Seismic review of a typical low rise commercial building – a case study

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ABSTRACT

The Case study building was designed and built in 2003. The building is a single storey rectangular shaped 25m x 21m steel portal frame structure with precast concrete panels. The building is typical of a modern commercial building in New Zealand.

The building was assessed to have a seismic rating below 34%NBS(IL2) and is in the process of being strengthened.

This paper will suggest a process for how to go about completing a review of this type of building and discuss some of the things to watch out for. Options for strengthening are also briefly discussed.

1 OVERALL PROCESS WHEN WE FIRST LOOK AT A BUILDING

When you first look at a set of plans for a building it can be difficult to determine the designers intended structural system. Sometimes the intended system is clear, however a reviewer needs to make sure that the design intent was carried through with appropriate detailing and connections. A reviewer also needs to be cautious with well-presented modern plans. Design deficiencies can be somewhat obfuscated by being placed in a setting of modern drafted plans.

When starting to look at a structure, the author suggests the following as a process. This will form the basis of an initial high-level review, which may then inform an initial seismic assessment, and if needed, detailed seismic assessment.

1. Familiarise yourself with the structural plans.
2. Identify the global lateral load resisting system in each primary direction (transverse and longitudinal)
3. Follow a load path
4. Focus on connections

When completing the above steps, as a reviewer you may notice items of concern (flags) which will highlight a need for further review. Identifying these flags can generally be completed without having to complete calculations.

Depending on the scope of engagement, once the above review is completed, some hand calculations and/or basic modelling can be completed to confirm items as needed.

A reviewer should also be familiar with recent research and publications, as this can assist with highlighting potential areas of concern. For example, for this type of structure the SESOC Journal article 'Design and Remediation of Low Rise Industrial/Commercial Buildings' is a good reference.

1.1 Familiarise yourself with the plans

Visit the structure and look for structural elements and what detailing you would expect to see. For example, if there is a steel portal frame, can you see any fly bracing? How is the knee joint built? If there is tension only bracing, look at the connections – do they 'node' (ie meet at a common intersection point)? If there is transfer struts look at the connections – do they look to be able to work in tension and compression? Take as many photos as you can of the structure, components, and connections.

When looking at a building, both the structural and architectural plans are needed to complete the picture of the building. During the site visit confirm if there have been any alterations. Was the building constructed in accordance with the drawings?

Look at the plans to see where the lateral loads are being resisted – for example, is it a frame, or is it a gravity beam with posts? Are the base connections aiming for 'pinned' or 'fixed' type connections?

Find the heavy parts, the heavy tall parts, how are they connected at the top? Are there any proprietary products and have they been used appropriately?

1.2 Identify the global lateral load resisting system in each primary direction

For each primary direction, identify how the building works. Where are loads being transferred, and where are the primary lateral load resisting elements.

Note that identifying a global lateral load resisting system is not the same as confirming a compliant and reliable load path.

1.3 Follow a load path

For a specific element of the structure, identify what path the seismic loads take before they are dissipated into the surrounding soils.

Start with an out-of-plane part and follow the load path all the way to the foundations where the loads are dissipated. Do this for each primary direction and wherever there is a change in system.

1.4 Focus on connections

Having identified the load path, look at the links in the load path chain. How do they work and where are the loads applied and resisted? Identify if there are any eccentricities and if there are any vulnerabilities in the connections that may lead to premature failure? Have proprietary items been used appropriately?

2 CASE STUDY BUILDING – AN EXAMPLE

The building being considered was designed and constructed in 2003. It is in a high seismic zone.

2.1 General Building Description

The building is a relatively simple low-rise commercial structure, typical of many buildings in regional New Zealand. The building is single storey and has a rectangular floor plan of 25.1m x 21.7m. The building is split into a retail space and a trade space, with a central office/amenities area. The office/amenities area has a mezzanine, with the upper level used for staff facilities.

The building has the following general features:

- The floor slab is 125mm thick reinforced concrete slab-on-grade, with 200mm wide edge thickenings.
- The roof is supported by 250/13 DHS steel purlins at 1.5m centres. The purlins span onto 360UB45 portal frame rafters centrally. At the ends the purlins span onto a 200PFC rafter providing vertical support at one end, and 170mm thick precast concrete panels at the other end.
- The two central portal frames have 360UB45 columns which are supported via pad footings.
- The side boundary wall is 150mm thick pre-cast reinforced concrete panels which are seated on isolated pad footings at the panel ends.
- The street front is generally glazed, however there is one 150mm thick precast concrete panel.
- The inside of the offices and mezzanine area is architecturally finished, with wall linings and a ceiling concealing structural elements.
- The trade space is generally unlined, with the structural elements exposed.

3 A REVIEW

Following the steps outlined above, the following is how the author would complete a seismic review of this building.

3.1 Familiarise yourself with the structure

The available consent plans included structural plans and basic architectural plans. No alterations appear to have been completed since the structure was originally built. No flags present on an initial look at the consent plans – ie there is no unconsented works, the structure appears to be built as per the plans, and there are no signs of structural degradation.

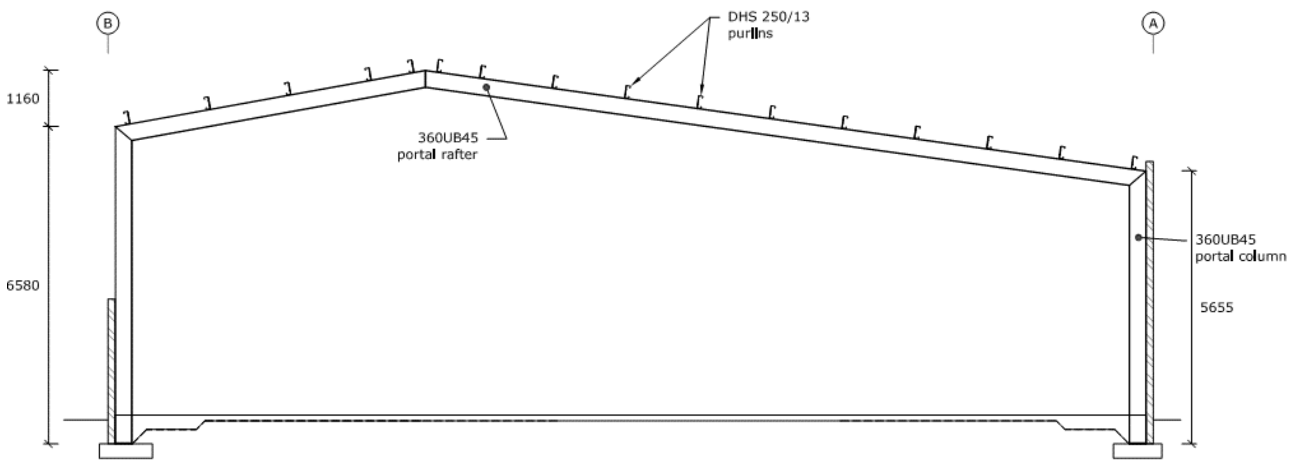

Figure 1: Typical Cross Section

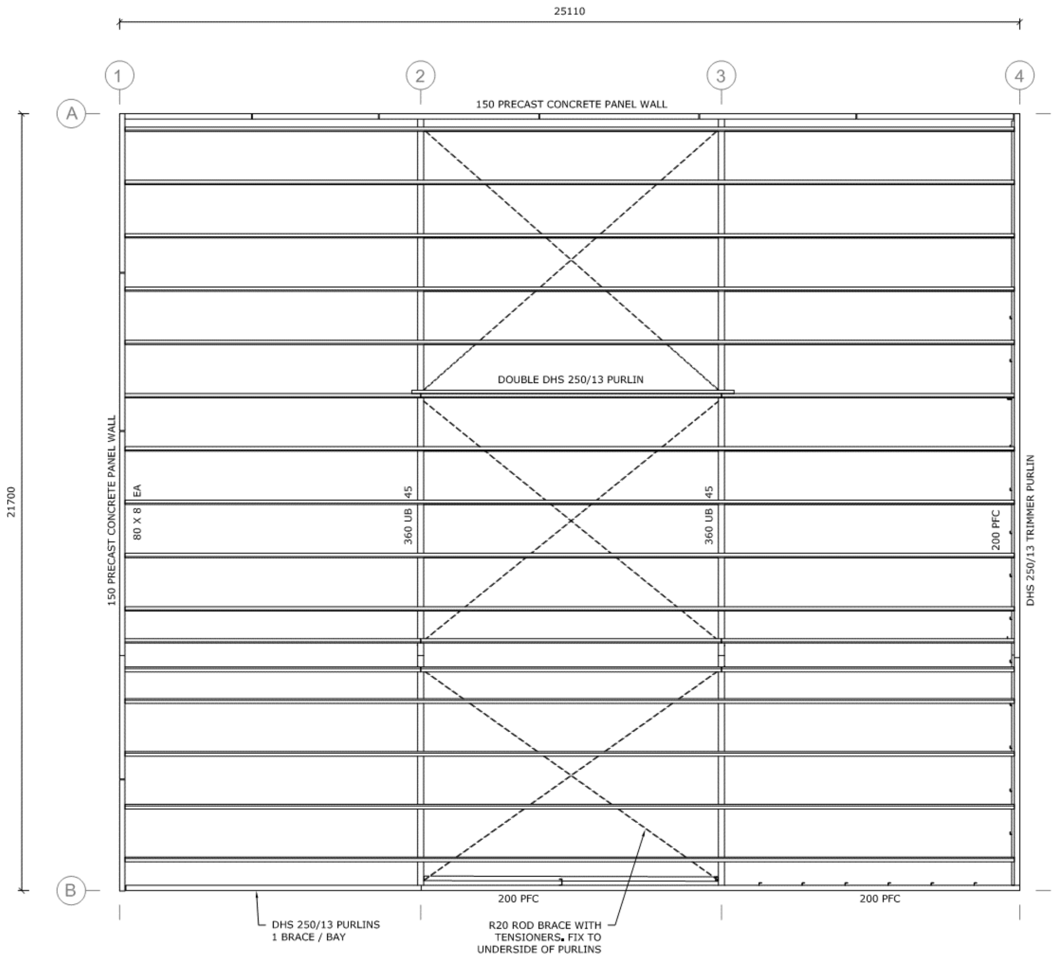

Figure 2: Roof framing plan

Figure 3: View from inside of Grid 1 wall

3.2 Global Lateral Load Resisting System

On an initial look, there is an identifiable global lateral load resisting system, further described below, and illustrated in Figure 4 following.

3.2.1 Longitudinal global lateral load resisting system

In the longitudinal direction the earthquake loads are resisted as follows.

- Earthquake loads are primarily resisted by the in-plane concrete panels on the rear side wall, and the tension and compression brace on the front side wall.
- The (yellow) out-of-plane end walls are supported at the top with a horizontal equal angle acting as a collector beam, which is supported in turn by the roof purlins acting as struts transferring the loads back to the roof cross bracing.
- Roof loads and roof cross bracing loads are transferred to the primary load resisting elements by the tension only bracing and struts in the roof plane.

3.2.2 Transverse global lateral load resisting system

In the transverse direction earthquake loads are resisted as follows.

- Earthquake loads are resisted by the steel portal frames (shown yellow), and the in-plane precast concrete panel end walls (also yellow).
- Roof loads are supported directly by the steel portal frames.

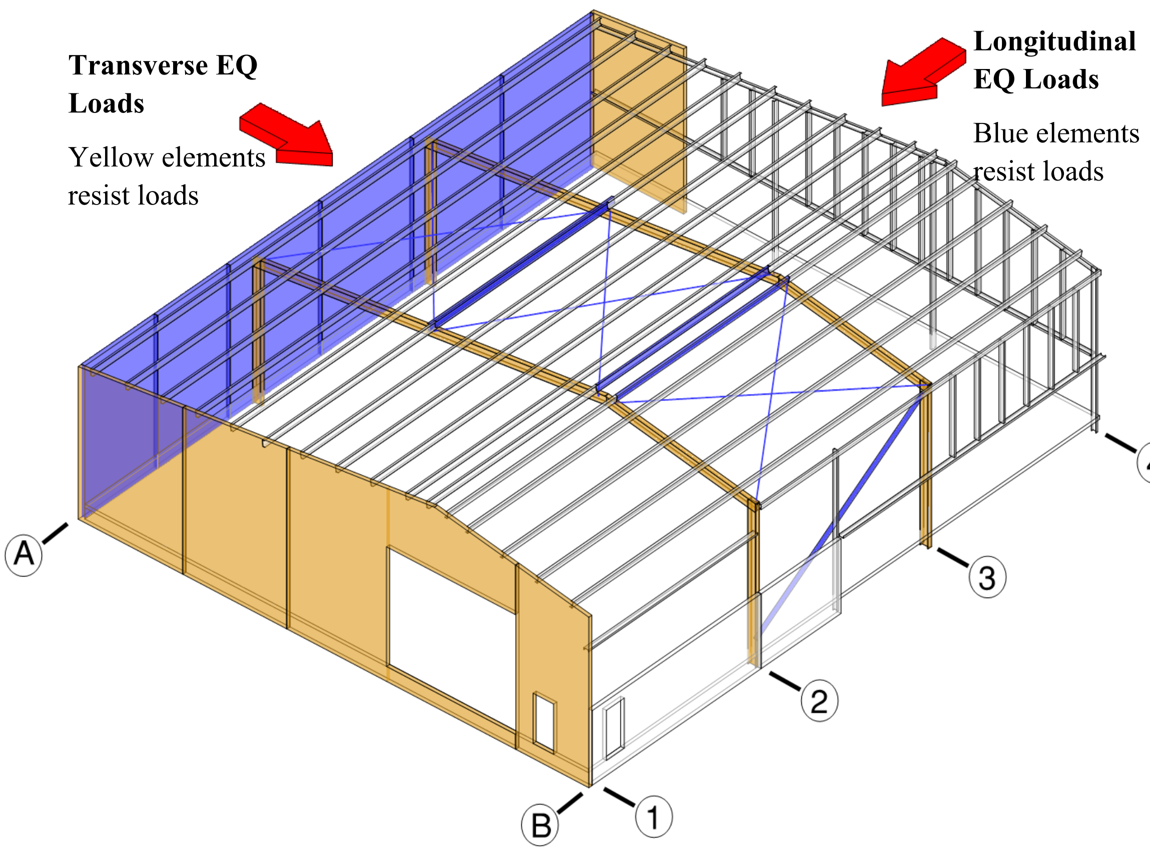

Figure 4: Global load path identification

3.3 Follow a Load Path

Having identified the global lateral load resisting system, a look at the load paths is then required. For this paper, only a selection of elements have been discussed below, however it is noted that for a proper review the load path at each change in system should be completed.

3.3.1 Longitudinal Load Paths

3.3.1.1 Grid 1 Panel out-of-plane

The load path for a precast panel on Grid 1 acting out-of-plane is to be reviewed. The panel chosen is reasonably tall and slender, with a height of approximately 7m and a thickness of 170mm.

The panels on Grid 1 span out-of-plane, from the ground to roof level. At roof level, the panel loads are transferred to the purlins which act as struts. The purlins transfer forces along their length to the portal frame rafters. The portal frame rafters must bend in the weak direction to transfer loads out to the cross-bracing struts. The roof plane tension-only bracing then transfers loads out to the side walls.

On Grid A, the load is then transferred into the precast concrete panel. The panel transfers forces in-plane to its base, where the proprietary inserts transfer forces into the slab and foundations which are then dissipated into the surrounding soils.

On Grid B, the load is then transferred into the angled tension and compression brace. The brace transfers forces to the portal frame column footing, where the footing base plate and connection transfer forces into the foundations which are then dissipated into the surrounding soils.

The above is illustrated in the figure 5 below.

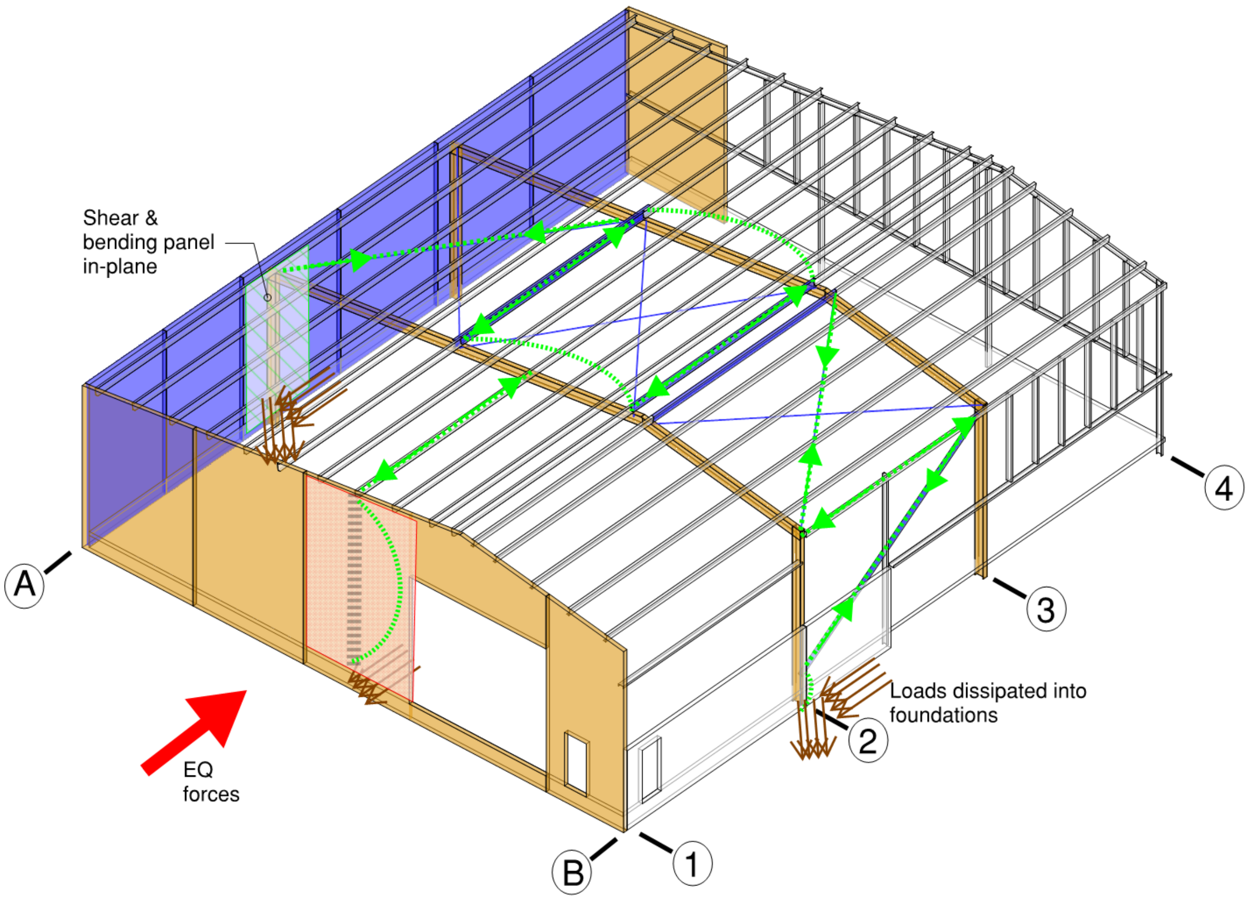

Figure 5: Load path for out-of-plane support of a precast panel on Grid 1

The flags raised when following this load path are as follows.

- The ability of the purlins to act as compression struts and in bending to support the high gable end (Grid 1) concrete panels
- Reliance on the purlins to act as strut members in the roof plane bracing system
- Reliance on weak direction bending of the portal frame rafter to transfer heavy concrete panel loads
- The tension roof bracing loads are resisted by a single panel on Grid A as there is no joint between the panels. It is unlikely that this is acceptable considering the demand on the inserts as well as the reasonably small foundations.
- The resistance available for the uplift component on the foundations when the wall brace is in tension.

3.3.2 Transverse Load Paths

3.3.2.1 Grid A Panels Out-of-Plane

In this direction one specific precast concrete panel is also reviewed. This is a precast panel on Grid A acting out-of-plane.

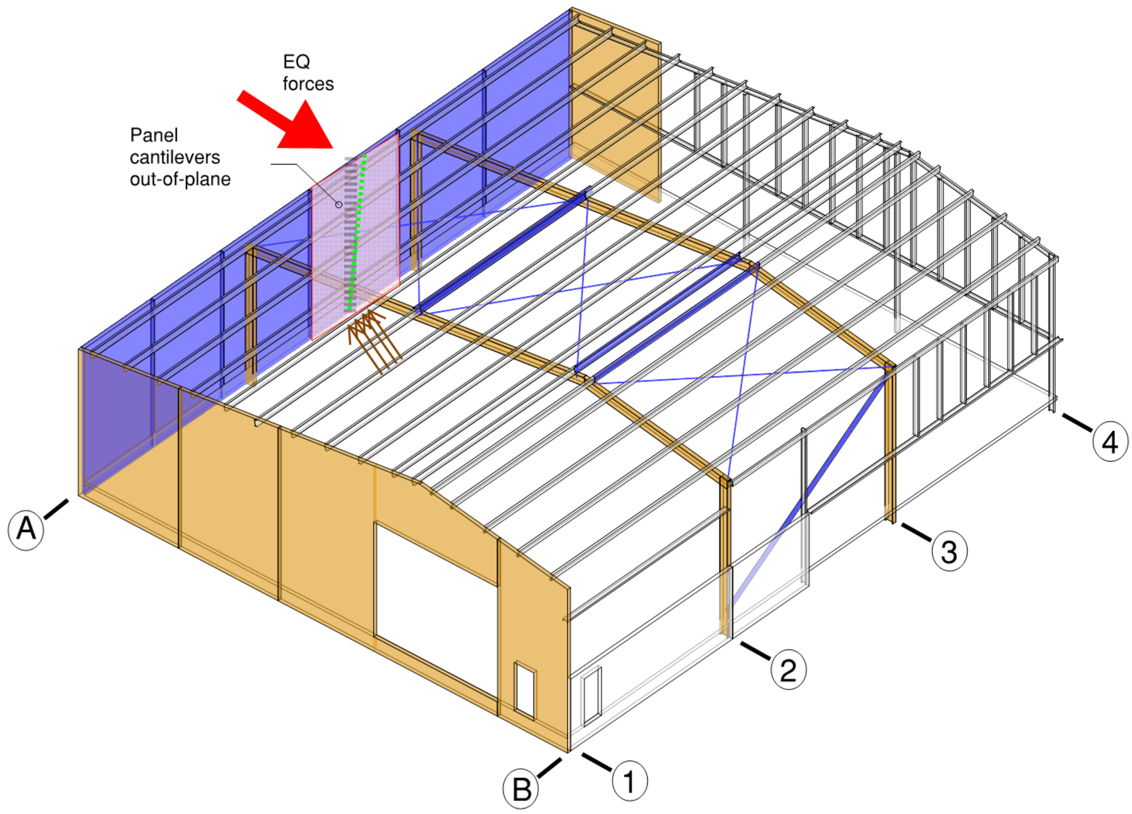

Figure 7: Load path for out-of-plane support of a precast panel on Grid A

In our global review, it was assumed that the primary load resisting system is the portal frames, and in-plane end walls on Grid 1 and 4. However, on inspection of the structural plans it is noted that there is no collector to support the panels at the top. While there are some smaller weld plates, these are nominal in size only.

This means the only available load path to resist seismic loads is via the panels cantilevering from their base.

The flags raised when following this load path are as follows.

- A 150mm thick precast panel is unlikely to be able to cantilever 6m in a high seismic zone.

3.3.2.2 Portal Frames

The portal frames span 21m and have a knee height of around 6m. The plans show a 360UB45, and a base detail that does not appear able to achieve fixity. There are no fly braces

The flags raised when following this load path are as follows.

- Excessive drift is likely with this size frame supporting heavy concrete parts
- Rafter and column segment lengths will be excessive with no lateral restraint to the bottom/inside flange when it is in compression
- The 360UB45 sections is a category 3 member (Cowie 2009), limiting the system to a nominally ductile response

3.4 Look at connections

Having identified the load paths, the next step is to focus on the connections, ie the links in the load path chain. A selection of connections is further discussed below, however each connection should be reviewed.

3.4.1 Connections for Longitudinal Load Path

There are several critical connections which need to work for this load path to act as intended.

3.4.1.1 Longitudinal connection – precast concrete panel to purlin/strut

The first connection in this load path is the connection between the precast concrete panels and the roof purlins. The detail on the plans is shown in figure 9.

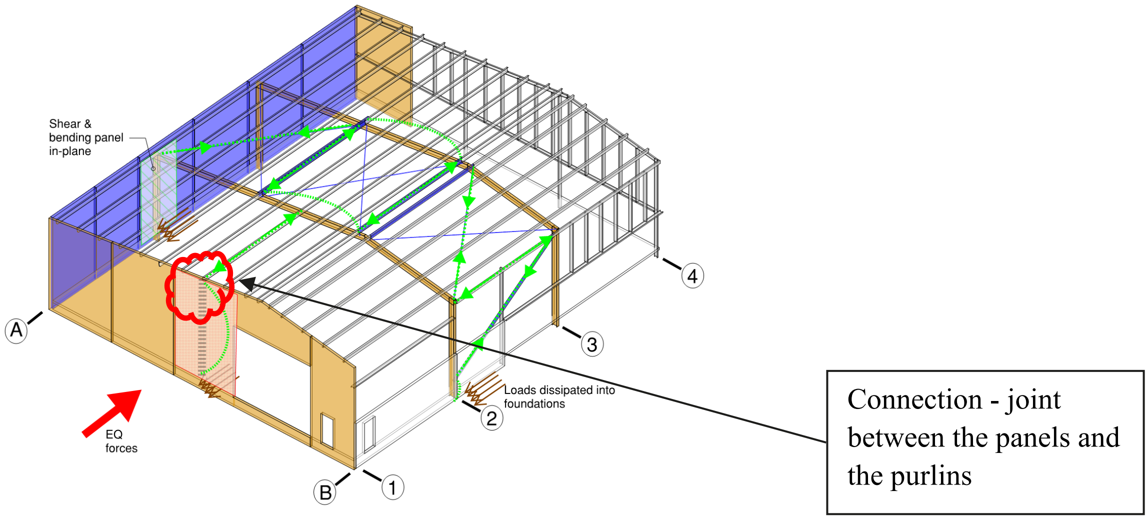

Figure 8: First connection for support of top portion of precast panels on Grid 1 out-of-plane

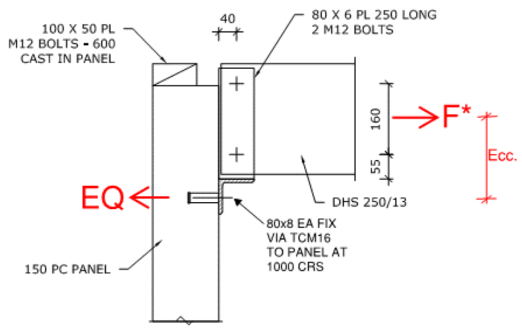

Figure 9: Connection of precast panels to strut

As can be seen, the connection has the following issues identified from a visual review. No calculations are needed to identify these deficiencies; however, calculations would be necessary to confirm the capacity of the connection.

- Highly eccentric connection
- The capacity of the bolts in the thin-walled purlin steel section will likely limit how much load can be transferred to the purlin (tear out)
- The TCM16 inserts are at 1m centres, so the EA must act in bending to transfer loads to the strut cleats
- The cleat bending and weld to the EA
- The pull-out capacity of the TCM insert, which are non-seismic rated
- Prying action at the insert

It should also be noted that this connection is relied on to transfer loads in the other direction, ie roof loads need to be transferred to the concrete panels in-plane on Grid 1. This connection is also deficient for loads in this direction.

3.4.1.2 Longitudinal connection –Purlin/strut to Portal Rafter to Tension Bracing

Another connection in this load path is the connection between the roof purlins/struts and the portal frame rafter. The detail on the plans is shown in figure 10.

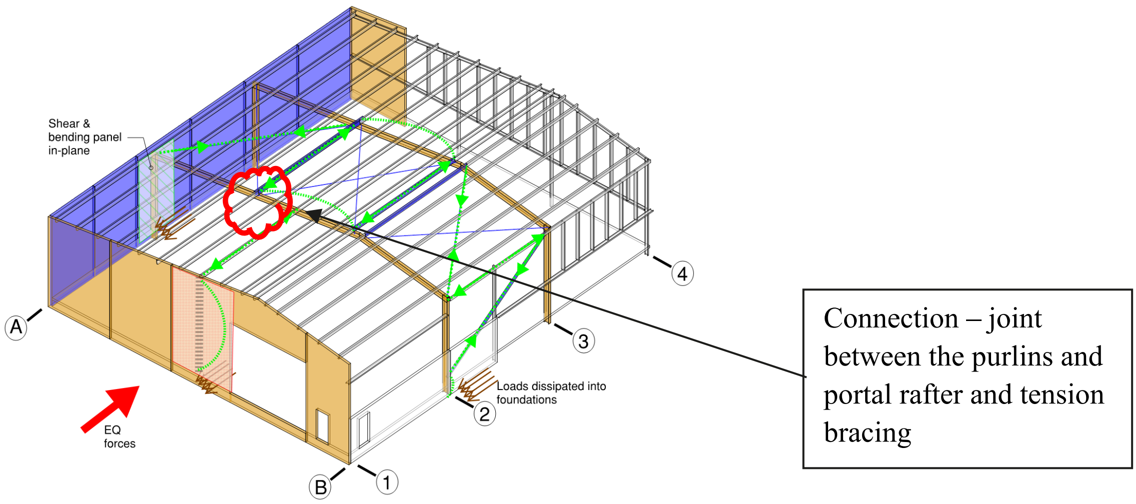

Figure 10: Location of connection under review

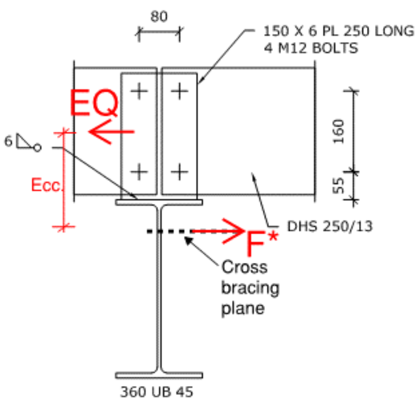

Figure 11: Section of connection of purlin struts to tension-only bracing

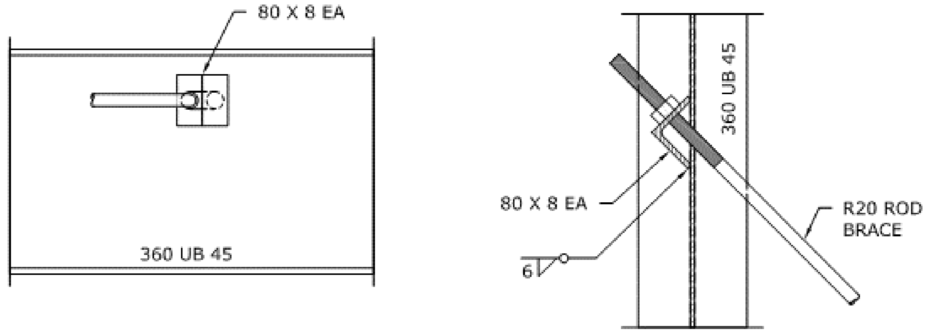

Figure 12: Extract from structural plans of connection of purlin struts to tension-only bracing

As can be seen, the connection has the following issues identified from a visual review.

- Eccentric connection with both vertical and horizontal offsets between the point of applied loads and the point of resistance.
- A reliance on indirect load path (web bending) to transfer loads
- The capacity of the bolts in the thin-walled purlin steel section will likely limit how much load can be transferred to the purlin (tear out)
- The cleat bending and connection to the UB

Structural details are for individual components (see figure 11 and 12), however when the collated load path detail is drawn the eccentricities become clearer (see figure 13).

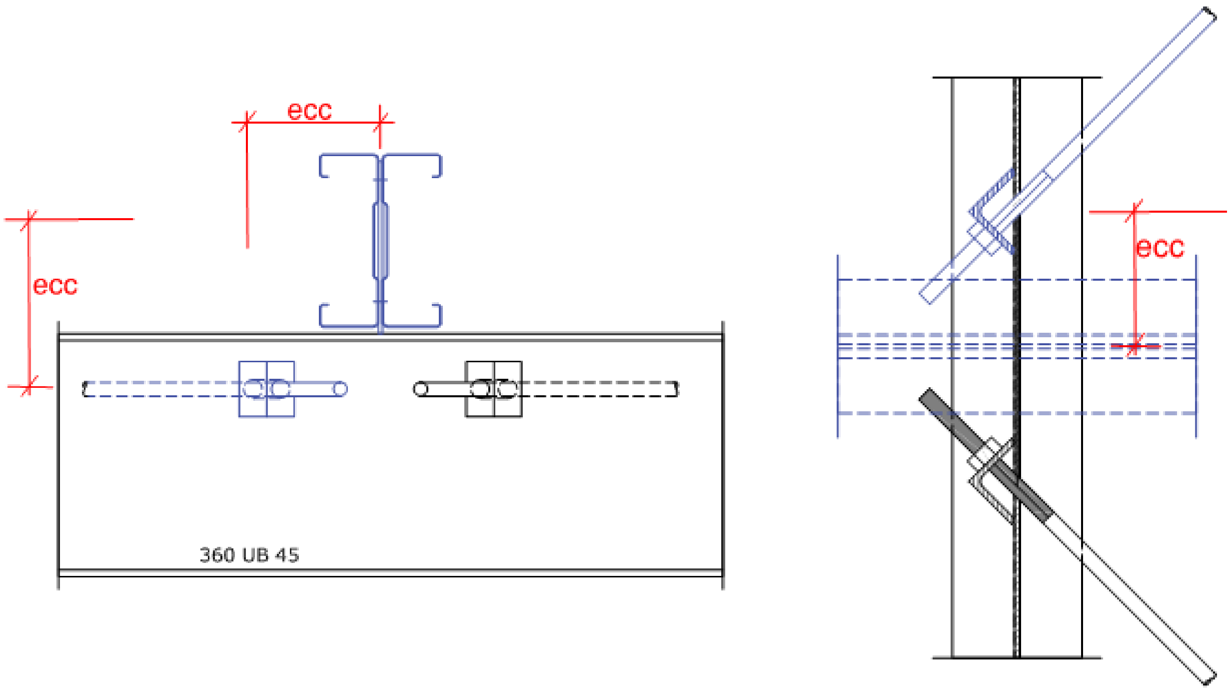

Figure 13: Completed elevated and plan view of connection of purlin struts to tension-only bracing noting eccentricities

3.4.1.3 Longitudinal connection – Tension bracing to strut

The angle tension/compression brace on Grid B is the only load path for longitudinal loads on this side. It is required to transfer reasonably substantial loads from the heavy gable end wall precast panels out-of-plane. The details provided on the plans are shown in figure 15.

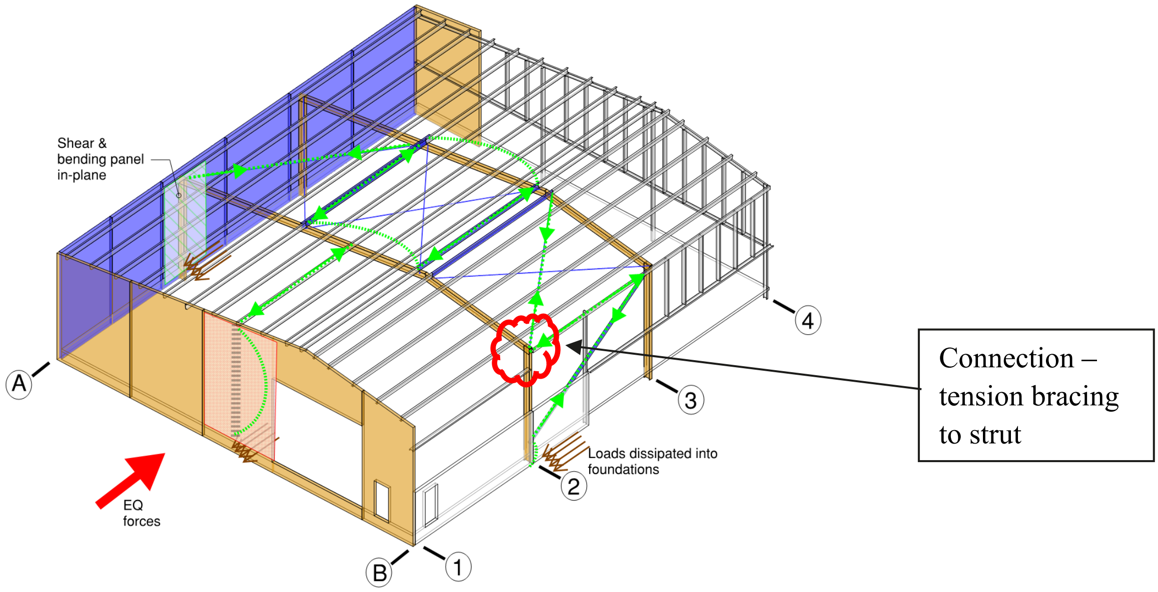

Figure 14: Location of connection under review

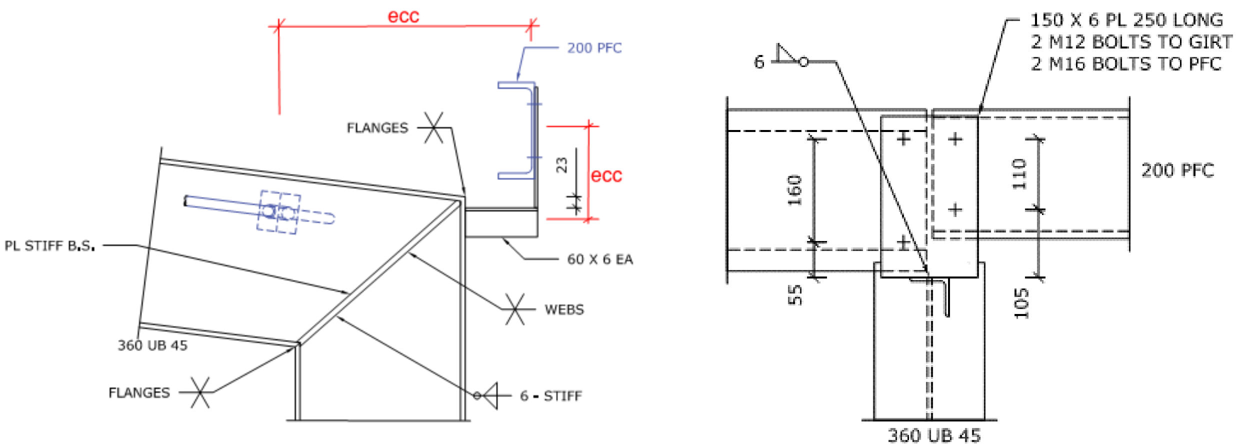

Figure 15: Connection of tension brace to strut in section (left) and elevation (right)

As can be seen, the connection is extremely eccentric and relies on multiple indirect load paths to transfer loads.

- Eccentric connection with both vertical and horizontal offsets between the point of applied loads and the point of resistance.
- A reliance on cantilever bending and torsion of a 60x6 EA stub
- Loads to be transferred through the knee joint arrangement
- M16 bolts specified, with no grade.

The poor detailing of this joint would make quantifying the joint capacity difficult.

3.4.1.4 Longitudinal connection – Strut to Angled wall brace

Assuming transfer of loads through the above connection is possible, the strut loads then need to be transferred to the angled tension/compression brace. These loads are reasonably substantial, as they include the heavy gable end wall precast panels out-of-plane. The location of this joint and the details provided on the plans are shown in figure 16 and 17.

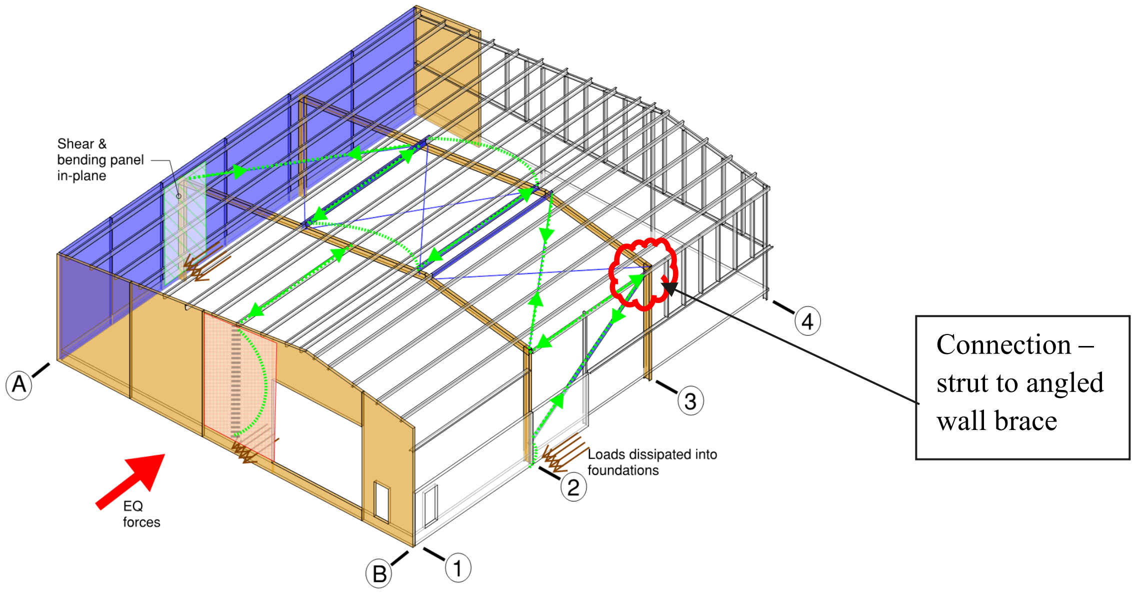

Figure 16: Location of connection under review

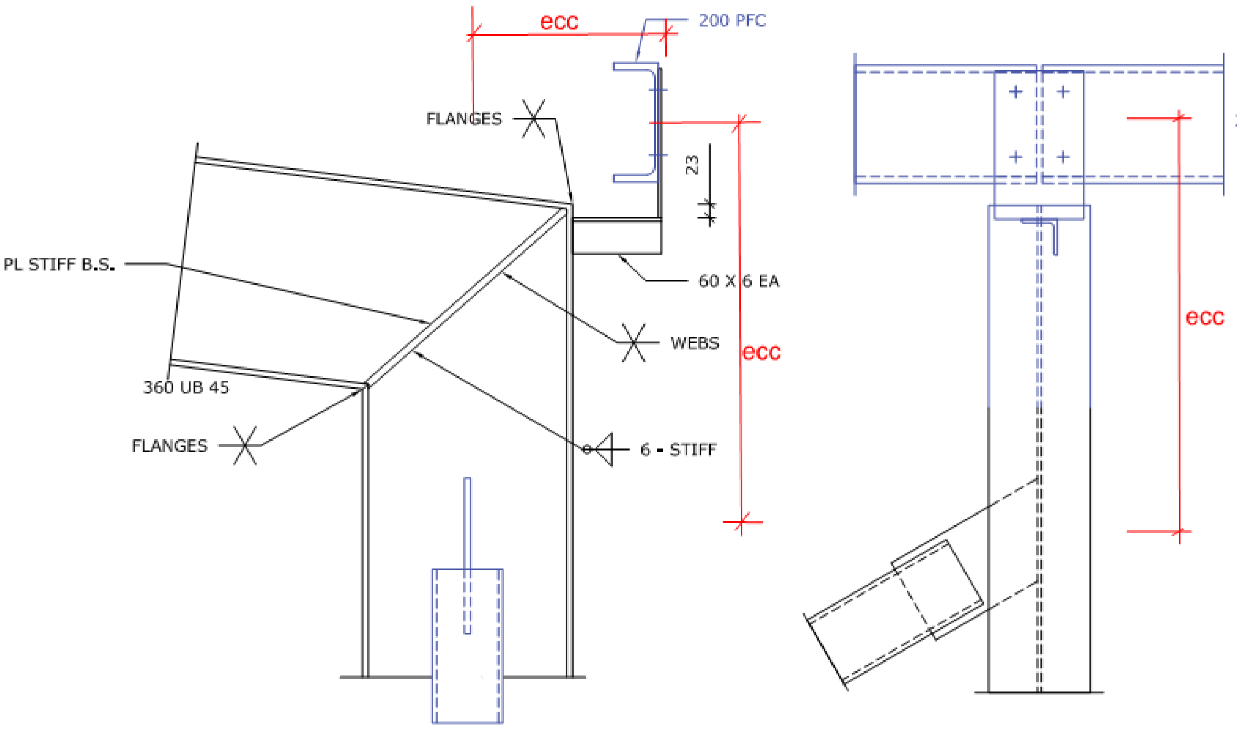

Figure 17: Connection of tension brace to strut (details from plans, blue elements added for clarity)

As can be seen, the connection is extremely eccentric and relies on multiple indirect load paths to transfer loads.

- Eccentric connection with both vertical and horizontal offsets between the point of applied loads and the point of resistance.
- A reliance on cantilever bending and torsion of a 60x6 EA stub
- Weak direction bending of the portal column
- Cleat bending and connections
- M16 bolts specified, with no grade.

The poor joint detailing makes quantifying the joint capacity difficult.

3.4.2 Connections for Typical Transverse Load Path

There are several critical connections which need to work for this load path to act as intended.

3.4.2.1 Transverse connection – precast concrete panels out-of-plane

As discussed above, there is no collector present to support the top of the precast concrete panels. Therefore, the first connection is the connection between the precast concrete panel and the footings.

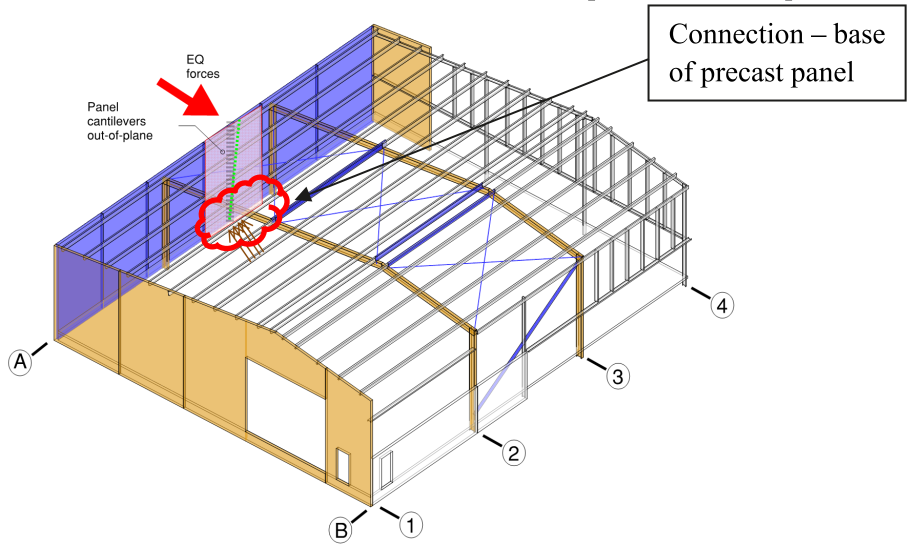

Figure 18: Location of connection under review

A review of the drawings shows that there is a proprietary insert present. An engineer would usually assume a typical proprietary panel type connection, however on closer inspection of the plans it is seen that a TCM12 insert is specified, not a RB12. These inserts are a significantly smaller threaded rod insert, as seen in the image below.

Figure 19: RB12 insert (left) and TCM12 inserts (right)

Recent research has highlighted the poor performance of this configuration of the proprietary panel insert connection, with a reliance on concrete to act in tension (Hogan 2018). This configuration of a threaded rod insert detail will fail when the panels reach reasonably low levels of drift (Hogan 2018).

A review of the reinforcing details at the footing is also needed.

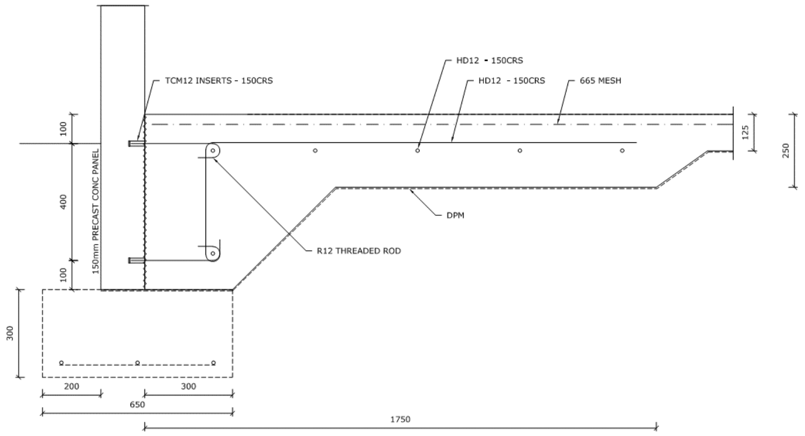

Figure 20: Connection detail at base of panels on Grid A

The detailing around the footing highlights the following concerns.

- TCM12 inserts with very shallow embedment into the precast panel
- Poor detailing with limited ability to develop the footing reinforcing
- The threaded rod is of uncertain material.
- The footing size is relatively small compared to the panel size and may not be adequate for overall stability. If the slab is required for additional capacity, the fixing between the two, particularly to transfer tension forces from the bottom footing reinforcing bar, is poor.

It should be noted that this detail is likely to be unacceptable for a post-fire stability load even once remediation of the seismic structure is completed.

3.4.2.2 Transverse connection – Portal Frame

The critical portal frame connections are the knee joint and footing base plate, and to a lesser extent the apex joint. For this example, we will review the knee joint.

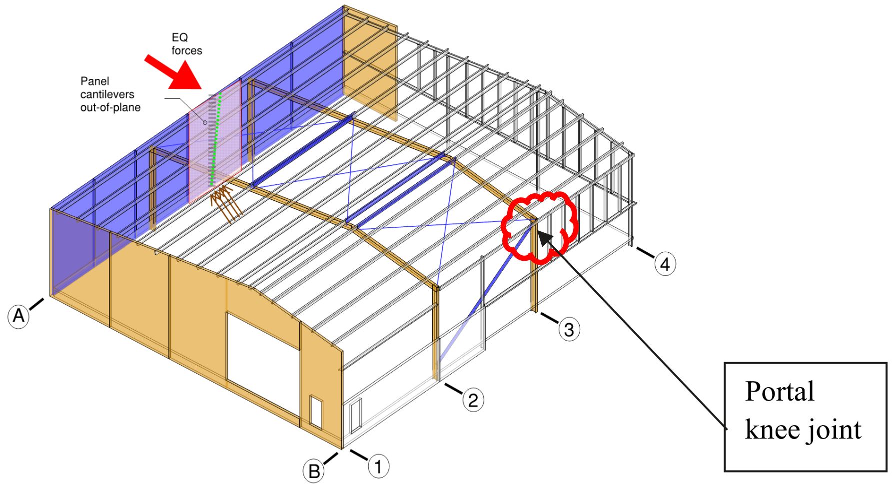

Figure 21: Location of connection under review

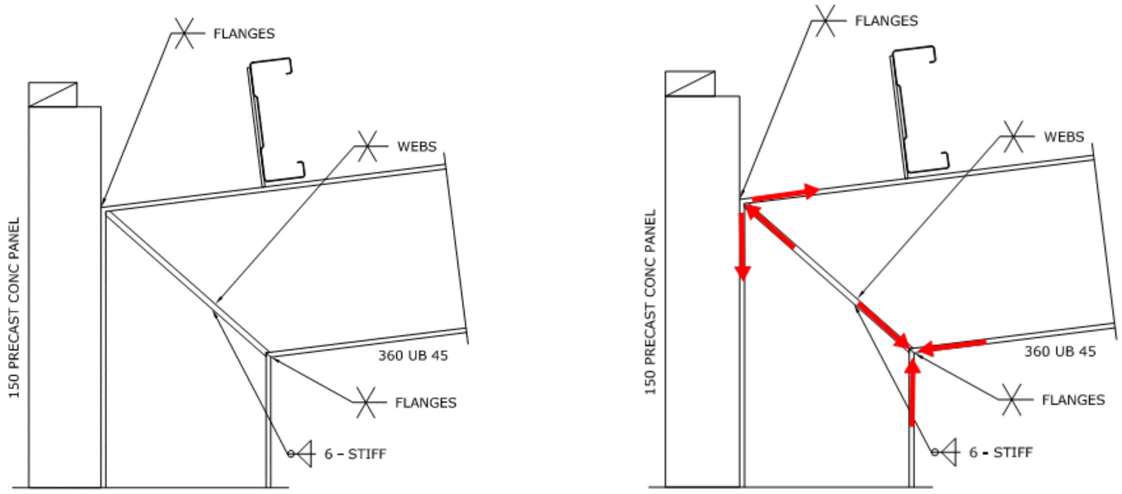

Figure 22: Connection detail at base of panels on Grid A

The detailing around the knee joint highlights the following flags.

- A 10mm Grade 250MPa plate is unlikely to resist the forces from two 9.8mm Grade 320MPa flanges
- No lateral restraint to the inside flanges of the column
- The quality of the butt weld to the flanges at an acute is difficult to achieve and may not be covered under AS/NZS5131

Basic calculations show that the knee joint capacity is significantly lower that the section capacity.

3.5 Summary of review

The review identified the following areas of the structure as deficient.

- The steel portal frames exceed drift (movement) requirements
- The steel portal frame segments do not meet strength requirements, lack of lateral restraint
- The steel portal frame knee joint does not meet strength requirements
- The roof plane bracing has indirect and eccentric load paths
- The angled wall brace and eaves strut does not meet strength requirements
- The heavy concrete panels are insufficiently tied to the structure for out-of-plane loads
- There is a mezzanine floor which has no specified bracing

4 REMEDIATION

Seismic remediation options were focused on the most economical solution, which had the least impact on the existing floor plan.

4.1 Transverse

In the transverse direction, the following options for remediation were investigated.

- Secure the out-of-plane panels by
  - Installing a new collector at the top of the precast panels, spanning between in-plane end walls and portal frames.
  - Installing a new epoxied dowel connection to secure the panel base to the footings.

- Improve the portal frames as follows.
    - Providing some base fixity with rigid connections to a new ground beam
    - Install new knee brace to reduce demand on knee joint
    - Install fly bracing to provide lateral restraint

4.2 Longitudinal

In the longitudinal direction, the following options for remediation were investigated.

- Secure the out-of-plane panels by
    - Installing new structural steel collector beams and columns and improve the connection to the roof purlins. These columns are supported at the top by new struts which connect to the new roof plane struts.
    - Install new roof plane Donobrace bracing and SHS compression struts with concentric connections
- Grid B wall bracing
    - Replace the existing eaves strut and angles brace. Members must have joints with concentric load paths, and Donobrace cross bracing
    - Provide reliable load path for the uplift demand for the new bracing
- Grid A wall bracing
    - Provide a shear connection between the in-plane panels

5 SUMMARY

The following is some common issues that are seen on these types of buildings, however we note that each building is different and there is likely to be other items worthy of more scrutiny.

- Knee joints with diagonal stiffeners
- Lack of fly bracing to rafters and columns
- Diagonal tension bracing with struts/connections which do not node
- Non-symmetrical transom members and eccentric connections at top of tall precast concrete panels, particularly gable end panels
- Reliance on DHS purlins as struts
- Shallow embedment of proprietary inserts at panel base to footing connection
- Eccentricities in connections
- Category 3 or 4 UB sections

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