# Design recommendations for concrete wall-to-steel beam bolted web plate connections

*C. Pascua*
Holmes NZ LP, New Zealand & University of Auckland, New Zealand

*R. Henry, C. Toma & C. Clifton*
University of Auckland, New Zealand.

## ABSTRACT

Buildings with mixed-material structural systems that combine concrete walls and steel frames have become increasingly prevalent in New Zealand due to their efficiency and economy. While connection detailing is recognised as critical for the performance of buildings, limited research has focused on concrete wall-steel beam connections, and guidelines on mixed-material systems and connections are lacking. To address these gaps, a study has been undertaken on concrete wall-steel beam connections, starting with a review of fifty recently constructed concrete wall-steel frame buildings in Auckland and Christchurch to understand the current state of practice. Experimental tests were conducted on four full-scale concrete wall-steel beam subassemblies to quantify the connection performance, including rotational capacity and failure modes, and to evaluate potential detailing improvements. A nonlinear numerical model was developed on OpenSeesPy to investigate the influence of connection detailing on global building response and local member demands. The building review revealed that bolted web plate connections with headed stud anchors are the most common detail used. While these connections are typically assumed to be pinned in analysis, the experimental tests demonstrated that they can generate significant moments. Concrete breakout was identified as a potential failure mode, which can be delayed using slotted holes in web plates and bent reinforcing bar anchors. Upon subjecting the numerical model to Ultimate Limit State (ULS) and Maximum Considered Earthquake (MCE) ground motions, it was found that the moments developed in the connection influenced out-of-plane actions and axial demands on concrete walls that are connected out-of-plane to steel beams. Based on these findings, design recommendations are provided for concrete wall-steel beam bolted web plate connections based on capacity design principles.

# 1 INTRODUCTION

There has been an increasing prevalence of mixed-material structural systems that combine concrete walls and steel frames in New Zealand (Bruneau and MacRae, 2017), with examples shown in Figure 1. This observation, coupled with a lack of specific design and detailing guidelines for concrete wall-steel beam connections, underscores the need for comprehensive research to ensure that these structures behave as intended during moderate to severe earthquakes. Previous research (Hou et al., 2006; Guo et al., 2018; Shahrooz et al., 2004) highlights the critical role of connections in building seismic performance, particularly in mixed-material structural systems. While limited studies have been conducted on concrete wall-steel beam connections (Roeder and Hawkins, 1981; Shahrooz et al., 2004; Guo et al., 2018; Li et al., 2003; Dai et al., 2007; Jia et al., 2013), the applicability of existing international research to the New Zealand context is uncertain due to differences in construction trends.

Furthermore, current structural design standards in New Zealand are compartmentalised by material (NZS3101:2006, 2006; NZS3404:1997/2001/2007, 1997) and do not explicitly address the design of mixed-material structural systems. While these standards provide general design provisions for mixed-material connections, detailed design guidance is severely lacking. This compartmentalisation also results in a lack of integration in design practices, with guidance documents typically developed by separate industry groups focusing on either steel or concrete. Consequently, design guidelines for concrete wall-steel beam connections are primarily based on anchorage to concrete, and no comprehensive guidance exists to address the entire design process for these connections (NZS3101:2006, 2006; ACI 318-19, 2019).

*(a) A five-storey commercial building with steel gravity frames, core and perimeter concrete walls, and an internal eccentrically-braced frame. Photo: Bruneau and MacRae (2017)*

*(b) A three-storey retail building in Christchurch with steel moment-resisting frames and perimeter walls acting as a dual system.*

*(c) A nine-storey apartment building in Auckland with concrete walls and steel gravity frames.*

*(d) A hotel building in Auckland with concrete walls and steel gravity frames.*

*Figure 1: Examples of buildings in Christchurch and Auckland using a combination of concrete walls and steel beams*

To address gaps in research and design guidelines, a study was conducted on concrete wall-steel beam connections, which comprised three phases:

1. **Building review:** A review of 50 concrete wall-steel frame buildings in Auckland and Christchurch was conducted to understand current design practices and typical connection details. These were supplemented by discussions with engineers.
2. **Experimental testing:** An experimental programme was conducted on four full-scale concrete wall-steel beam subassemblies, each incorporating variations in connection detailing. The tests were designed to quantify the rotation capacity of concrete wall-steel beam connections, identify failure modes and investigate the effectiveness of potential detailing improvements.
3. **Numerical modelling:** A numerical model of a case study building was developed on OpenSeesPy (Zhu et al., 2018), with different connection conditions assumed based on the experimental results. Nonlinear pushover and time-history analyses were conducted to evaluate the implications of different connection conditions (pinned vs non-pinned) on the global building response and local member demands.

This paper summarises key findings from each phase of the study. Synthesising all findings, design recommendations are proposed for concrete wall-steel beam connections based on capacity design principles.

## 2 BUILDING REVIEW

The building review (Pascua, Henry and Toma, 2023) provided insights on the current state of practice of concrete wall-steel frame buildings in New Zealand. Key observations included:

- New Zealand buildings are different from the design practice of concrete wall-steel frame buildings in other countries, which are typically high-rise, comprising concrete core walls and perimeter steel gravity frames. Instead, New Zealand buildings tend to be low- or mid-rise, with a broader variety of wall configurations (e.g. core, perimeter, interior) and steel framing systems (e.g. moment-resting, eccentrically-braced, concentrically-braced, gravity).
- A wide variety of connection detailing was observed during the building review, further highlighting the lack of design guidance to achieve a consistent approach. Nevertheless, it was found that bolted web plate connections with headed studs, as shown in Figure 2, were the most common connection detail used. While these connections are typically idealised as pinned during design, research on steel framing systems has shown that these connections can develop significant stiffness and moment resistance when subjected to large rotations. Similar behaviour could arise in concrete wall-steel beam connections.
- Common design variations for bolted web plate connections include the use of floor starters, slotted holes in the web plate and different types of anchorage to the wall. New Zealand engineers also use a range of design guidelines to design connection detailing, emphasising the necessity to establish clear and consistent design guidelines for commonly used concrete wall-steel beam connections.

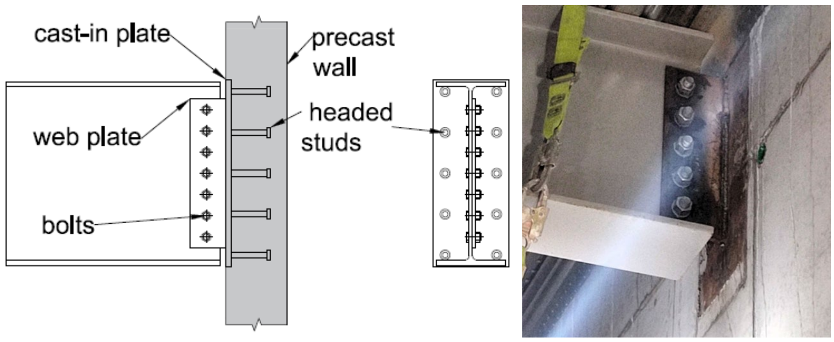


*Figure 2: Concrete wall-steel beam bolted web plate connection.*

## 3 EXPERIMENTAL TESTING

The experimental tests (Pascua, Henry, Toma, et al., 2023) provided a detailed understanding of the seismic performance of concrete wall-steel beam bolted web plate connections, with key findings as follows:

- Concrete wall-steel beam bolted web plate connections designed using current design standards and following existing practices in New Zealand are vulnerable to non-ductile failure characterised by concrete breakout, as shown in Figure 3. Excessive connection slip was observed in the test specimens, raising concerns about the gravity load capacity of damaged connections in buildings.
- The rotational stiffness of concrete wall-steel beam bolted web plate connections at lower rotations is primarily attributed to a combination of bolt slippage and bolt hole elongation due to localised yielding. Wall deformation due to the imposed actions can also contribute to the total connection deformation at higher rotations.
- Adding a floor slab with continuity reinforcement increased the stiffness and moments that developed at the connection. The inclusion of the floor shifted the centre of rotation of the connection from the mid-height of the beam to the floor level and caused a significant reduction in connection rotation capacity.
- The tests successfully demonstrated strategies to enhance connection rotation capacity and ductility. Slotted holes allow for more bolt slippage, resulting in higher flexibility and increased rotational capacity. However, once the bolts began bearing on the web plate, the connection stiffened and imposed greater demands on the wall.
- Using bent reinforcing bar anchors into the wall increased the concrete breakout strength, allowing larger wall deformations prior to failure, thus increasing rotation capacity. The lower reinforcement tensile strength of the bent reinforcing bars compared to the headed studs allowed them to yield prior to concrete breakout, resulting in increased ductility and rotation capacity. While using bent reinforcing bar anchors did not alter the eventual concrete breakout failure mode, it prevented sudden connection slip even after failure and slightly increased the concrete breakout area.

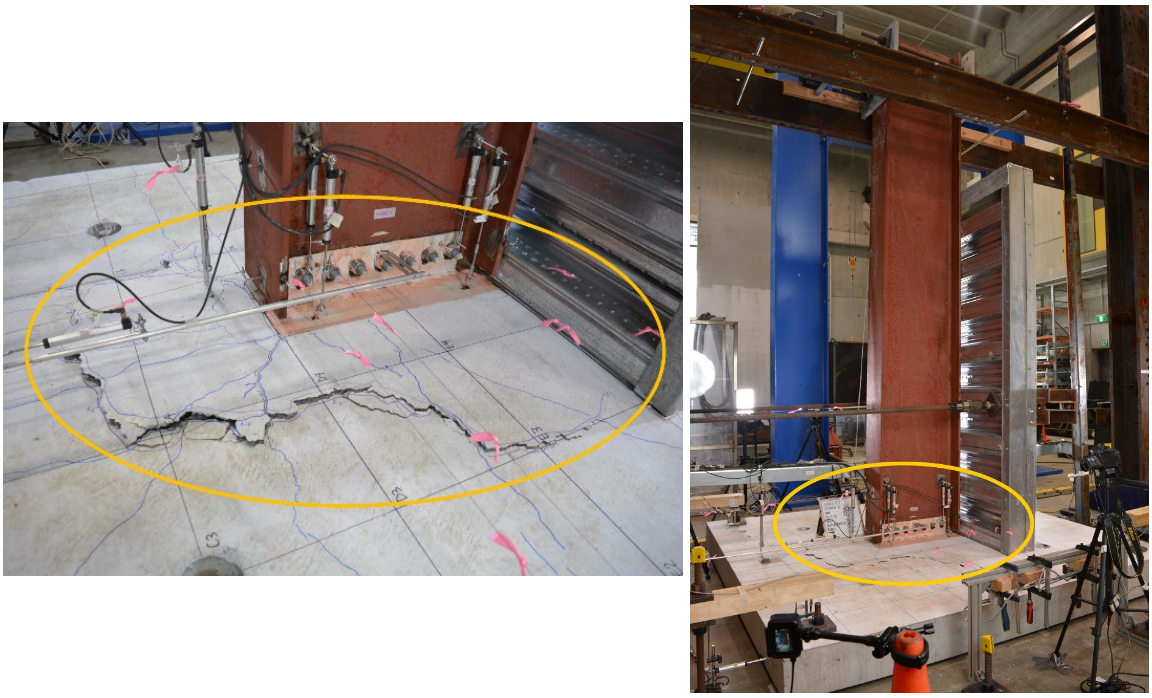

*Figure 3: Concrete breakout failure in one of the test specimens*
*NOTE: Test subassemblies were rotated 90° (i.e. the wall was horizontal and the beam vertical)*

# 4 NUMERICAL MODELLING

Nonlinear modelling of a case study building informed by the connection experimental data, combined with parametric analyses, demonstrated the influence of connection conditions on the global building response and local member demands. The key findings are summarised below:

- Changing the concrete wall-steel beam connection conditions assumed during analysis from pinned to non-pinned does not significantly affect the global building response nor local demands on lateral load-resisting elements. However, doing so generates significant overstrength moments at the connections that induce different actions on the concrete walls connected out-of-plane to steel beams. This results in a significant increase in out-of-plane shear force and bending moment demands, and variations in axial demands.
- Concrete breakout failure occurred in the concrete wall-steel beam bolted web plate connections with round holes and headed stud anchors when the building was subjected to ULS and MCE ground motions. Prior to breakout failure, full overstrength moments were induced on the concrete walls.
- Concrete breakout is less likely to occur during ULS ground motions if the connection anchorage is changed from headed studs to bent reinforcing bar anchors, although concrete breakout failures are still possible in more flexible buildings. At both ULS and MCE ground motions, moments close to full overstrength may still develop at the connections.
- Using slotted holes in concrete wall-steel beam bolted web plate connections can further reduce the likelihood of concrete breakout failure when subjected to ULS ground motions—more significantly than connections that use bent reinforcing bar anchors. Even in flexible buildings, ULS ground motions are not likely to result in concrete breakout failure of the connections. During MCE ground motions, concrete breakout can be prevented by using slotted holes, but this might be more challenging to achieve in flexible buildings. Using slotted holes also reduces the overstrength moments induced by the connections on the concrete walls, particularly during ULS ground motions.

# 5 DESIGN RECOMMENDATIONS

## 5.1 Strength hierarchy for concrete wall-steel beam connections

As demonstrated by the experimental tests, concrete wall-steel beam connections designed using current design standards and following existing practices are vulnerable to non-ductile failure characterised by concrete breakout. The excessive connection slip resulting from concrete breakout also poses concerns about the gravity load capacity after damage has occurred. Implementing a capacity design approach with a suitable hierarchy of failure modes is necessary to suppress these undesirable connection failure modes and ensure a reliable ductile response with sufficient margin to collapse.

A capacity design approach requires first identifying the desired yielding element or inelastic mechanism. The desirable failure modes for concrete wall-steel beam connections are thus listed below in order of preference:

1. Yielding of the connection web plate
2. Yielding of the steel anchors

Meanwhile, the following failure modes should be suppressed due to their brittle and sudden nature:

- Bolt shearing
- Weld fracture
- Concrete breakout

- Steel anchor fracture
- Anchor pullout
- Concrete side-face blowout
- Concrete pryout

### 5.1.1 Yielding of the connection web plate

Yielding of the web plate can provide a desirable ductile response to protect the connection from brittle failure modes (Hyland et al., 2008; Shahrooz et al., 2004). Another advantage of using the web plate as the yielding element and controlling failure mechanism is that the web plate can be more easily repaired or replaced after damage compared to other components. To ensure that the web plate yields prior to the occurrence of other potentially brittle failure modes in the anchor group, the capacity design procedure suggested by Shahrooz et al. (2004) can be used. This is in addition to using the Steel Construction New Zealand guidelines (Hyland et al., 2008) that aim to prevent brittle failure modes in the bolted web plate.

Under certain conditions, the Shahrooz et al. (2004) procedure may lead to impractically thin web plates that could be susceptible to buckling. For instance, when the concrete wall thickness limits the anchor embedment length, resulting in low concrete breakout capacity. Ideally, the wall thickness would be increased to improve the anchorage strength and maintain the desired strength hierarchy, but this may not be practical given other design constraints. In such cases, there are two other ways to increase the concrete breakout capacity, as follows:

1. Experimental tests conducted by Shahrooz et al. (2004) show that placing concrete wall-steel beam connections within confined boundary elements can increase the concrete breakout capacity.
2. The Concrete Capacity Design method by Eligehausen et al. (2006), adopted in ACI 318-19 (2019), recommends using supplementary reinforcement to improve concrete breakout capacity.

### 5.1.2 Yielding of the steel anchors

Ductile steel anchors with well-defined yield responses can be used instead of headed studs to allow yielding of the anchors to precede concrete breakout. As found in the experimental tests, using bent reinforcing bar anchors instead of headed studs can increase the connection rotational capacity through yielding and allowing larger wall deformations prior to concrete breakout. Therefore, if the reinforcing anchorage is sufficient, it may be possible to rely on the yielding of the anchor reinforcing at the wall face as the primary yielding mechanism for the connection. However, it must be ensured that brittle failure modes in the anchorage, such as weld fracture, are still prevented. Further research may be required to investigate this solution when yielding the web plate is impractical.

## 5.2 Overstrength moment capacity

Per the recommended capacity design approach, the overstrength moment capacity of the concrete wall-steel beam joints should be considered when assessing the design actions acting on the wall. Numerical modelling results indicate that full overstrength moments may or may not develop at the connection when slotted holes are used. Nevertheless, it is recommended to apply full overstrength moments unless it can be proven that connection rotation demands are sufficiently low to prevent the development of full overstrength moments for demands exceeding ULS.

A proposed procedure for calculating the overstrength moment capacity of the connection is summarised below:

1. Calculate the resistance of a single bolt element in shear. Assuming that all of the web plate bolts contribute to the bending resistance, calculate their total tensile capacity, $T$.

2. Calculate the maximum feasible capacity of the concrete floor slab in compression using Equation 1 below:

$$C = 0.85\, f'_c\, b_{eff}\, a \quad (1)$$

where $a$ is the effective depth of the slab above the steel deck ribs. When the deck is parallel to the web plate and the beam, the effective depth is equal to the full depth above the steel deck ribs, $r$. On the other hand, if the deck is perpendicular to the web plate, the effective depth is taken as $0.6 \cdot r$. The effective width of the compression block $b_{eff}$ is taken as the effective flange width for flexural overstrength calculations of beams, in accordance with NZS3101:2006 (2006).

3. The smaller of $C$ or $T$ will govern the overstrength moment capacity. Assuming there is no external axial force acting on the connection, then $C$ should equal $T$. If tension controls, find the compression block depth $a$ that will satisfy equilibrium. If compression controls, select fewer bolt elements to generate the tension force at overstrength.
4. Calculate the positive overstrength moment $M_{pos}$ (i.e. when the slab is in compression), where the moment arm is measured from the centroid of the bolts and the centroid of the slab in compression.
5. Calculate the negative moment capacity as $M_{neg} = 1.1 \cdot M_{pos}$.

### 5.3 Detailing recommendations

The experimental tests demonstrated that using web plates with slotted holes is an effective way to provide connection rotational capacity by allowing bolt slippage. In one of the tests, slotted holes in the web plate were designed to accommodate up to 3% rotation, which aligns with recommendations in the Steel Construction New Zealand guidelines (Hyland et al., 2008) for steel-to-steel frame connections. Results from numerical modelling indicated that allowing for up to 3% connection rotation reduces the likelihood of concrete breakout, even at MCE ground motions. Given these findings, it is recommended that a slotted hole be used with sufficient length to permit restoration beyond MCE. As discussed above, a capacity design approach should still be used to ensure a ductile web plate yielding failure controls after the slot travel has been exceeded.

The tests also showed that using ductile bent reinforcing bar anchors into the wall increased the concrete breakout strength, allowing larger wall deformations prior to failure, thus increasing rotation capacity. The lower reinforcement tensile strength of the bent reinforcing bars compared to the headed studs allowed them to yield prior to concrete breakout, resulting in increased ductility and rotation capacity. Even when the connection is capacity designed to ensure that web plate yielding controls, the use of ductile anchor bars provides a robust secondary yielding mechanism and is thus recommended for all concrete wall-steel beam bolted web plate connections.

## 6 SUMMARY

In this study, design recommendations based on capacity design principles were developed for concrete wall-steel beam bolted web plate connections, drawing on findings from experimental tests and numerical modelling.

- Experimental tests demonstrated that existing concrete wall-steel beam bolted web plate connections are susceptible to non-ductile failure modes characterised by concrete breakout, which can be delayed by using slotted holes in the web plate or replacing headed studs with bent reinforcing bar anchors. Given these findings, a strength hierarchy was recommended, prioritising a ductile failure mechanism (e.g., web plate yielding or yielding of the steel anchors) while suppressing brittle ones (e.g., concrete breakout, bolt shearing and weld fracture, etc.)

- While bolted web plate connections are typically idealised as pinned during analysis for design, experimental tests demonstrated that they could generate significant moment resistance. Numerical modelling results indicated that the moments generated in concrete wall-steel beam connections result in additional out-of-plane shear and bending moment demands on the walls, and variations in axial demands. As such, a procedure for estimating the overstrength moment capacity of the concrete wall-steel beam joints is proposed, which should be considered when assessing the design actions acting on the wall.
- Although using slotted holes and ductile bent reinforcing bar anchors did not suppress the eventual concrete breakout in the tests, both can contribute to higher connection rotational capacity. When implemented alongside the capacity design procedure, slotted holes and ductile anchors provide added robustness to the connections and are recommended in the design of all concrete wall-steel beam bolted web plate connections.

## 7 ACKNOWLEDGEMENTS

This research was funded by the University of Auckland Doctoral Scholarship, Te Hiranga Rū QuakeCoRE– a New Zealand Tertiary Education Commission-funded Centre and The Kate Edger Educational Charitable Trust. The authors would also like to acknowledge Auckland Council, Christchurch City Council, Andrew Thompson, Tim Shannon, Jamaledin Borzouie, Cameron MacPherson, Chris Hurst, Andrew Clarke, Hsen-Han Khoo, Karl Dawe, and Andrew Gaul for their assistance and inputs during the study, Steel & Tube Composite Floor Decks Limited New Zealand for their donation, and Dr. Max Stephens for his assistance in numerical modelling.

## 8 REFERENCES

ACI (American Concrete Institute) (2019). ACI 318-19 Building Code Requirements for Structural Concrete and Commentary. American Concrete Institute.

Bruneau M, MacRae GA (2017). Reconstructing Christchurch: a seismic shift in building structural systems. *The Quake Centre, University of Canterbury*.

Dai SB, Huang J, Zhang LQ, Zhu J (2007). Research on mechanical performance of high strength bolt connection joint between steel beam and concrete wall. *Wuhan Ligong Daxue Xuebao/Journal of Wuhan University of Technology* 29:103–107.

Eligehausen R, Mallée R, Silva JF (2006). Anchorage in concrete construction. Berlin: Ernst & Sohn.

Guo K, Yao M, Zhang B, Li Xuan, Hu Xiamin (2018). Calculation of initial rotational stiffness of single plate shear joints connecting steel beam and RC column. *Gong ye jian zhu* 48:173–178.

Hou G, Chen B, Miao Q, Liu X, Huang J (2006). Design and research on composite steel and concrete frame-core wall structure. *Jianzhu Jiegou Xuebao/Journal of Building Structures* 27:1–9.

Hyland C, Cowie K, Clifton C (2008). Structural steelwork connections guide. Manukau City.

Jia L, Liu X, Chen Y, Zhao W (2013). Effect on mechanical performance of non-planar joints between steel beam and concrete wall. *Shenyang Jianzhu Daxue Xuebao (Ziran Kexue Ban)/Journal of Shenyang Jianzhu University (Natural Science)* 29:998–1005.

Li G, Qu B, Sun F, Ho GWM, Kwok MKY (2003). Cyclic loading tests of steel beam to concrete wall joints in steel-concrete mixed structures. *Journal of Building Structures* 24:1–7.

NZS3101:2006 (2006). NZS3101: Concrete structures standard Part 1: The design of concrete structures. Wellington: Standards New Zealand.

NZS3404:1997/2001/2007 (1997). NZS3404: Steel structures standard Part 1. Wellington: Standards New Zealand.

Pascua C, Henry R, Toma C (2023). Review of recently constructed concrete wall-steel frame hybrid buildings. *Bulletin of the New Zealand Society for Earthquake Engineering*.

Pascua C, Henry R, Toma C, Clifton C (2023). Experimental Tests on Concrete Wall-Steel Beam Connections. In A Ilki, D Çavunt, and YS Çavunt, editors *Building for the Future: Durable, Sustainable, Resilient*. Lecture Notes in Civil Engineering. Cham: Springer Nature Switzerland, pp. 1712–1721.

Roeder CWW, Hawkins NM (1981). Connections Between Steel Frames and Concrete Walls.pdf. *Engineering Journal / American Institute of Steel Construction* 18:22–29.

Shahrooz BM, Deason JT, Tunc G (2004). Outrigger Beam–Wall Connections. I: Component Testing and Development of Design Model. *Journal of Structural Engineering* 130:253–261.

Zhu M, McKenna F, Scott MH (2018). OpenSeesPy: Python library for the OpenSees finite element framework. *SoftwareX* 7:6–11.