed at Christmas 2018. In addition, the investigation reviewed possible remedial action to repair the damage to the building. The terms of reference also included a request to consider any recommendations for the future, with the intended purpose of assisting in avoiding problems with high-rise construction such as those addressed in this report.

Based on all available information, the following opinions, recommendations and findings of the investigation are presented. These are listed below under each term of reference (TOR) provided by the Secretary of the NSW Department of Planning.

TOR 1 – Causes of damage

1. The as-constructed hob beam / panel assembly was under-designed, according to the National Construction Code (NCC) and the Australian Standard for Concrete Structures (AS3600[1]), at a number of locations in the building. This left the hob beams susceptible to failure by shear compression and bursting.
2. The decision, taken after the initial design[2], to grout only partially the joints between the hob beams and panels, significantly raised the levels of stress in the hob beams on levels 4, 10, 16 and 26.
3. Construction and material deficiencies likely precipitated the observed major damage to hob beams on Level 10-C (electrical conduit and reinforcing steel in the cover region, and a panel repair) and Level 4-A (lower strength concrete than used in hobs elsewhere and partial grout coverage).
4. The observed damage in the concrete panel at Level 10 and in the Level 10 floor slab was likely a consequence of the adjacent hob beam failures and not the original cause of the damage observed at Level 10.

TOR 2 – Making the Opal Tower safe for occupancy

5. Appropriate rectification works can address deficiencies in the original, as-constructed, structural design and ensure the building is compliant with the NCC.
6. Significant rectification works are necessary to ensure that the building and all its structural components satisfy the NCC and specifically the current AS3600-2018
7. The damaged hob beams should be rectified to provide the required load carrying capacity.

[1] AS3600 refers to the the 2009 version of the standard which was current at time of construction, unless stated otherwise
[2] 'Design' refers to structural design in this report, unless stated otherwise.

8. Other hob beam / panel elements of similar as-constructed, structural design may not comply with the NCC and AS3600-2009 and, if so, will require rectification works. We also recommend checking of the forces in other structural elements adjacent to the hob beams, such as the columns.
9. We agree *in principle* with the rectification works planned to date, noting that these have advanced considerably since our interim report was released but have yet to be agreed by all parties and independently certified.
10. We recommended that a detailed analysis be undertaken of the potential redistribution of loads from the damaged elements to ensure that other newly loaded building elements, before and after rectification works, have suitable capacity and to avoid future damage. A preliminary analysis has been carried out and indicated structural loads satisfied the NCC in the non-damaged parts of the building structure. Nevertheless, this finding should be robustly and independently verified.
11. We recommend that all designs and construction associated with the rectification works be checked and certified as safe for building occupancy by qualified independent structural engineers.
12. The viability of residents re-entering the building extends beyond the structural issues considered here and hence beyond the scope of this investigation. Nevertheless, we would recommend that items 9-11 listed above be completed prior to re-occupation.

TOR 3 – How to avoid this type of incident in the future

We recommend the following should be implemented:

13. The creation of a government Registered Engineers database developed in partnership with an appropriate professional body.
14. Independent third party checking and certification of engineering designs and subsequent changes to the design of critical elements by a Registered Engineer, including confirmation of what are the critical elements for all major construction projects.
15. Critical stage, on-site checking and certification by a Registered Engineer that construction is as per the design for all major construction projects. All changes to identified critical structural elements that are proposed and made during construction should also be certified by an independent Registered Engineer.
16. An online database be created, where all certifications may be viewed by a broad range of stakeholders including owners and prospective owners; before, during and after construction. The aim is to increase transparency of the approval and certification process.
17. A Building Structure Review Board be formed, with the major purpose being to establish and publish the facts relating to structural damage of buildings arising from design and construction, investigate their causes and to recommend changes to Codes and Regulations where appropriate.

Introduction

The Opal Tower is a high-rise residential building located in Sydney Olympic Park, NSW. It consists of 36 storeys above ground and 3 basement levels below ground. Construction of the building was completed in 2018 and occupation of the 392 residential apartments commenced in the second half of 2018.

A photograph of the Opal Tower is shown in Figure 1. The building is characterised by its overall triangular prismatic shape, with a number of insets in the three external faces of the building (see Figures 1 and 2). These architectural features are referred to as “slots” on some design drawings.

On Christmas Eve 2018, residents of the Opal Tower reported loud noises, including a loud “bang”, reportedly of internal origin, and presumably associated with the structure of the building. Early investigations of the source of these loud noises identified cracks in a load-bearing panel on Level 10 of the building, forming one of the exterior walls at the base of one of the inset slots. Later investigations revealed further cracking of the hob beam supporting the cracked load-bearing panel. Subsequent investigations also identified other cracked concrete structural members at Level 4 of the building, again at the base of an inset slot feature.

Because of safety concerns, residents of the building were evacuated, first on Christmas Eve 2018. They were subsequently allowed to re-enter and then asked again to depart the building on 27 December 2018, following more detailed checking of structural elements and specifically the identification of the additional structural damage on Level 4 of the building.

On 27 December 2018, the NSW Department of Planning and Environment (DPE) engaged Professors John Carter and Mark Hoffman to investigate a number of matters related to the cracking of the concrete structural members in the building, including the likely causes of the observed cracking. Following initial investigations, Professor Stephen Foster was also engaged to assist in the investigations, on the recommendation of Professors Carter and Hoffman.

This report contains a description of the investigations carried out and presents the findings, recommendations and opinions of the investigators.

Terms of Reference

The terms of reference of the investigation were provided by the Secretary of the NSW Department of Planning as follows:

1. *“Determine the basis of the failure, what happened and how?*
2. *The immediate steps that need to occur to ensure the safety of the building for its occupants.*
3. *Any other recommendations on what needs to happen to avoid incidents like this in the future.*”

This final report provides findings for all three terms of reference. An earlier, interim report, dated 14 January 2019, provided preliminary findings, based upon information available at that time, with respect to the first two terms of reference.

Building Structure

The Opal Tower is a reinforced concrete building with post-tensioned concrete floor slabs. It has a reinforced concrete central core structure, which houses the lifts and fire stairs. The floors of the building are supported by the core walls and reinforced concrete columns and precast concrete elements. A particular feature of the building is the inset slots located on each external face of the building (see Figures 1 and 2). The walls of these inset slot sections are constructed largely from precast reinforced concrete panels (with some cast in situ panels). The walls composed of these panels have been designed to carry gravity loading, effectively acting as columns, transmitting vertical loads (from floors above the inset slots and from floors intersecting them) to the individual supporting columns below each inset slot feature. The columns of the building are founded on individual pad footings and the central core is supported on shallow spread footings. All footings are founded on shale bedrock.

The major structural design of the building was carried out by WSP, an international engineering services company. The design of the post-tensioned concrete floors was carried out by Australasian Prestressing Services (APS). The precast wall panels were fabricated by Evolution Precast Systems (Evolution). The building was constructed by Icon Co, an Australian building contractor and part of the Kajima Corporation of Japan (Icon).

Investigation Activities

Our investigations included the following activities:

1. Multiple visits to the Opal Tower site and inspection of the damaged structural members in the building, and members in similar locations;
2. Review of the design of relevant sections of the building and related documentation;
3. Review of construction records and quality control records;
4. Review of defect notice No. 84;
5. Viewing of a security camera recording of the garden area in the slot on Level 10 where damage to the panel was first observed;
6. Inspection and review of elements of the structure repaired during initial construction (Columns C1 on Level 6, C38 on Level 7, and C21 on Level 8 as well as the Level 13 floor slab);
7. Discussions with representatives of the building's structural designer (WSP), floor slab designer (APS) and builder (Icon);
8. Discussions with the engineering representative of the Opal Tower Strata Committee (Cardno);
9. Discussions with the Executive of the Opal Tower Strata Committee;
10. Discussions with senior figures associated with the building industry nationally and in NSW; and
11. Consideration of unsolicited advice and information provided by members of the engineering profession and the public.

Activities 1 to 6 listed above were focused on various structural elements in sections of the building located on Levels 3, 4, 6, 7, 8, 9, 10, 13, 16 and 26, as well as the basement level B3. All areas of known structural damage, both major and minor, were inspected. In particular, we inspected all inset slot regions of the building focusing on the structural panel walls and their supporting hob beams, and the floor plates adjacent to damaged hob beams.

The discussions listed as activities 7 to 10 above aided our understanding of the technical design and construction issues relating to the Opal Tower as well as providing useful background information pertaining to the building industry and current building practices.

Activity 11 listed above was necessary to provide due consideration to the concerns expressed by individuals and to reflect on the unsolicited information provided. It was not possible to individually acknowledge these contributions to our investigation, but we take the opportunity to do so collectively now.

We were also assisted in these various tasks by staff of the NSW Department of Planning and Environment. We wish to thank the Department for this assistance.

We note that the opinions and findings expressed here are our own and not necessarily those of any other party, including the Department.

We wish to thank all parties who provided information and advice to this investigation. Their cooperation and assistance were invaluable.

Observed Damage

During the numerous visits to the site of the Opal Tower, we inspected and re-inspected a number of locations where significant damage had occurred to load bearing concrete members.

The areas of significant structural damage are located on Levels 4 and 10 of the Opal Tower. The approximate locations of these damaged regions are shown in Figures 3 and 4.

Photographs of some of the damaged concrete structural members are shown in Figures 5 to 12. Specifically:

On Level 10:

1. A hob beam spanning between columns C21 and C38 (along grid line C shown in Figure 4) and the Panel A resting on it – see Figures 5 to 8. Cracking was also observed in the floor plate adjacent to column C21 – see Figure 9. This was the damage observed on Christmas Eve and is considered to be major damage.

On Level 4:

2. A hob beam spanning between columns C16 and C34 (along grid line A shown in Figure 3) – see Figure 10. This also appears to be major damage.
3. A hob beam spanning between columns C2 and C22 (along grid line B show in Figure 3). These cracks could be considered minor *at this stage* – see Figure 11.
4. Cracking was also observed in the floor plate between Levels 3 and 4 – see Figure 12. This was considered to be major damage.

It is noted that the vertical load lines along which the observed major damage occurred are different and hence these areas of damage are likely to be unrelated to each other.

From the security camera footage referred to previously, we observed cracking in the bottom corners of the bottom panel (Panel A) on Level 10. The time stamp on this video recording indicated that the cracking of the panel commenced at approximately 2.16 pm on Monday 24 December 2018 and continued for approximately 8 seconds.

Consequences of Damage

As indicated already, all residents were evacuated from the building by about 27 December 2018 to ensure their safety and to allow an assessment to be made of the extent and severity of the damage to the building's structure.

Furthermore, soon after the structural damage to the building was observed, WSP and Icon instigated a program of installing props under the damaged areas, as a precautionary measure, to ensure the safety of these areas of the building.

The greater proportion of the loading carried by a reinforced concrete building's structure arises due to gravity and the self-weight of the structure itself (usually called the "dead loading").

When structural damage occurs to an individual element(s) in a building, as eventuated in the Opal Tower, it is often associated with overloading of one or more of the structural elements of the building in combination with other factors. The damaged elements then no longer have the capacity to carry the loads that are imposed on them in the same manner, and at least some of that load will be redistributed to be carried by other sections of the structure.

Given the inevitable redistribution of the loading as a consequence of the damage to the hob beams and neighbouring elements, checks should be carried out to assess the consequences of load redistribution and an assessment made of the capacity of other elements of the structure to withstand the extra loading imposed on them as a consequence of that redistribution.

An analysis of this type has been carried out indicating an increase in some column loads above the original design load but to levels that would not exceed the requirements of the NCC. We advise that this analysis should be verified by a qualified independent structural engineer.

A feature of the building's design is that most, if not all, major columns in the building had been designed so that their maximum axial load carrying capacity far exceeded the design loading imposed on them, indicating a very high factor of safety to these critical elements. However, a preliminary analysis of the splitting forces near the interface with the two hob beams reviewed (Level 4 – grid line A and Level C -grid line C) indicates that this aspect of the design should be confirmed by a qualified engineer for all such features.

We have found no evidence contradicting our interim assertion that the building is overall structurally sound, although there is significant damage to some elements. It should be noted that extreme environmental events, while rare, could precipitate further damage and consequently it would be prudent not to delay rectification works.

In addition, our inspection of the columns that were reported to us as having been repaired during construction (Columns C1 on Level 6, C38 on Level 7, and C21 on Level 8) revealed no evidence of structural distress. Repairs of this type are not unusual during construction. Details of the repairs to these particular columns were provided by Icon.

Cause(s) of Damage

After inspecting the damaged areas of the building, we initially hypothesized a number of factors that may have been a contributing cause of the observed cracking of the concrete hob beams on Levels 4 and 10, the damaged precast panel on Level 10 and the damaged floor plate between Levels 9 and 10 and Levels 3 and 4. These factors are categorized as follows:

1. Environmental factors such as major storms, heavy rainfall, high winds and extreme changes in temperature causing unexpected and potentially damaging loading of the building;
2. Poor quality construction materials;
3. Issues with the foundations, namely differential settlement of the pad footings supporting the building's columns;
4. Poor quality workmanship or errors during construction; and
5. Flaws or errors in the design of the structural systems.

We considered and assessed each of these factors in some detail and ultimately concluded that not all of the factors were relevant to the damage observed to the Opal Tower. Further details of this assessment are provided as follows.

Environment

In particular, the environmental factors were considered to be highly unlikely to have contributed to the damage because the meteorological records for the few months preceding the failure, and particularly in the period immediately prior to and on 24 December 2018, show no extreme or adverse conditions. The rainfall records show some significant downpours in the months leading up to Christmas, but they were considered not to be unusual.

Materials

In our interim report, dated 14 January 2018, we indicated that there was no evidence in the documentation we had reviewed to that date to indicate that the materials used in construction were inferior in quality or did not meet the specifications required.

Further test records of materials used in construction, received by us after our Interim Report was issued, revealed at least one case where concrete used in a hob beam may not have reached its specified 28 day strength. This instance is described in greater detail later in this report, when the possible causes of damage are addressed (see discussion under the heading 'Damage at Level 4 – Grid Line A'). The reason for not being definitive in the previous statement, is that there was, and remains, some uncertainty about what strength concrete was actually specified for the hob beams, as explained in more detail later.

Foundations

In general, differential settlement of the footings of a building can occur for a variety of reasons. For example, neighbouring columns may experience large differences in their compressive loading or the ground beneath neighbouring footings may vary markedly in terms of stiffness and strength. Differential settlement is also likely if the ground beneath some footings, but not others, softens over time, perhaps due to local wetting of the ground beneath the footing causing softening of the foundation material.

The records we inspected reveal that all column footings for the Opal Tower structure were founded on shale of low to medium strength, with the majority being medium strength. The records we reviewed indicate that the spread footings supporting the tower core and all but two of the 40 individual pad footings supporting the tower columns were inspected by a geotechnical engineer prior to the pouring of concrete to form the footings. All inspected footings were certified by the geotechnical engineer as suitable to carry a maximum allowable bearing pressure of 3.5 MPa. We could not find inspection records for columns designated as C8 and C40 (see Structural Drawing 4419 S02.051 A for column designations and locations).

However, if differential footing settlements had been a contributing cause of damage to the building, and specifically the damage observed on Levels 4 and 10, we would have expected to observe cracking in the floor slabs and at floor-column connections in the lower levels of the building. Our inspections of these areas of the building indicated no such damage. So on the basis of this observation and the documentary evidence of the condition of the shale foundation at the time the footings were poured, we concluded that differential settlement of the column footings is unlikely to be a contributing factor to the structural damage observed on Levels 4 and 10 of the Opal Tower.

Construction

There are a number of points noted where construction differed from the design and / or Standards:

(a) Grouting: design drawings indicate that full grout coverage was expected between the panel and the hob beam. However, during construction only the inner surfaces of approximately 50-70% of the joint width appear to have been grouted, consistent with the shop drawings which show the grout extending over only the inner portion of the hob beam to panel connection. Furthermore, coring of the Level 4 hob beam revealed incomplete grout coverage in some places. This partial grout coverage led to an eccentric bearing load and elevated bearing and bursting stresses on the hob beams;

(b) Inadequate cover concrete, specifically in the hob beam spanning columns C21 and C38 on Level 10, the location of some reinforcing steel in the vicinity of the hob to column connection, the encroachment of discontinued (anchored) column bars into the cover zone, and the placement of an electrical conduit within the cover zone in this area;

(c) A dowel bar between the hob beam and the panel on Level 10 was observed to be incomplete, possibly cut during construction;

(d) The original design drawings of the building indicate precast concrete panels of a thickness corresponding to the width of the hob beam upon which they rest. However, the panels were manufactured to be 20 mm thicker and erected so that they overhang the inside face of the hob beam. For example, on Level 10 the panel was originally designed to be manufactured 180 mm thick to correspond to the hob beam width, but was constructed to be 200 mm thick and overhang the inner face of the hob beam by approximately 20 mm;

(e) Potentially inadequate tensile capacity in the horizontal direction in the bottom region of Panel A on that rests on the hob beam spanning columns C21 and C38 on Level 10. There is compelling evidence indicating that the wrong size reinforcing bars were placed in this area during manufacture of this particular panel – 20 mm diameter bars were used instead of 28 mm diameter bars (see Figure 8); and

(f) We could find no evidence, during our site inspections and in the construction photos and photographs of damaged hobs, that reinforcement cross-ties were incorporated in those hobs to resist bursting forces.

In regard to the timing of the observation of damage, it is likely that the damage occurred after progressive build-up of load on the structure as apartments became occupied, culminating with the observed damage at Level 10 on 24 December. It is unclear when the observed damage on Level 4 occurred.

The architectural design where the major damage to the hob beam has been observed on Level 4 is quite different to that of the damaged hob beam on Level 10. The cause of the damage observed on Level 4 and Level 10 is considered in greater detail in following sections of this report.

Structural design

Our investigations have identified at least two areas of the as-built structure, which, in our opinion, do not meet all requirements of the relevant Australian Standard, AS3600 Concrete Structures and therefore do not meet the requirements of the National Construction Code Volume 1 (NCC). The specific areas of the building coincide with the locations of the most serious damage observed to the concrete structure. Our specific findings are:

(a) At Level 4 of the building – inadequate bursting (or splitting) resistance of the hob located immediately above column C34; and

(b) At Level 10 of the building - inadequate bursting (or splitting) and / or bearing resistance of the hob at the locations of its connections to columns C21 and C38.

These findings are described in greater detail below, together with the reasons that support our opinions expressed here.

Damage at Level 4 – Grid Line A

The observed damage to the hob beam spanning columns C16 and C34 at Level 4 has been described previously. Our detailed investigations of this damage focussed on the region of the building structure in the vicinity of column C34, where damage was observed, and included the hob and the precast panel that sits upon it, as well as the connection between the hob and the panel. These investigations included both hand calculations and numerical modelling using the finite element method which specifically incorporated the (possibly non-linear) behaviour of reinforced concrete (RC) structures. The hand calculations were undertaken to assess the validity of the finite element results and the observed failure mechanism.

The finite element study investigated specifically the load-deflection behaviour (up to failure) of column C34 at the level of the soffit of the Level 4 floor slab, as well as the stresses and strains induced in the concrete in the column, floor slab, hob and precast panel. Typical numerical predictions of the stresses in the transverse plane are shown in Figure 13 and a possible strut-and-tie model to describe the load path through the connection is shown in Figure 14. Such predictions were made to assess the performance of these structural elements and to observe the predicted mode of deformation. In particular, a focus of these studies was ascertaining whether bearing and / or bursting of the hob were possible causes of the observed damage.

The hand calculations considered the capability of the hob in both bearing and bursting. The axial forces passing through the pre-cast wall panel to the hob beam connection, and then into the columns, were addressed. Some of these calculations adopted the 'strut and tie model' describing equilibrium of forces in the hob beam (Figure 14). This hand calculation method followed the approach specified in AS3600.

The finite element analysis (Figure 13), albeit preliminary, indicated significant splitting forces in the column adjacent to the hob beam. It would be prudent to undertake a more detailed analysis of this feature and to confirm if appropriate bursting reinforcement is in place. Rectification works may be necessary pending the outcome of the abovementioned detailed analysis.

The damage observed in the hob beam above Column C34 at Level 4 is shown in Figure 15. This image indicates bowing of the reinforcement steel outwards from the beam and opening of the stirrup. Also noticeable is a lack of cross-tie reinforcement to guard against splitting failure..

It is notable that the observed damage was constrained to the inside facing of the hob beam; the outside of the hob beam at the critical section was supported by a lateral garden bed wall (Figure 16) built integrally with the slab and against the hob beam. This wall likely provided support to the outer side of the hob beam forcing the damage inward where such support was lacking. This damage remained "hidden" until exposed on 27 December 2018 after removal of an internal wall in the adjacent apartment. It is not known when this damage occurred.

The site observations of the damaged beam are consistent with a bursting failure.

There are contradicting views and documentation as to the design strength of the hob beam concrete on Level 4. Notwithstanding, 65 MPa concrete was understood to have been poured during construction as it was specified for the puddle pours in the slab around the columns and it was considered expedient to use the same batch of concrete when pouring the hob.

During our investigations, and subsequent to the issue of our interim report, records of strength for the concrete used to construct the hob beam were provided to us. These reveal 28 day strengths of these concrete samples as 50 MPa, where 65 MPa concrete was ordered for supply, indicating that the concrete in the hob may also have been of a lower strength. Our independent analysis of concrete core testing samples, extracted and tested in January 2019 by Mahaffey Associates, did not contradict this observation.

Clearly, this mis-match in design strengths points to a possible and unfortunate ambiguity in the interpretation of the design documentation.

We have drawn conclusions from our numerical analyses of the as-built design, combined with hand calculations and field observations of the damaged hob beam at Level 4 – Grid Line A. In our opinion, these are as follows:

1. With the design loads assumed, the strength of the Level 4 hob beam spanning columns C16 and C34 does not meet the requirements of AS3600–2009 (which was the operative version of the code at the time the structure was designed);

2. The observed spalling of the hob beam cover concrete above and adjacent to column C34 implies that the beam is in a state of high stress;
3. The strength of the concrete in the "as constructed" hob beam was lower than that assumed in the design;
4. Splitting forces are significant and the tie-reinforcement provided was inadequate to resist these forces; and
5. The cause of the damage to the hob was by bursting (also known as splitting) of the concrete in the hob beam section.

Damage at Level 10 – Grid Line C

The observed damage to the hob beam spanning columns C21 and C38 at Level 10 has been described previously. In this case, our detailed investigations of the Level 10 damage focussed on the region of the building structure in the vicinity of columns C21 C38, and as for Level 4 included the hob and the precast panel that sits upon it, as well as the connection between the hob and the panel. These investigations included both hand calculations and numerical modelling using the finite element method. The numerical modelling included consideration of the conduit located in the cover region and the repaired concrete patch in the panel. The hand calculations were undertaken to assess the validity of the finite element results and the observed failure mechanism.

The damage in the hob-beam above Columns C21 and 38 at Level 10 is shown in Figures 17 to 20. For the hob-beam above column C38, Figure 17 shows splitting along the lines of shear compression, indicating high levels of stress on each of the in-plane and out-of-plane surfaces. While bursting appears to be the dominant mode of failure, bearing stresses appear to have also been influential in forming the failure surfaces.

Figure 18 shows observations presented to us of the hob beam above Column C38 when the walling was opened. These images reveal evidence of splitting along the hob centreline. A crack, running the length of the hob beam between the supporting columns, was also observed at the soffit of the Level 10 floor slab (Figure 19). Splitting of the hob and wall panel is also evident in Figure 20.

These observations are consistent with our calculations that indicate a lack of capacity of the hob against bursting. As for Level 4, no cross-tie reinforcement is evident in the hob-beam at either location where spalling or crushing occurred.

We have drawn conclusions from our numerical analyses of the as-built design, combined with hand calculations and field observations of the damaged hob beam at Level 10 – Grid Line C. In our opinion, these are as follows:

1. With the design loads provided by WSP and assumed in our calculations, the strength of the Level 10 hob beam spanning columns C21 and C38 and the wall panel above it do not meet the requirements of AS3600–2009;
2. The observed spalling of the hob beam cover concrete above and adjacent to column C38 implies that the beam is in a state of high stress;
3. Splitting of the wall panel and hob beam are evident and the area of tie-reinforcement provided was inadequate to control these forces;
4. A number of construction issues were observed that may have added to the adverse stress conditions. These include an electrical conduit passing through

the cover concrete in a zone of high stress immediately above column C38 and a patch repair of the wall panel, again in a high stress region; and

5. Construction issues observed in the Level 10 C hob beam to precast panel connection that, in our opinion, were not influential on the failure include a cut dowel bar and inadequate anchorage of hob beam shear fitments (90 degree hooks located within 50 mm of the concrete surface – refer AS3600–2009 Clause 8.2.12.4).

Investigations by Others

During the course of our investigation other parties became involved, either assisting our investigations or those conducted separately by Icon and WSP, or providing advice to the Owners Corporation of the Opal Tower. Much of this additional information has been made available to us with the approval and cooperation of Icon, WSP and others.

The additional parties include the following:

1. Cardno, an engineering services company with structural engineering expertise, engaged by the Owners Corporation of the Opal Tower. We understand that Cardno has been involved in reviewing the proposed rectification measures for the Opal Tower;
2. Rincovitch, a company with structural engineering expertise, engaged by Icon to independently review the design of the building and the proposed rectification works;
3. Slab Scan Pty Ltd, a company that specialises in structural investigative reporting and the application of ground penetrating radar to locate post-tensioning, reinforcing, and electrical and other services in concrete. In this case Slab Scan was commissioned to carry out investigations of the precast concrete panels and the associated supporting hobs throughout the Opal Tower and specifically those on Levels 3, 4, 9, 10,15, 16, 25 and 26. The objective of their investigation was to confirm the as-built reinforcement details. All hob beams on Levels 4, 10, 16 and 26 were accessible at the time of the investigation and their reinforcement was assessed; and
4. Mahaffey Associates, specialist consultants in concrete technology and structure condition assessment, who were engaged by Icon to undertake strength testing of precast wall panels and hob concrete at the Opal Tower.

The reported findings of Slab Scan are most pertinent and provide a measure of confidence that the investigated structural elements were generally constructed according to the original shop drawings, with a few exceptions. The exceptions generally relate to the hob beams and were described as "*shear tie spacing was slightly sporadic*".

Proposed Rectification

As previously mentioned, soon after the structural damage to the building was observed, WSP instigated a program of installing props under the damaged areas, as a temporary measure, to ensure the safety of these areas of the building.

Icon and WSP have briefed us on the structural principles behind their proposal for permanent repair of the damage observed on Levels 4 and 10 and strengthening of the associated structural members, viz., the hob beam and lowest panel at these locations. We also understand that, as advised for consideration in our interim report, rectification works to bolster other hob beam / panel elements on Levels 4, 10 and 16 are being undertaken, and considered for Level 26. We understand that this bolstering will include a combination of grouting of the hob to panel joints, the provision of cast in situ sandwich panels enclosing the hob and the panel that sits immediately upon it, and the addition of exterior columns adjacent to some pre-cast panel walls. We understand that the joint between all hob beam / panel elements has now been retrospectively fully grouted and we support this as a preliminary measure.

It is our opinion that the structural *principles* behind the proposal for rectification are sound, as stated in our interim report, and considerable progress has been made in this regard.

However, we have not received complete details of a structural analysis of the proposed rectifications. We recommend that detailed plans for the proposed rectification works should be checked by an independent qualified structural engineering organisation.

As mentioned previously, the observed damage on Levels 4 and 10 will have caused load, designed to be taken by the damaged elements, to be redistributed to other parts of the structure. A preliminary analysis has been carried out indicating an increase in some column loads above the original design load but to levels that would not exceed the requirements of the NCC. We advise that this analysis should be verified by a qualified independent structural engineer.

In addition to restoration works for the hob beam and wall panels on Levels 4, 10, 16 and possibly 26, it is recommended that the following additional structural elements should be checked for adequacy with respect to their load carrying capacity and rectification work be undertaken, if needed:

1. All hob beams and connecting wall panels in the building of similar design;
2. Other components that may be subjected to splitting forces, such as columns supporting hob beams; and
3. The longitudinal tension force that may derive in the hob beam connecting columns C16 and C34 at Level 4 resulting from discontinuation of the panels at the expansion joint.

We remain available to provide further advice to government once the full details of the proposed rectification scheme have been determined.

It is also our opinion that appropriate rectification works can address any deficiencies in the original, as-constructed, design and should ensure the building is compliant with the NCC.

The Future

Our third term of reference asked us to make any other recommendations on what needs to happen to avoid future incidents such as the one discussed in this report. Our investigations of this rare but concerning case of structural damage in a relatively new high-rise apartment block, have provided us with relevant, important and unique insights.

Australia enjoys a strong regulatory environment in construction, especially in regards to building structural safety, through the National Construction Code and associated mechanisms, including in New South Wales. This has provided Australia with an excellent record in terms of building structural safety with few if any of the catastrophic incidents recorded in many other international jurisdictions. Standards and Codes are generally built into our regulatory systems to specify minimum safety criteria, which must be attained.

Australia is also home to some of the world's best architects, design engineers and construction companies who enjoy high international reputations for their work globally, including the firms associated with the design and construction of the Opal Tower.

However, community and consumer expectations rise far higher than just overall building structural safety, with a reasonable belief that all components of a building should be structurally sound and stable. In the case of the Opal Tower, this expectation was clearly not satisfied.

Structural design and construction codes in Australia are based upon the principle of performance pathways, which focus on overall building performance requirements rather than specifying how it is to be constructed. This approach enables innovation and evolution in terms of architectural appearance and construction techniques, and has become a celebrated feature of the Australian built environment. This includes not only Performance Solutions under the NCC but also performance-based design and construction in accordance with Australian Standards. Performance-based design and construction enables the creation of attractive novel architectural and structural design solutions with increasing efficiencies, countering the architectural 'sameness' and higher construction costs that can arise from highly prescriptive construction procedures.

While it was not within the scope of our review to look closely at the certifications that took place on the Opal Tower, we found no evidence that the building certifiers had been deficient in regards to statutory expectations. Nevertheless, there was a range of construction issues that occurred which were not compliant with Australian standards, and aspects of the design which led to structurally inadequate sections of the Opal Tower. While no evidence has been found that those responsible for certifying work did not conform with requirements, it is evident that a number of checks for compliance were not undertaken or undertaken with insufficient rigour.

Through the course of the investigation of the Opal Tower, it has become evident that tensions between the application of performance-based design and construction and the regulatory environment and processes have led to deficiencies where community expectations of building quality have not been met. We believe that these can be resolved with improvements to the regulatory environment without altering the benefits of the current overarching approaches to design and construction in New South Wales and Australia.

From the outcomes of our investigation we make the following recommendations. The first three recommendations, if they had been in place, would have significantly reduced the likelihood of, or avoided, the Opal Tower damage. The last two are put forward as mechanisms to raise the overall standards of building design and construction and community confidence.

1. **Creation of a Registry of Engineers.** Registered engineers should have a high level of competency including recognised qualifications benchmarked to international education standards, minimum level of professional practice and currency of continuing technical professional development (particularly important in an evolving field such as building design and construction). The Registry should be managed by government in partnership with an appropriate professional body.

   Certifications and approvals associated with the design and construction of a building should then only be undertaken by Registered Engineers in their specialised area of expertise.

2. **Independent third party certification of engineering designs.** All engineering designs for major projects should require checking and certification by a Registered Engineer. For identified critical elements of a design, certification should be by a third party Registered Engineer, fully independent from the original designer.

   This requirement should also extend to all changes to critical elements that occur up until the completion of construction, and essentially to any alternations that may subsequently occur during the operational life of a structure.

   Major projects are those that are clearly significant; a detailed definition should be developed with all stakeholders.

3. **Regime of critical stage, on-site inspections by an independent Registered Engineer.** A mandated regime for inspections on major projects should be developed for critical stages of construction and for identified critical elements to ensure that construction is according to certified designs. Furthermore, these inspections should be undertaken by an engineer who is registered and present on-site. Recommendations for what constitute the 'critical stages of construction' should be made by the structural designer, and independently verified as a part of the design certification process.

   It would also be preferable to have a Registered Engineer on site who certifies that all elements of a building are as per the approved design.

4. **Raise transparency through the creation of an open repository for all certifications**. This repository may be accessed by a broad range of stakeholders including owners and prospective owners; before, during and after construction. This is intended to raise the accountability of certification processes and simultaneously provide confidence to the community that appropriate certifications are being undertaken, confirming the integrity of all aspects of design and construction.

   For the current investigation, we have been provided with all available information requested. As independent expert reviewers, however, we have noted that the time taken to obtain documentation and its curation and completeness was at times challenging. We do not believe that this is an ideal situation and that the community would benefit from increased transparency.

5. **Creation of a Building Structure Review Board.** This Board would consist of independent experts whose role would be to review major incidents of design and construction related structural damage to buildings. The Board's role would be to assess the causes of such incidents and to consider and recommend changes to codes and regulations arising from their findings.

   This would provide community confidence that expert independent consideration was being undertaken of serious incidents of damage and a mechanism for prompt and efficient adaption of codes and regulations in a performance-based design and construction environment.

Conclusions

This report has documented our investigations of the structural damage to the Opal Tower at Sydney Olympic Park, which first became apparent on Christmas Eve 2018.

We have considered all evidence put before us and have concluded that the causes of the observed damage were related to a combination of design and construction matters, in particular changes made after the original design and exacerbated by construction issues. The details of these causes and the reasoning behind our conclusions have been provided in the body of this report. We have not sought to indicate who was responsible for any of the causes, but rather to establish their structural basis. We have noted that, at times, documentation has been unclear in this regard.

We have also addressed the issue of remediation of the structural damage to the Opal Tower. Although full details of the remediation measures are yet to be determined, we have agreed in principle with the proposal for remediation that was put before us.

We have also responded to the terms of reference of our investigation by making five separate recommendations for future actions by government and regulatory bodies. These were aimed at avoiding situations like the one encountered with the Opal Tower and at improving the robustness of structural designs and the implementation of those designs during construction. These recommendations are also intended to improve the transparency and public accountability of the regulatory systems relating to the built environment in New South Wales and Australia.

John Carter, Mark Hoffman and Stephen Foster

Date: 19 February 2019

Figure 1. General view of the Opal Tower. Note the inset slots on the external faces of the building, each extending for multiple storeys (some 6 and others 10 storeys).

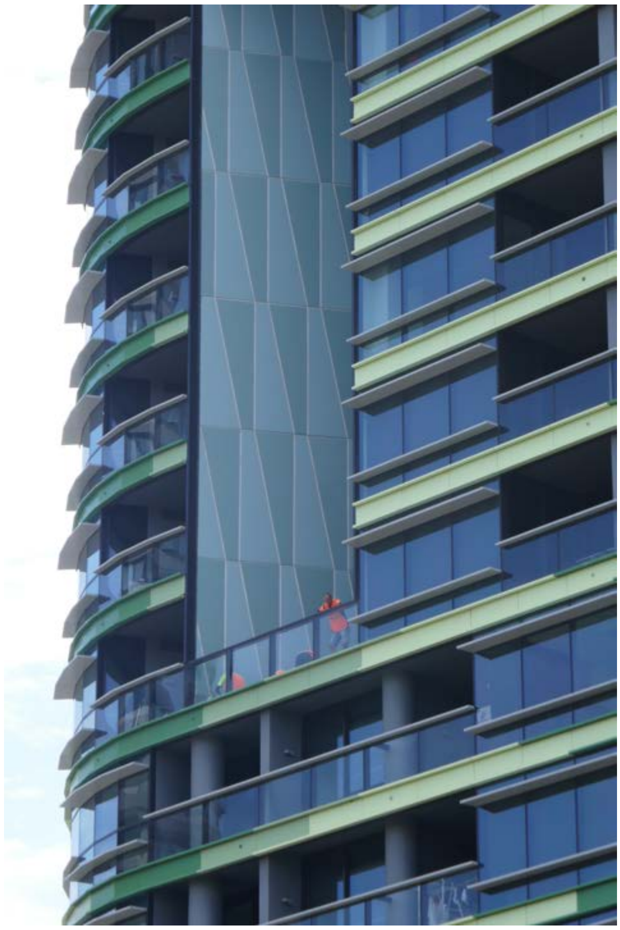

Figure 2. Close-up view of a 6 storey slot. Note the 6 panels forming the load bearing wall of the inset slot, each one storey high.

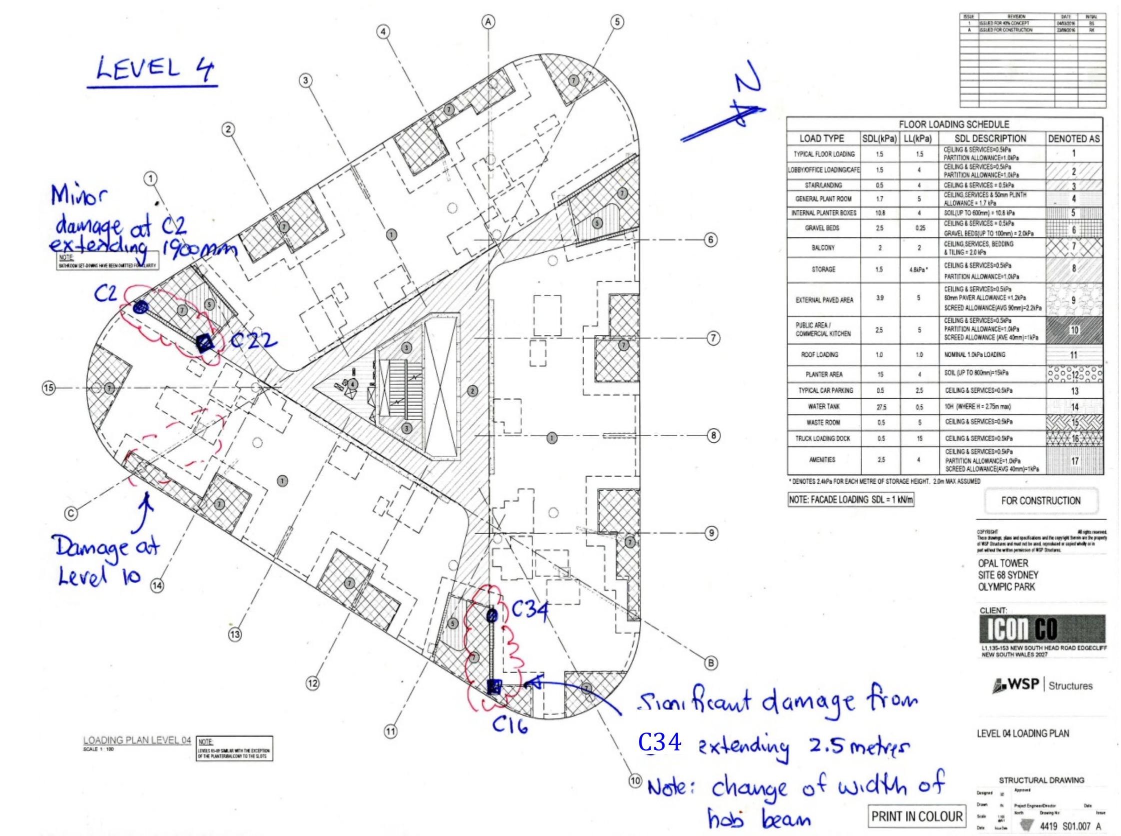

Figure 3. Plan view indicating locations of damage observed on Level 4

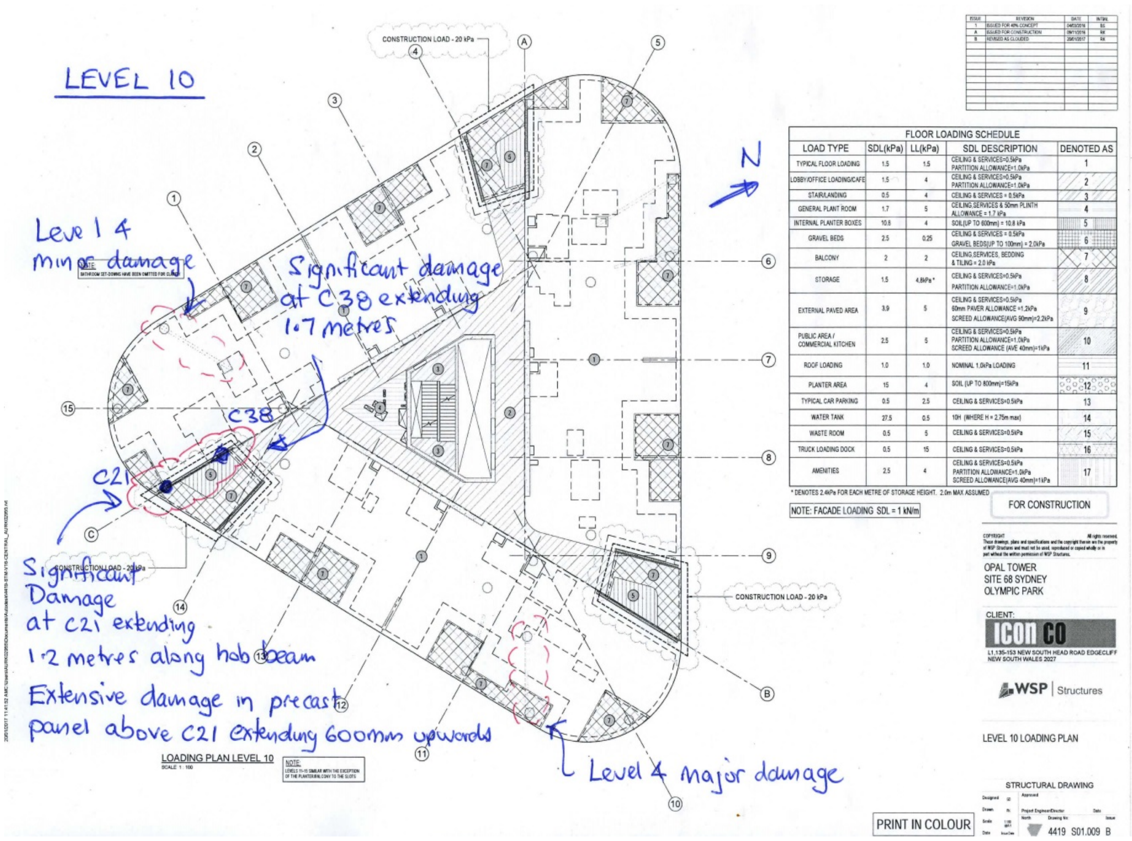

Figure 4. Plan view indicating locations of damage observed on Level 10

Figure 5. Damaged precast Panel A at Level 10 above column C21, before (top) and after (bottom) broken section of concrete removed.

Figure 6. Damaged precast Panel A at Level 10 above column C38, after some broken sections of concrete removed.

Figure 7. Photographs of the hob beam in the vicinity of column 38 at level 10, prior to pouring concrete (top photo), inside the building on 8 January 2019 after cracked concrete cover removed (middle), and outside on 8 January 2019 after the garden and waterproof covering removed (bottom). Note the positioning of the reinforcing bars, the encroachment of the column bars into the cover zone, the lack of anchorage of some horizontal bars, and the encroachment of a conduit into the concrete cover zone. The vertical dowel bars that engage with the precast concrete panels can also be seen in the top photograph.

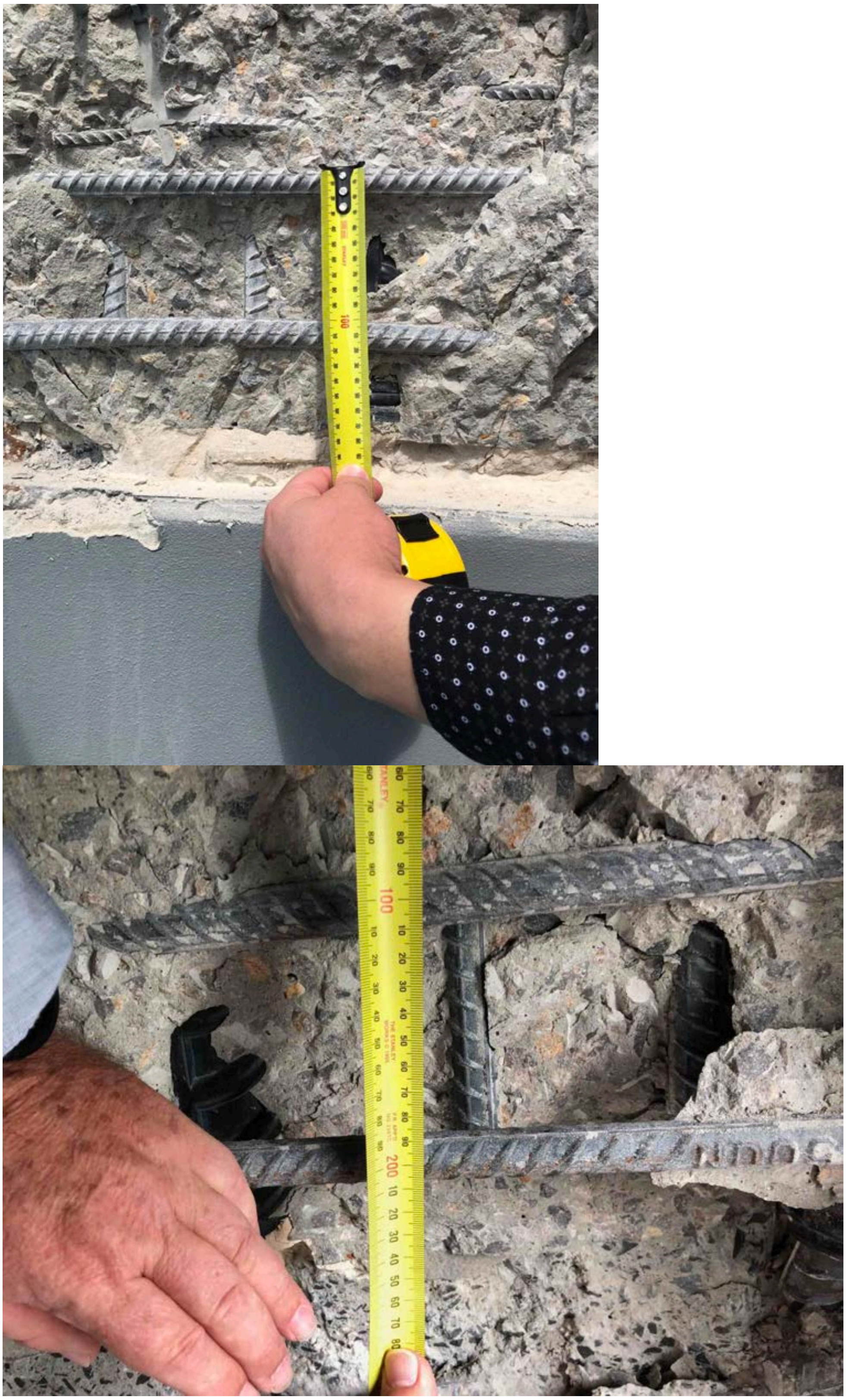

Figure 8. Photographs of the outside (top) and inside (bottom) of panel A at Level 10 just above hob beam adjacent to column 21, indicating N20 reinforcing bars at 100 mm centres in the lower portion of the precast panel. Note the exposed grout between panel A and the hob beam and the black plastic sheath for the joining dowel (top photo, right of tape measure).

Figure 9. Photographs of the damaged floor slab adjacent to column C21 on Level 10.

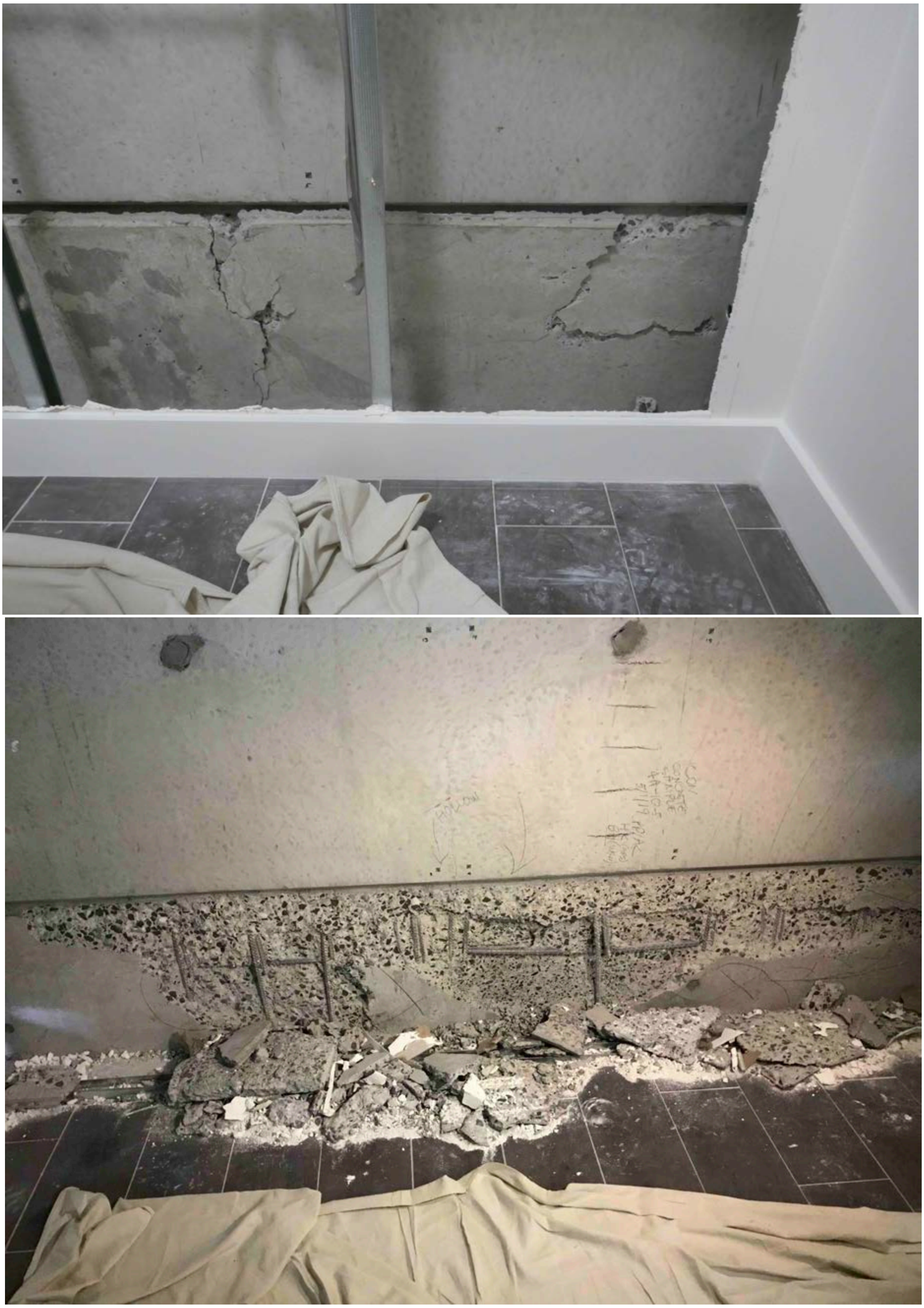

Figure 10. Photographs of the damaged hob beam on Level 4 near column C34 before (top) and after (bottom) cracked concrete removed.

Figure 11. Photograph of the hob beam and panel on Level 4 near column C2 with red lines indicating minor cracking.

Figure 12. Photograph of a crack in the floor plate between Levels 3 and 4.

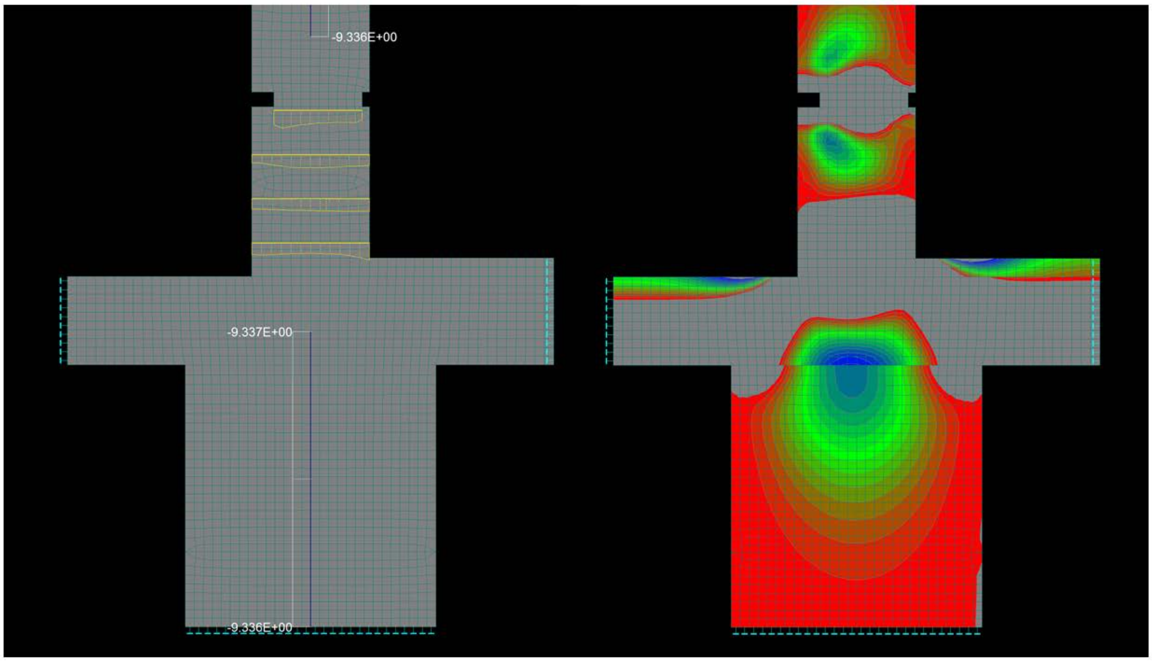

Figure 13. Typical distributions of axial stresses acting on the hob-beam (left) and tensile bursting stresses (right) – Level 4 Grid Line A.

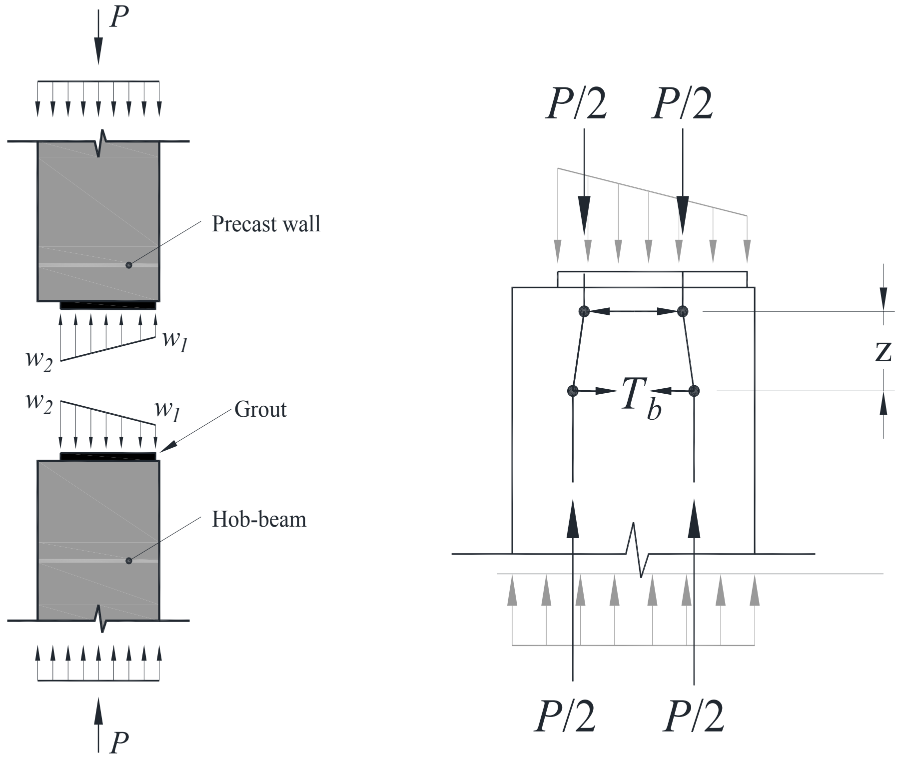

Figure 14. Schematic representation of axial forces and stresses passing through the wall panel to hob-beam grouted connection (left), and strut-and-tie model describing bursting forces that result from the disturbance caused by the joint's geometry (right).

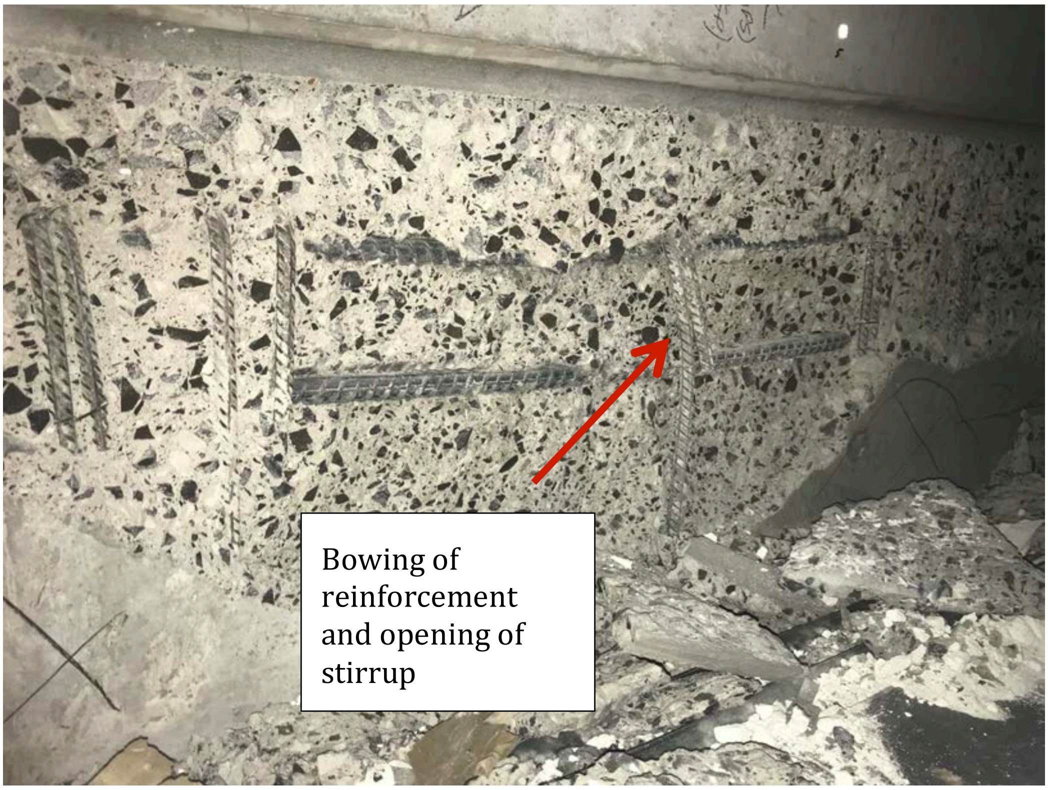

Figure 15. Damage in hob beam at Level 4 above column C34 showing bowing of reinforcement and opening of stirrup.

Figure 16. Lateral support provided to hob-beams at outside elevation through reinforced planter box hob – Level 4 Grid Line A.

Figure 17. Hob beam at Level 10 in the vicinity of column C34 (outside) showing splitting along shear compression crack band lines.

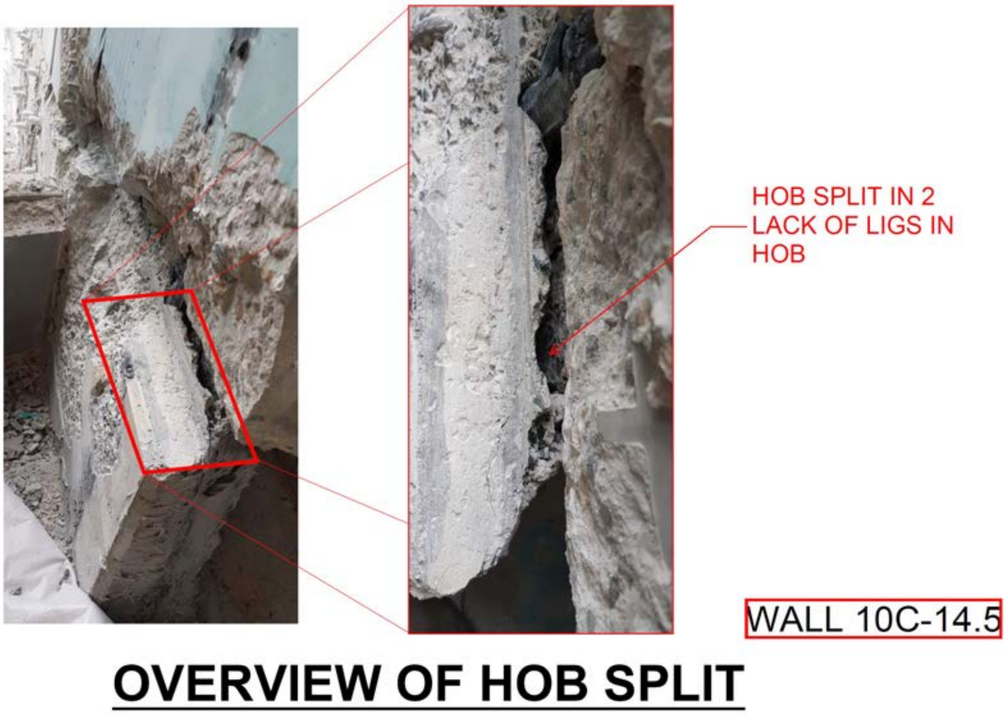

Figure 18. Photographs at Wall 10C-14.5 (Level 10 grid line C) documenting a splitting crack in the hob beam.

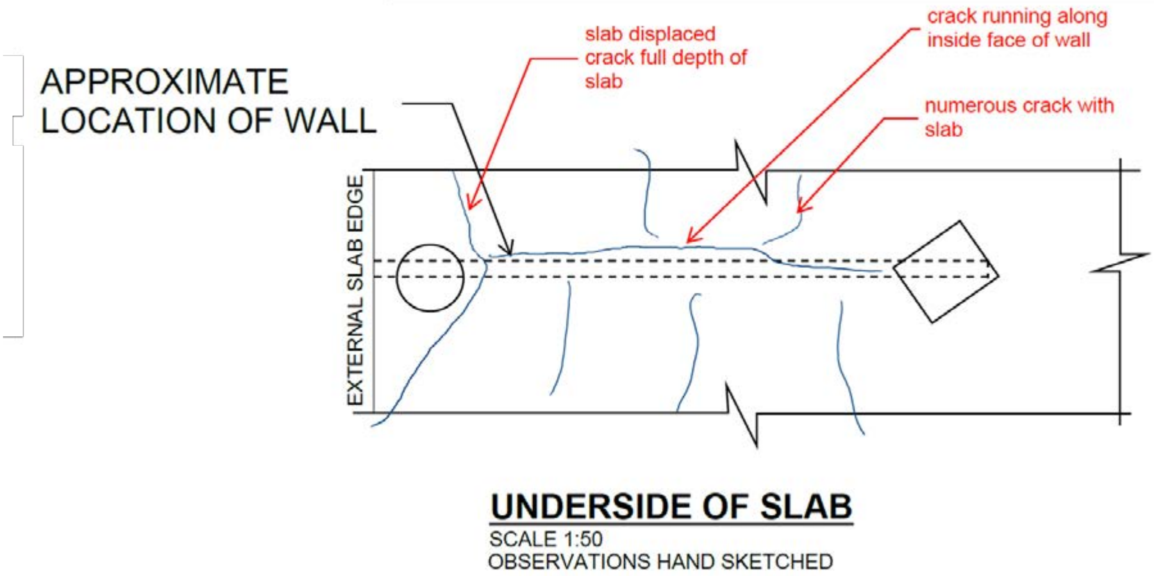

Figure 19. Drawing of the underside of Wall 10C-14.5 (Level 10 grid line C) documenting a splitting crack in the floor slab between columns C21 and at C38.

Figure 20. Hob-beam and precast wall panel at Level 10 in the vicinity of column C21 (apartment side) showing splitting of the precast panel and the damaged hob beam.