Engineering New Zealand Te Ao Rangahau

Warehouse design
Module 3: Transverse Load resisting system

December 2025

Purpose

This guide presents a principle-led approach to designing robust steel portal-frame warehouses using behaviour-led methodology. It is not a design manual and does not replace Standards – engineers must independently select and apply relevant Standards for their projects.

Philosophy

Following Nigel Priestley's teachings, the approach emphasises well-tied buildings with clear load paths, positive restraint and deliberate strength hierarchy over prescriptive code mechanics. Multiple philosophies work effectively when properly detailed, including:

- elastic and nominally ductile frames perform well with clear force paths and connections, avoiding brittle triggers
- capacity-designed frames requiring disciplined detailing to achieve intended hinge mechanisms.

In practice, many portal-frame designs are nominally ductile or elastic seismic load resisting systems (SLRs) because deflection control drives the design. The guide covers elastic, nominally ductile and limited-ductile portal frames from a behaviour-first perspective.

Core design principles

Choose the lowest ductility demand while meeting architectural and serviceability requirements, then ensure the core design principles are followed.

Successful structural design relies on five fundamental principles for structures resisting significant loads, particularly dynamic or impact actions.

When one of those principles is ignored or overlooked, it can lead to structural failure.

1. **Define the load**
   Accurately determine all loads the structure will experience, including:
   - nature (static, dynamic, impact)
   - magnitude
   - application point.

   Use loading standards (Verification Method) or a specific risk assessment (Alternative Solution) to define the loads. A clear definition of the load is essential for all subsequent steps.

2. **Establish a continuous load path**
   Design a complete path from the load application through structural members and connections to the ground. Every component must be identified and designed as an integrated system. Any weak link compromises the entire structure.

3. **Consider load distribution and stiffness**
   Structural elements deform under load, with stiffer elements attracting more force. Ensure member and connection stiffness are compatible to prevent unintended force concentrations on brittle components. Consider how the deflection of one element affects the forces transferred to the next.

4. **Verify capacity**
   Every member and connection must have sufficient capacity to resist expected forces. Check all failure modes: bending, shear, tension and buckling. Calculated demand must be less than the design capacity, with appropriate safety factors applied. Connections require careful detailing for constructability and force transfer.

5. **Design for gradual failure**
   Ensure predictable, gradual failure under extreme overload rather than a sudden collapse. Achieve this through overstrength principles, material selection and connection detailing. Design specific elements to yield in a controlled way whilst protecting overall system integrity and prioritising safety.

Transverse bracing load-resisting system

In single-storey warehouse structures, the transverse wind and seismic resistance is typically provided by moment-resisting steel portal frames. These frames must be configured and detailed to form a reliable and predictable lateral load-resisting system. Each component (including the rafters, knees, portal legs, and their foundations) plays a critical role in ensuring structural integrity during an earthquake.

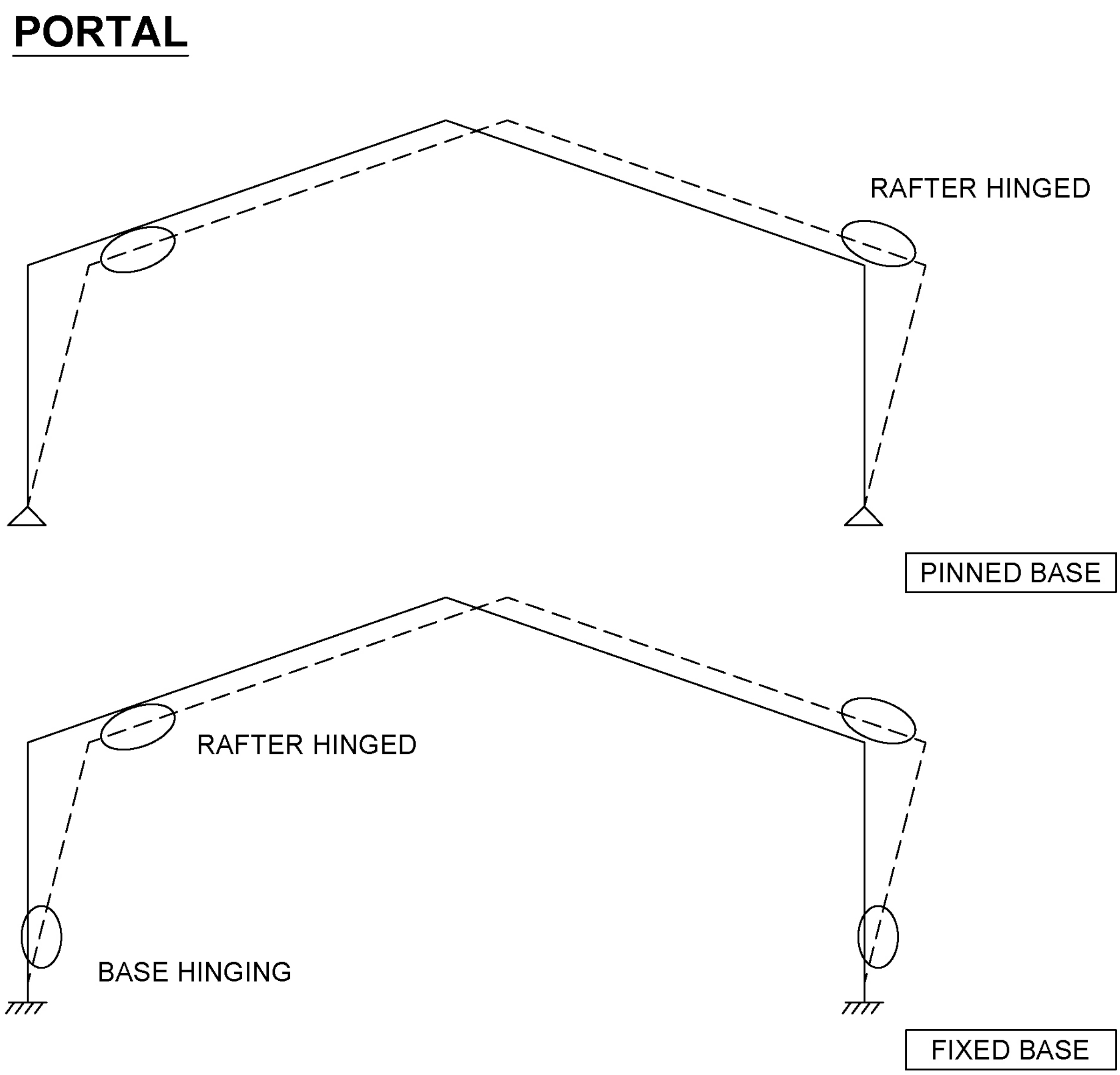
This document gives an overview of the concepts for each component. More details will be provided in the upcoming modules.

MODULE	CONTENTS
5 – Knee joints and buckling	• Hinge protection strategies • Lateral restraint methods • Stiffener design • Capacity design concept and example
6 – Base plates	• Capacity design • Uplift and sliding resistance • Anchor performance • Strut and tie example for foundation beam stirrups
7 – Concrete panels	• Structural vs. architectural elements • Reinforcement continuity • Out-of-plane stability • Connections
8 – Collector elements	• Collector identification • Capacity verification • Eccentricity mitigation • Fasteners • Connections

Portal frames

Portal frames are the main stabilising elements in the building's transverse direction. It usually consists of two vertical portal legs connected by a sloping or pitched rafter. The size, layout and spacing of portal frames must be selected to meet the requirements of strength, stiffness and displacement.

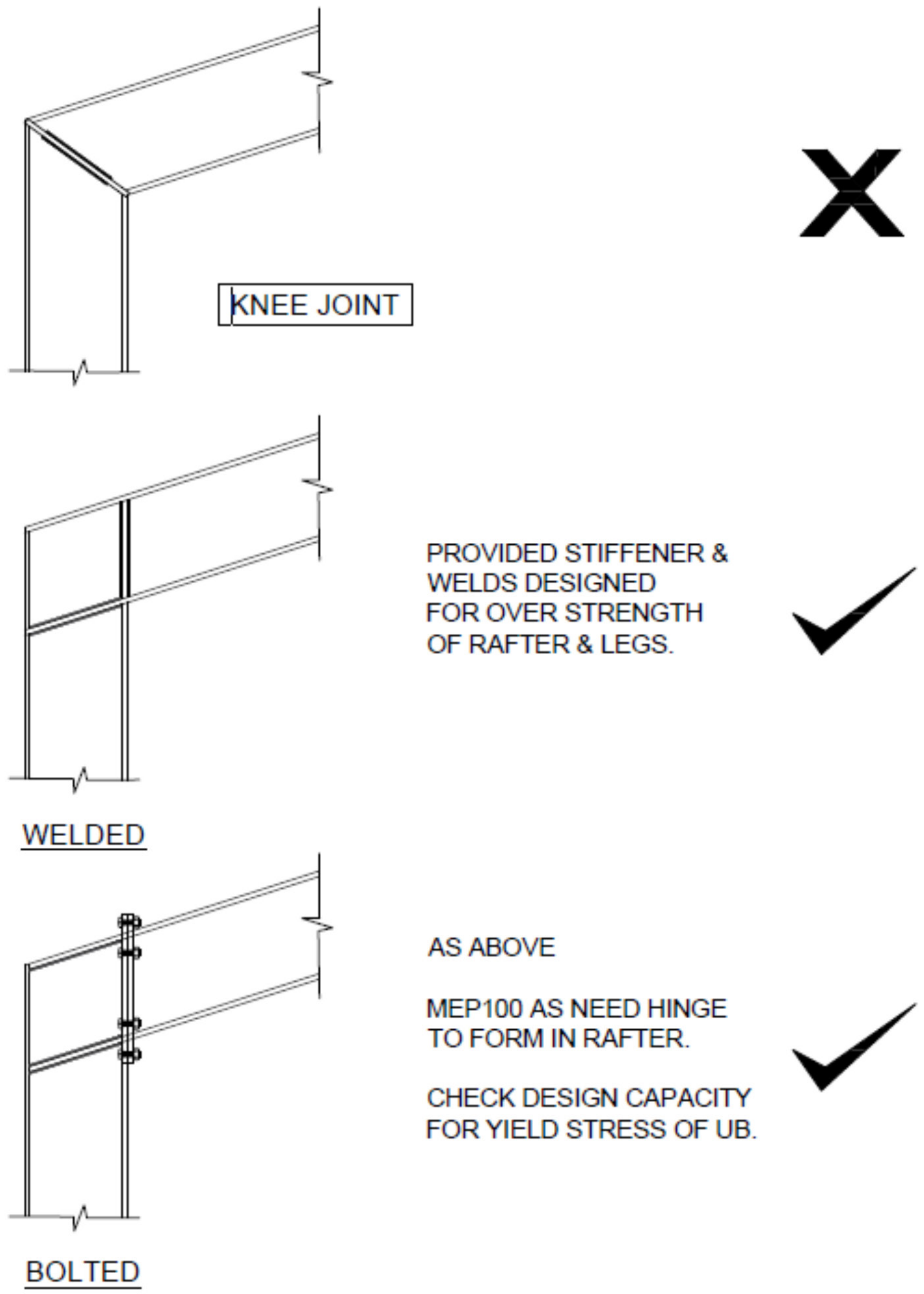
- Portal frames resist wind and seismic loads across the building's short direction and act as the primary lateral load-resisting system in the transverse direction.
- The sway mechanism must be clearly defined – with plastic hinges designed to form at the knee joints and possibly at the base.
- Member sizes and joints outside hinge zones should be designed to be stronger than, or with overstrength, to remain elastic and preserve the intended mechanism.
- Frame stiffness affects displacements – so span, height and spacing must be balanced to control lateral displacement.
- All connection details, including knee joints and base plates, must support the assumed overstrength capacity and allow for cyclic deformation.



Portal knee design

The portal knee is a critical connection zone between the rafter and the column in a steel portal frame. Its primary role is to transfer lateral moment and shear without yielding, ensuring the plastic hinge forms in the adjacent rafter. Correct detailing and strength hierarchy at the knee are essential for maintaining structural integrity and achieving a predictable response.

- Design the knee joint with sufficient strength and stiffness so that it does not become the critical failure location.
- The rafter adjacent to the knee must be the system's weakest and most ductile part. Similarly, the column should be designed for ductility or overstrength.
- Use moment-resisting end plate connections or full-strength welds that exceed the rafter's plastic moment capacity.
- Reinforce flange and web zones to prevent local yielding or instability under high seismic moments. Remember to check the yield stress of the members as they are not all the nominal 300 MPa.
- Ensure your analysis model matches your detailing, especially hinge location, joint stiffness and bracing assumptions.

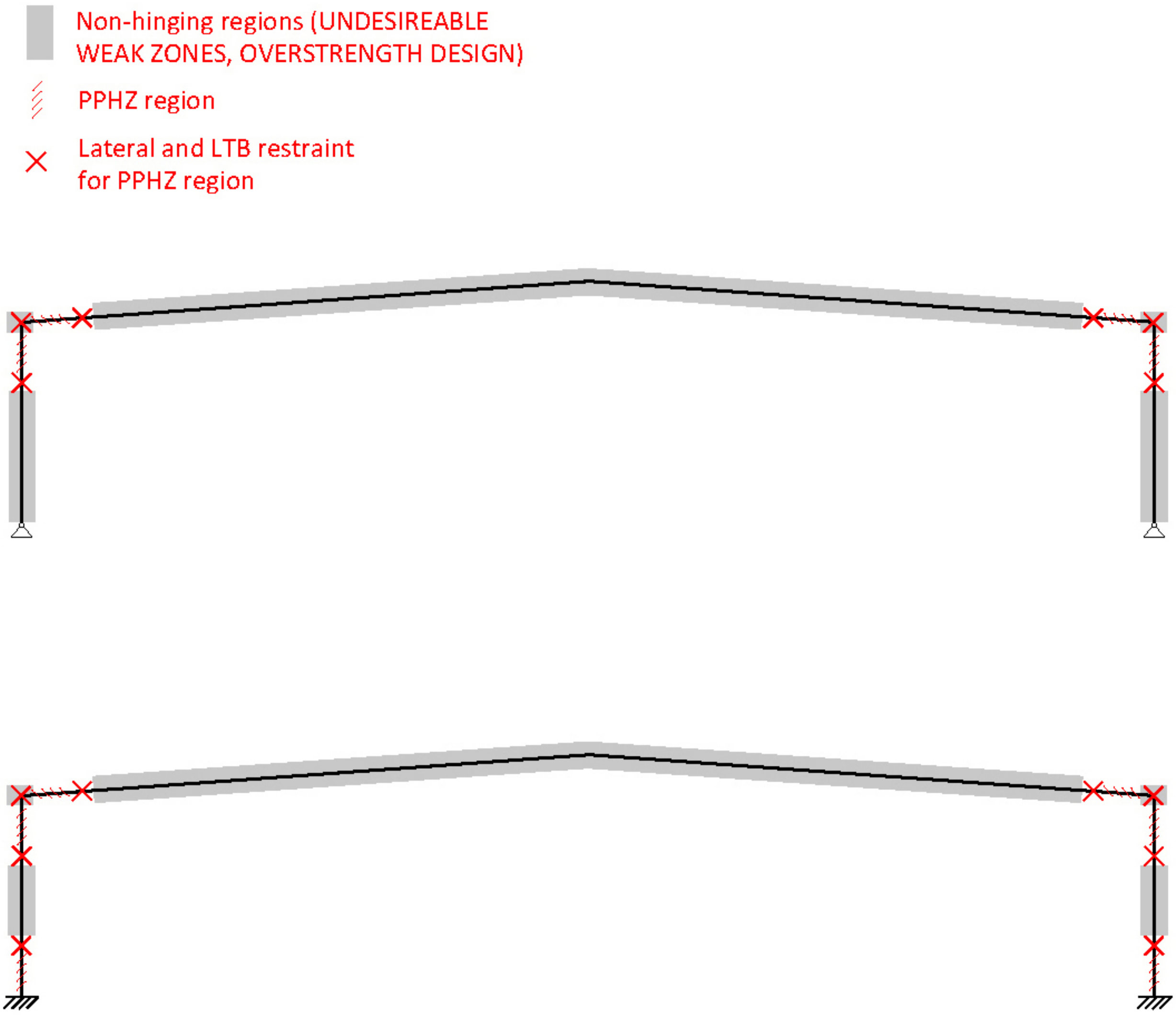


Plastic hinge formation

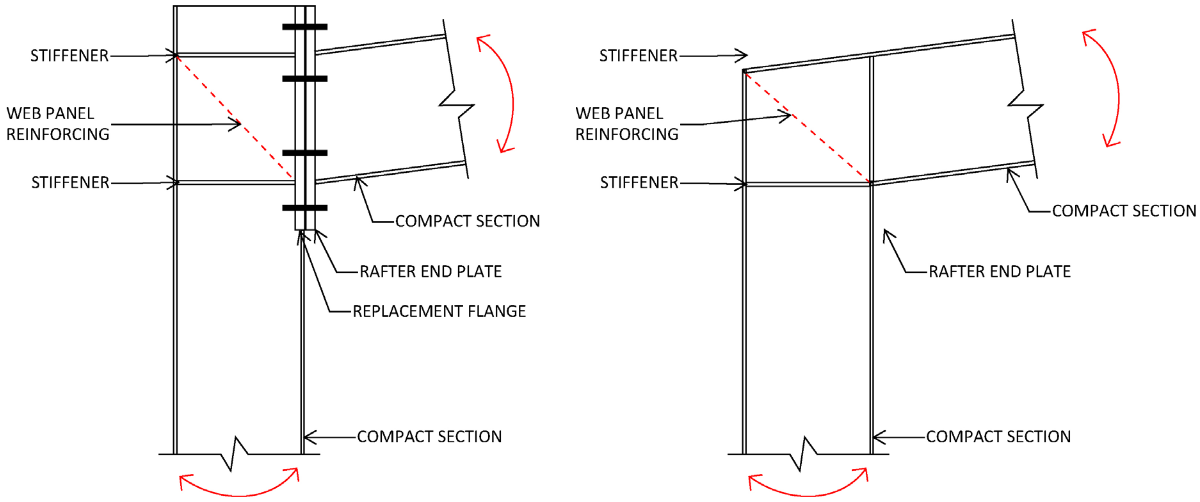
For seismic performance, the portal frame is often designed to form a sway mechanism, typically with plastic hinges forming in the rafter near the knee and possibly at the base of the portal legs. This mechanism must be clearly defined in the analysis model.

Whether the design follows a ductile or limited-ductility approach, the formation of plastic hinges should be reliable and predictable. All other parts of the frame must remain elastic under overstrength conditions.

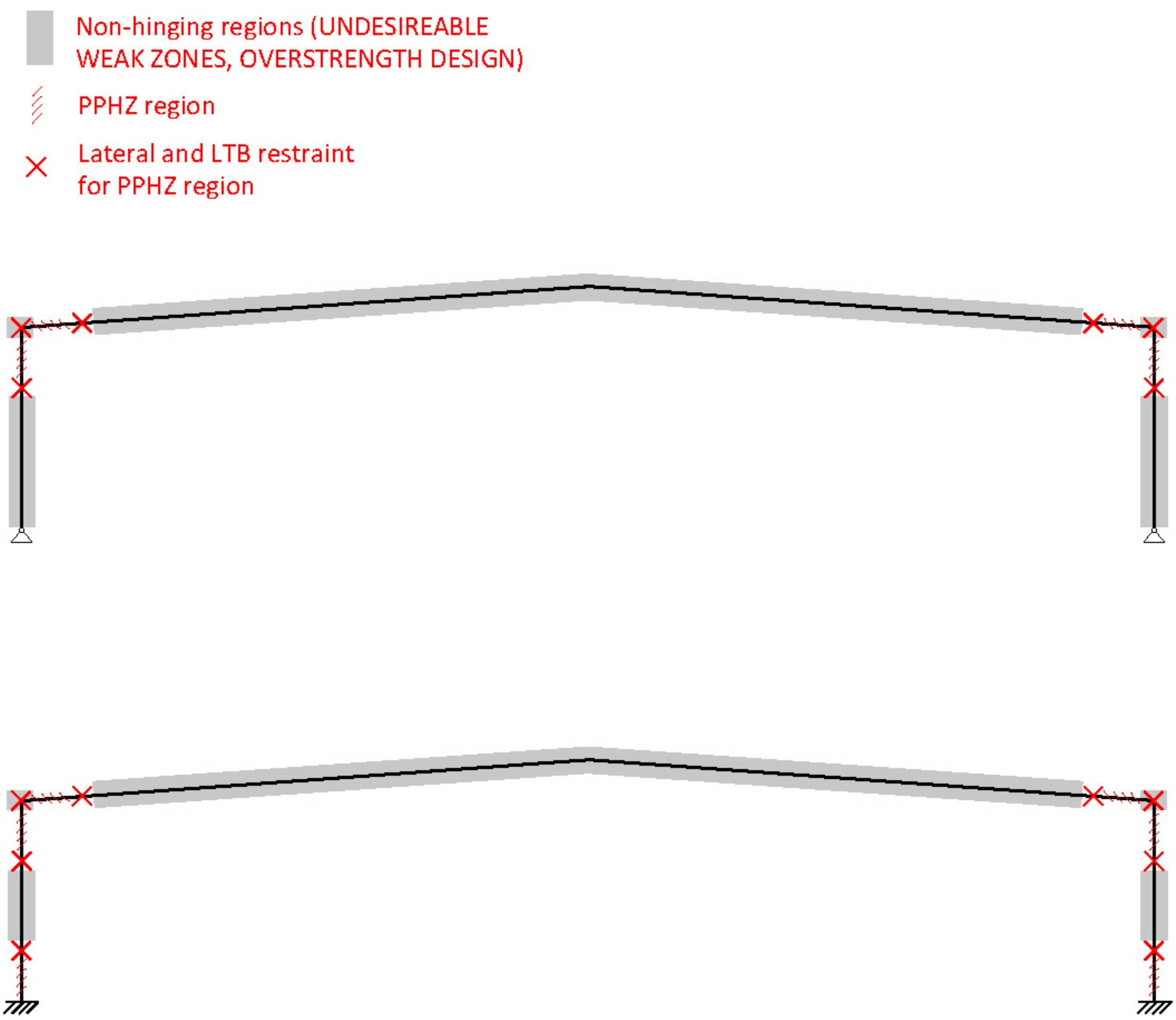
- **Plastic hinges should form predictably** in the rafters near the knees and possibly at the bases, not at uncontrolled locations.



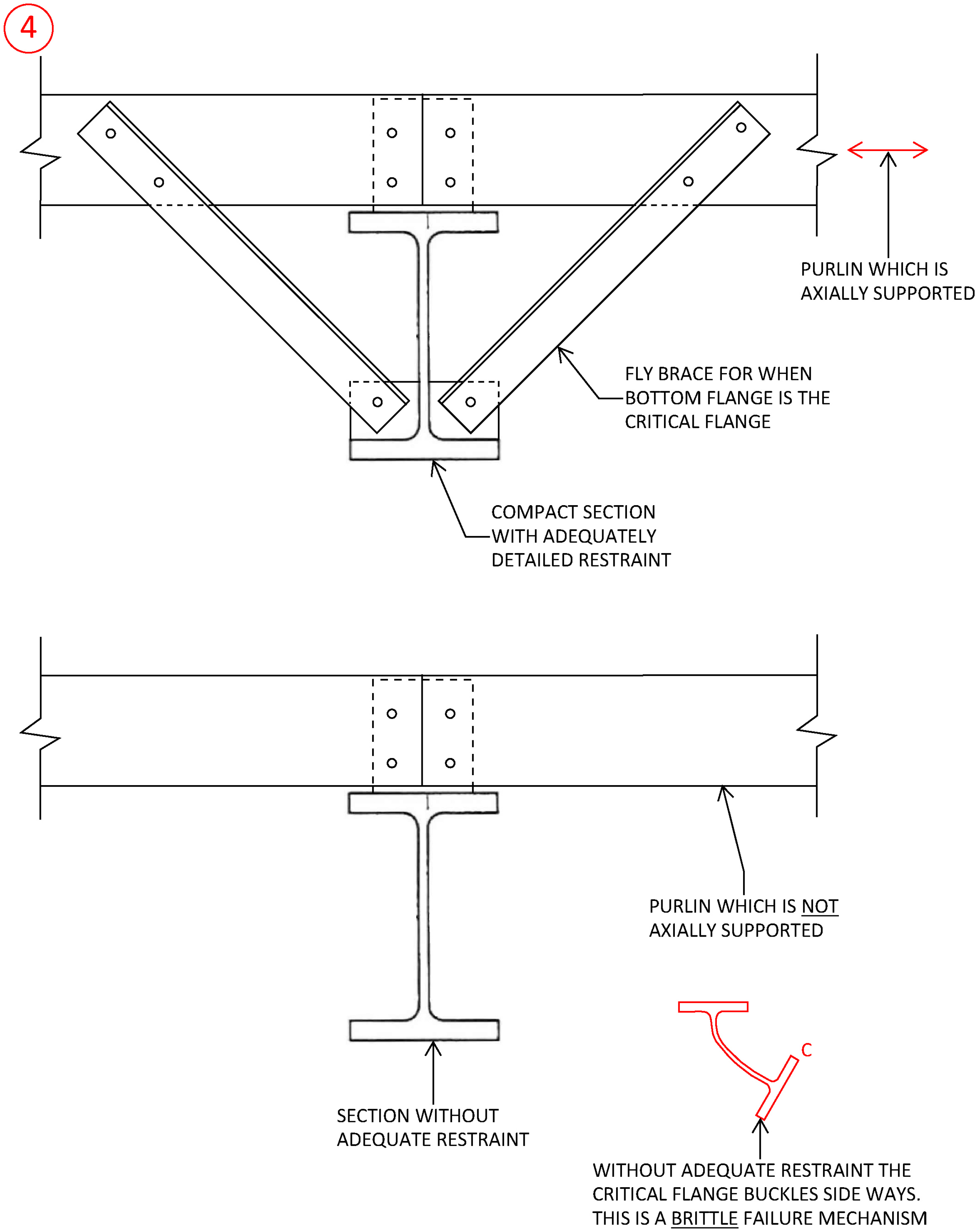
- **Whether limited or full ductility is used**, hinge zones must be identified and detailed to accommodate plastic rotation.



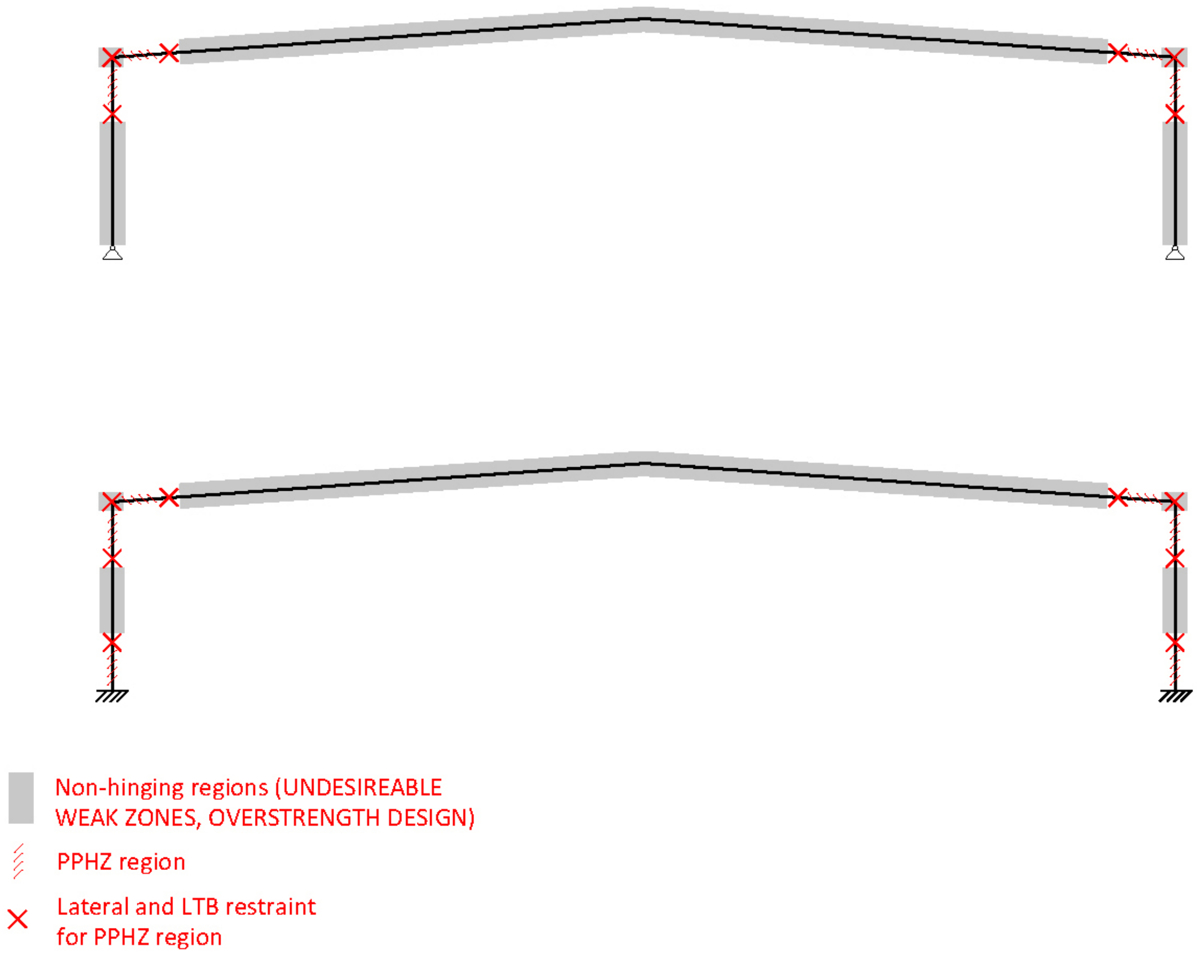
- **Outside the hinge zones**, overstrength design must be used to prevent premature yielding elsewhere in the frame.



- **Ensure that hinges can develop and rotate** without triggering instability or failure in connected elements (eg avoid lateral-torsional buckling).



- **Confirm that hinge formation aligns with analysis assumptions**, and that member, joint and connection detailing reflect this.



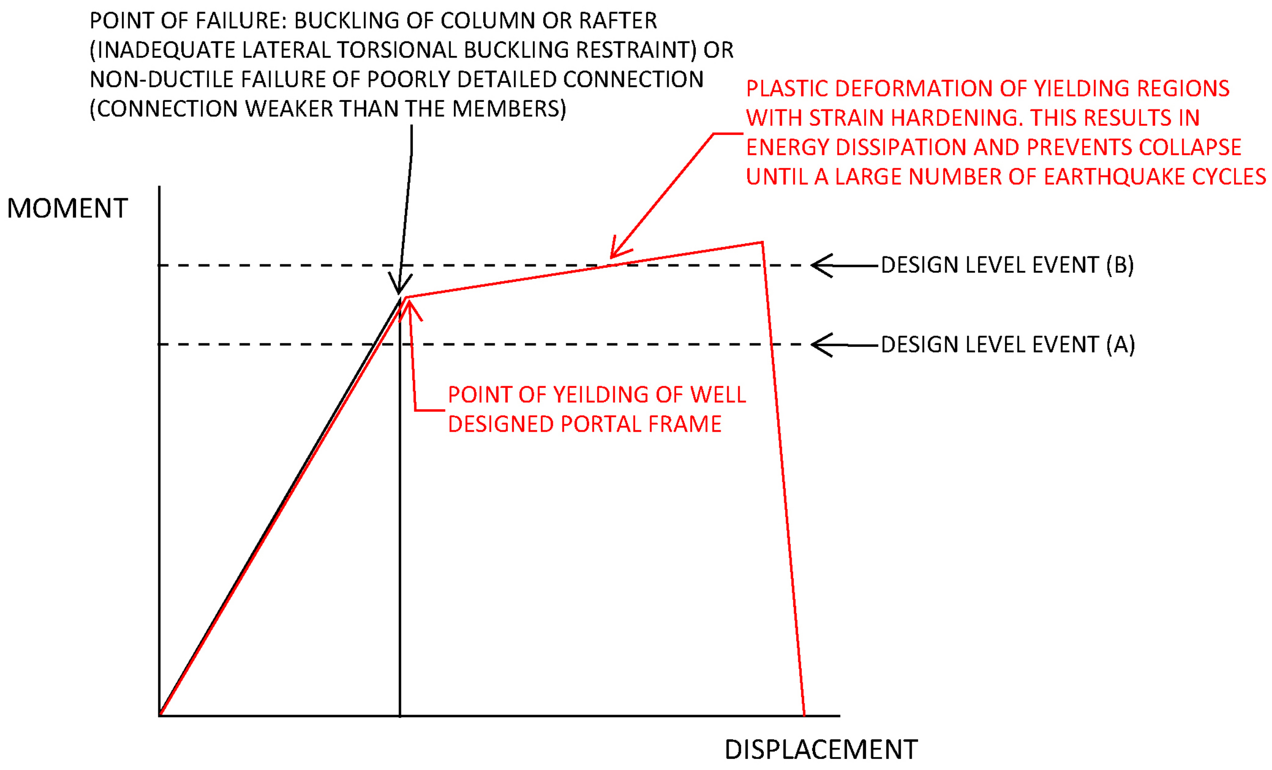
Even in elastic designs, regions where plasticity might occur (eg knees and bases) should be deliberately reinforced to allow limited rotation.

Design-level actions and expected behaviour

In this module, “design-level actions” refer to the actions you have set for life-safety verification (typically the project’s ULS actions) and the chosen serviceability actions. It’s expected that real earthquakes can exceed those actions. Our goal is not “no damage”, it is stable, non-brittle behaviour with damage concentrated in deliberate, ductile regions.

- **At serviceability actions**: structure responds essentially elastically; no loss of gravity capacity; drifts compatible with cladding and panels.
- **At design (life-safety) actions**: the intended sway mechanism forms (plastic rotation near the knees and, if adopted, at the bases); hinge zones are positively restrained against buckling; connections outside the hinge zones remain essentially elastic (overstrength protected).
- **Beyond design actions**: inelastic response will increase. Robust tying, hierarchy and restraint aim to prevent brittle triggers (buckling, connection fracture, panel out-of-plane instability), thereby maintaining gravity load support and preventing collapse.

Regardless of the ductility level, frames can perform well when weak links are removed and restraint, connections and hierarchy are carefully considered. The emphasis is on behaviour and detailing that avoids brittle limit states, not on a particular code category.



IDEALISED MOMENT DISPLACEMENT DIAGRAM OF A POORLY DESIGNED PORTAL FRAME

Torsional restraints

Fly braces are commonly used. However, in certain situations, such as locations where bird life and droppings are a concern, alternative systems may be considered.

To ensure stable hinge formation at the knee, the column and rafter compression flanges must prevent lateral-torsional buckling (LTB). Fly braces provide essential out-of-plane restraint to the inside flanges near the knee, where plastic hinges are expected to form.

Without effective restraint, hinge zones may buckle laterally before reaching their plastic moment capacity, compromising the intended seismic mechanism.

There can be other forms of restraints, including purlins/girts with suitable cleats between the rafter legs or long cleats and web stiffeners.

Role and function

Fly braces are typically short diagonal members connecting the compression flange of the rafter to a stiff, braced part of the diaphragm system (eg purlin, collector beam or roof bracing node). Their function is to:

- restrain lateral displacement of the compression flange under cyclic moment
- maintain the stability of the hinge zone during inelastic rotation
- prevent premature buckling that could shift the failure mechanism.

Detailing considerations

Connection to a rigid element

Fly braces must connect to structural elements with adequate in-plane stiffness. Simply connecting to a nearby purlin is insufficient, unless it is braced and can transmit the restraint force back to the diaphragm and ultimately to the ground.

Accumulated restraint forces

The LTB restraint force is not local – it accumulates from multiple frames in a row. NZS 3404 requires the design of fly brace load paths to account for cumulative restraint forces from up to seven frames (unless otherwise justified).

Geometric effectiveness

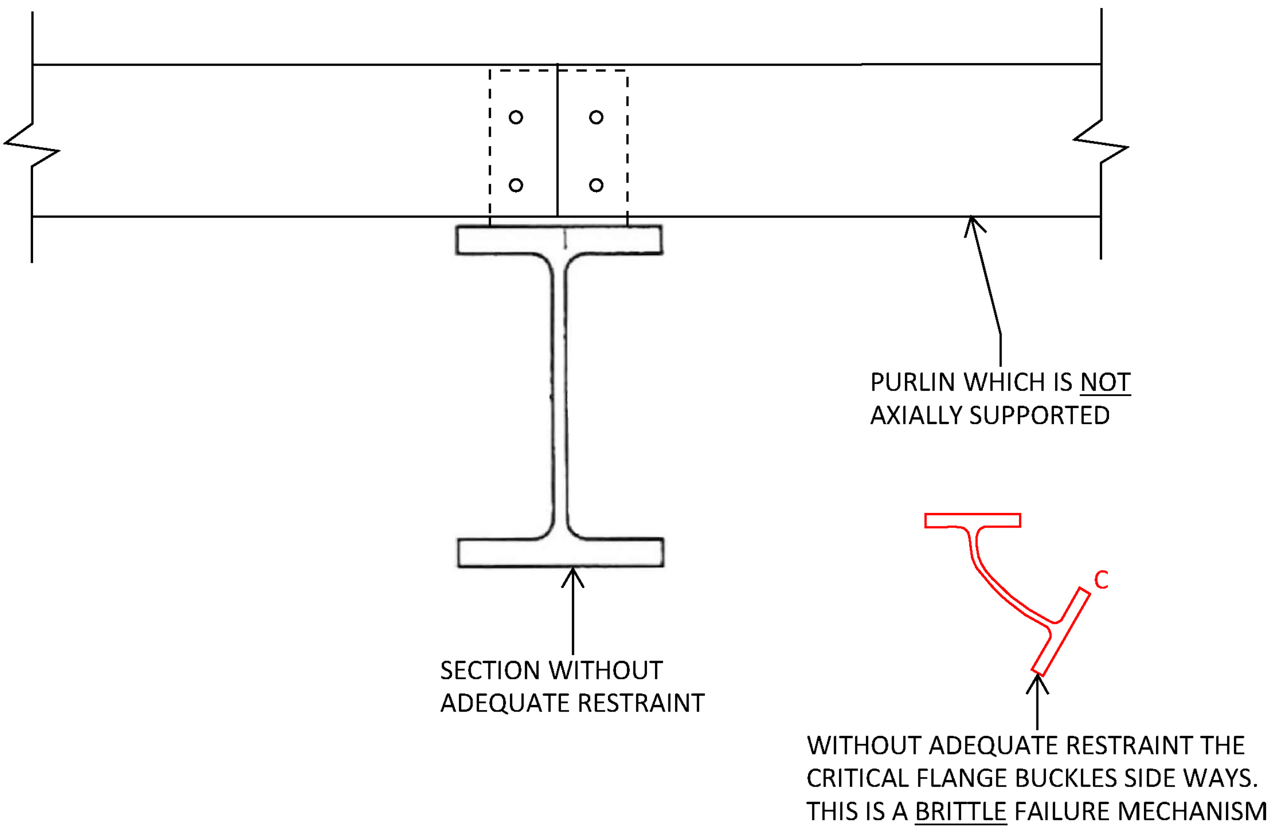
Where fly braces use bolted connections, oversized holes and small eccentricities between the end connections can result in ineffective restraint due to rotation and slippage. If slotted holes are used, then bolts are to be fully tensioned (/TF) to prevent slip. The detail must be geometrically effective.

Design considerations:

- Restraint details must transmit force without slip-rotation.
- Consider using slotted holes and high-friction or welded connections for improved restraint.
- Align brace lines so the load path is direct into a stiff, braced element (purlin line with a collector to roof bracing, or a dedicated strut) and demonstrate the full path back to the diaphragm.

Segment-based placement

The location and spacing of fly braces should relate to the buckling length of the compression flange, not simply a fixed spacing. Pay special attention to tall portal legs or long rafter spans that may be inadequately restrained.

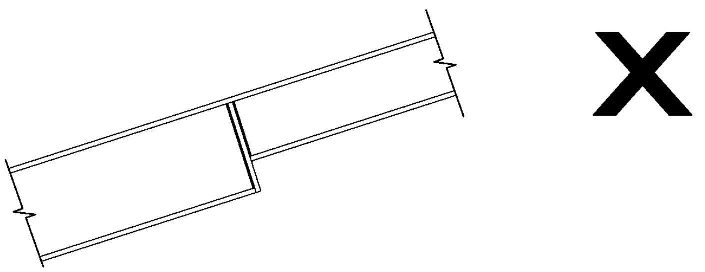


Rafter splices

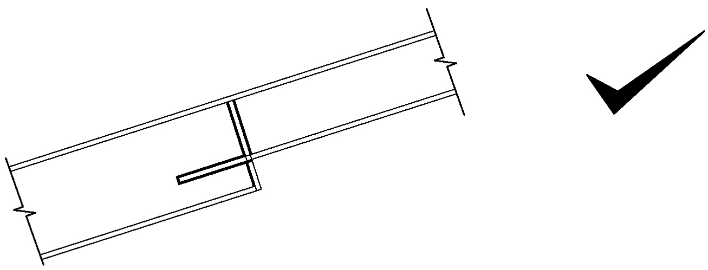
The rafter carries significant axial forces along its flanges. Both top and bottom flanges must be fully connected at section changes to ensure smooth force transfer without weak points.

Recommended detailing

- Join both flanges and the web, using full penetration butt welds or full-strength fillet welds. Weld size must match or exceed the capacity of the connected elements. Welds should be applied to both sides of the web and flanges to avoid warping and ensure balance.
- Where the section change is abrupt (eg from a larger UB to a smaller one), use tapered transitions or splayed joints to reduce stress risers. Sharp changes in stiffness can result in cracking or local yielding under cyclic or sustained loading. If the web of the smaller section is thinner, add web doubler plates or stiffeners near the join to increase shear capacity and stiffness. This prevents web distortion and improves fatigue resistance under repeated loading.



RAFTER JOINTS: SIZE CHANGES



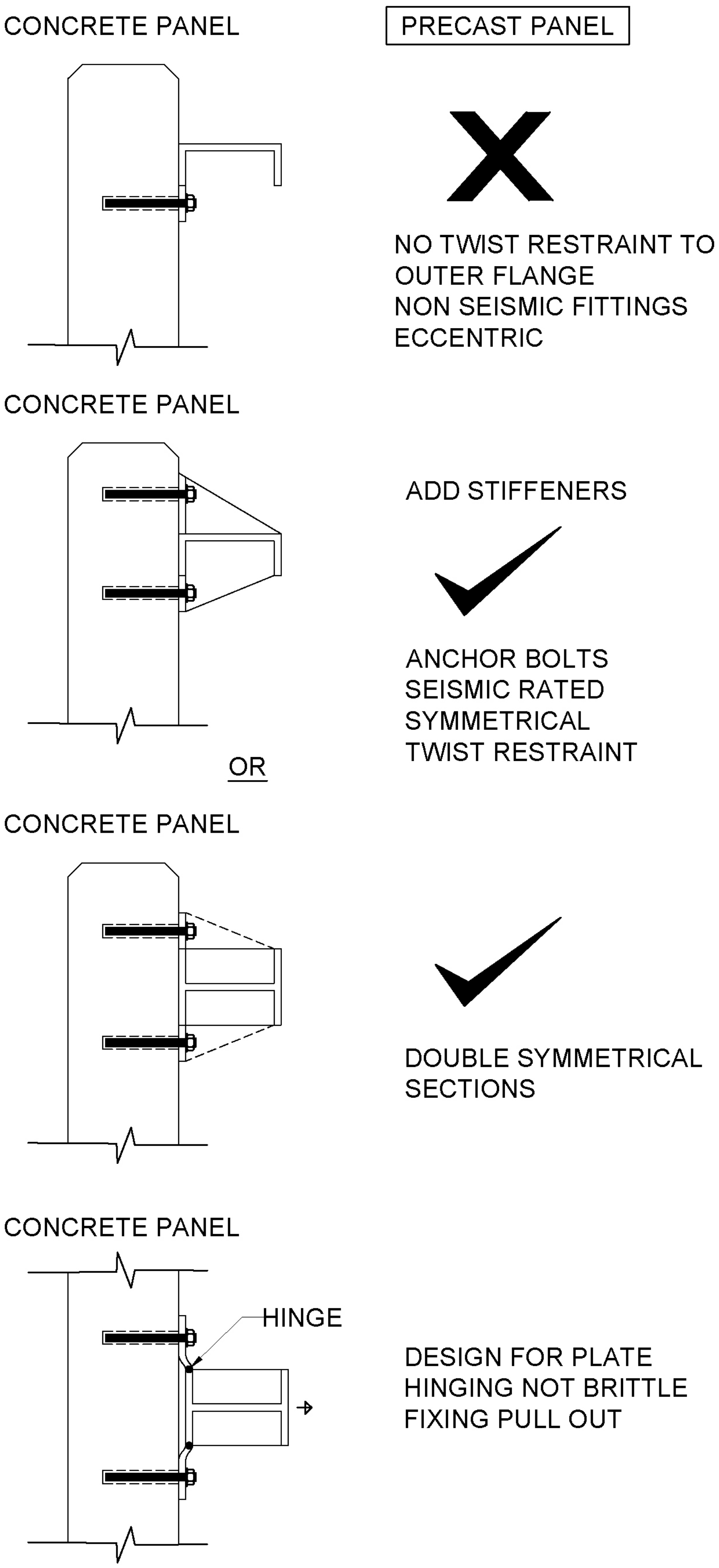
Collector beams

Collector beams are typically located at the top of the precast concrete panels, just beneath the roof diaphragm. These connections carry out-of-plane forces from the heavyweight panels into the portals while also connecting the roof bracing system for LTB restraints into the concrete shear walls.

They span horizontally between the portal legs and connect directly to the panel ends. Their alignment must be consistent with the intended seismic load path. The collector must directly link the panels and the portal frames, without unnecessary offsets or eccentricities.

As per Determination 2013/057, precast panels must be designed as a “part” and “the flange, etc, within the column itself, being the element which connects the part into the primary portal frame structure, be sufficiently strong to transmit the forces of this part through the connections”.

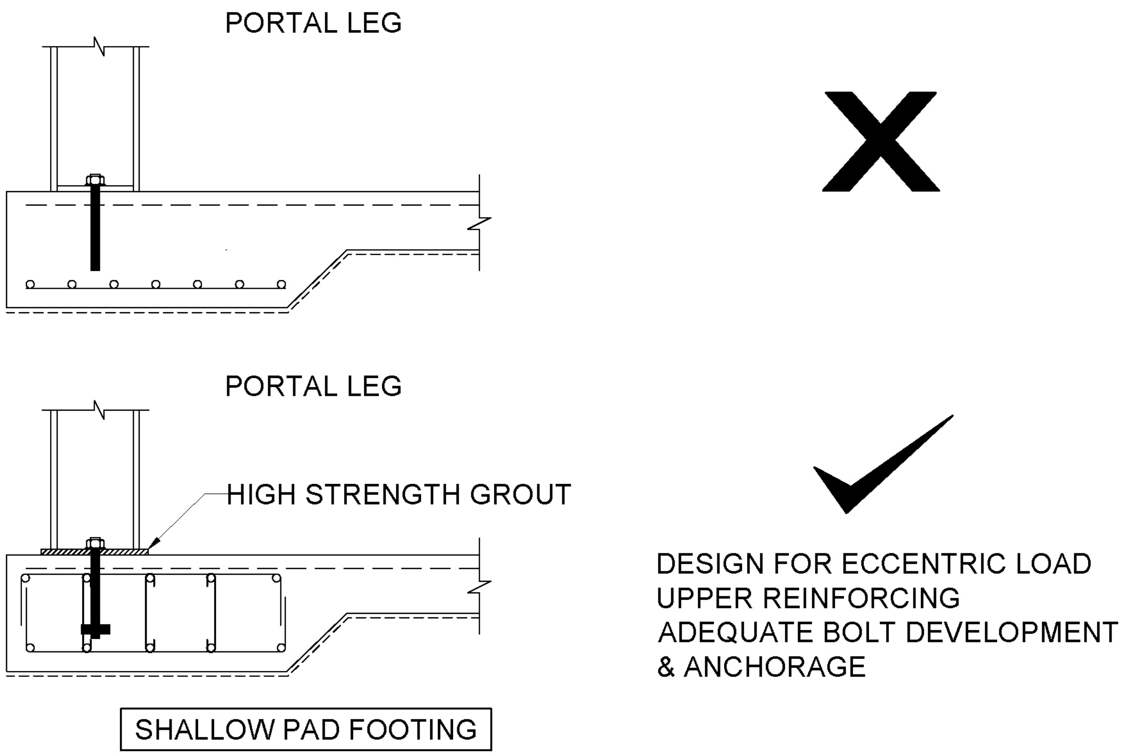
- Collector beams connect precast panels to portal frames and complete the seismic load path.
- Use sections with sufficient lateral restraint to avoid buckling and twisting. Ensure deflections are compatible with concrete panels to avoid panel cracking
- Detail connections into panels and frames to carry in-plane axial forces reliably.
- Avoid brittle or eccentric connection arrangements.
- Design the collector beam plate to yield – NOT the connections to the panel.
- Ensure the whole collector system is compatible with seismic deformation demands.


CONCRETE PANEL
PRECAST PANEL
NO TWIST RESTRAINT TO
OUTER FLANGE
NON SEISMIC FITTINGS
ECCENTRIC
CONCRETE PANEL
ADD STIFFENERS
ANCHOR BOLTS
SEISMIC RATED
SYMMETRICAL
TWIST RESTRAINT
OR
CONCRETE PANEL
DOUBLE SYMMETRICAL
SECTIONS
CONCRETE PANEL
HINGE
DESIGN FOR PLATE
HINGING NOT BRITTLE
FIXING PULL OUT

Shallow pad foundations

The foundations beneath the portal legs typically consist of shallow pad footings, which must be sized and detailed to resist the full range of seismic actions – including axial tension from uplift, shear from lateral loading and bending moments from plastic hinge formation at the base. Anchor bolts must be designed for capacity-level actions, with appropriate edge distances and embedment to resist concrete breakout and pull-out. The pad itself must be sized to provide sufficient weight and bearing area, ensuring stability against sliding and overturning. Coordination with geotechnical design is essential to confirm that bearing pressures and soil stiffness are compatible with the structural assumptions.

- Shallow pad foundations support portal legs and must resist axial uplift, shear and bending moments generated during seismic events.
- Foundation size must account for overturning from seismic actions – not just vertical gravity loads. Detail to avoid brittle failure.
- Anchor bolts must be embedded and spaced to resist overstrength actions, not nominal design values.
- Ensure edge distances, embedment depths and concrete strength are compatible with anchor demand and failure modes (eg pullout, breakout, concrete cone).
- Coordinate with geotechnical engineers to confirm bearing capacity, ground stiffness and settlement compatibility with structural assumptions.



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