EXAMPLE: Alternate Path Method for Wood Structures

Brian Crowder, P.E.

3/21/2005

Example Problem Statement

- Using facility defined in tie force example for wood frame[1] building, illustrate the use of the alternate path method.
- Three cases of vertical load carrying element removal will be illustrated
- For each case, the feasibility of using "bridging" in lieu of providing vertical tie force capacity for the element will be assessed
- Cases for removal
  - Removal of column in exterior north-south wall
  - Removal of interior column
  - Removal of exterior load bearing wall (east-west)

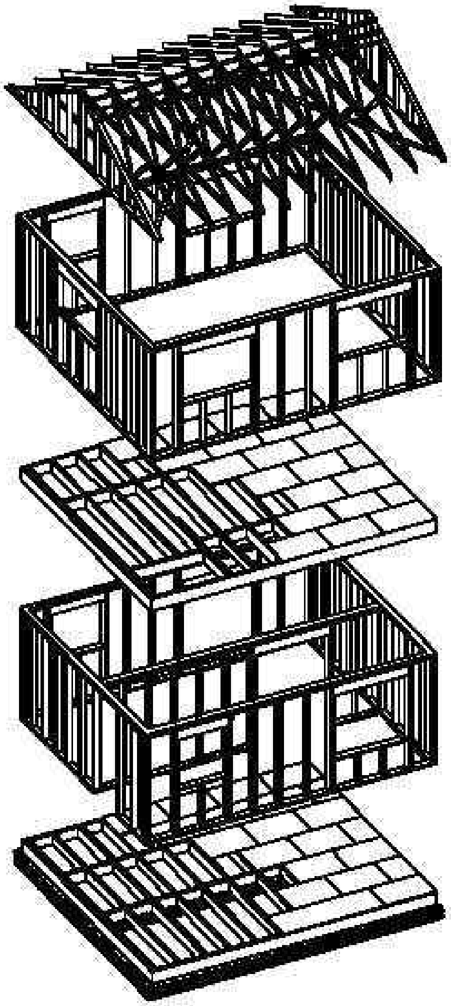
[1] Based on definition provided in AFPA/AWC "LRFD Manual for Engineered Wood Construction"

Background

- Much of the guidance presented in the UFC is based on British provisions to prevent disproportionate collapse
- Ability of wood frame structures to resist disproportionate collapse demonstrated in full-scale tests in U.K.

Platform Wood Frame Construction

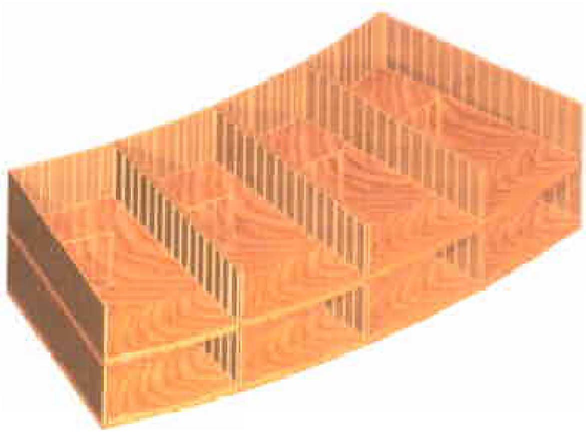
- **In U.K. wall and floor panels are often manufactured in the factory and installed on site**



Platform Wood Frame Construction

- Building in U.K. testing was platform construction and based on a cellular layout as illustrated below
- Numerous interior load bearing walls
  - –Shorten floor spans
  - –Provide redundancy, allow for load redistribution
  - –Significant lateral capacity

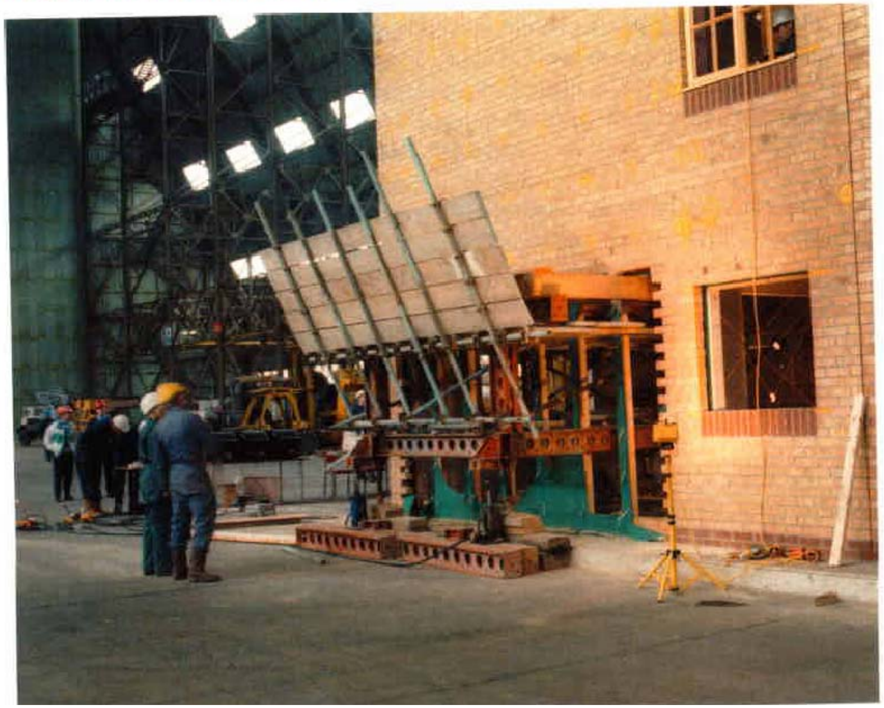
Cellular layouts



Cellular layouts are best suited to multi-storey platform timber frame. Internal load bearing walls may need to be strengthened to carry horizontal forces.

Disproportionate Collapse Testing

Disproportionate collapse test



Two load bearing walls were removed, one internal and one external to check the structural integrity

- Six stories
- 2:1 aspect ratio
- Platform-type timber frame (wood frame)
- Brick cladding
- Walls
  - Exterior 2x4 at 600 mm, two layers of plasterboard, and OSB sheathing
  - Interior 2x4 at 600 mm with two layers of plasterboard and OSB sheathing where needed for wind bracing
- Floors
  - 1-4th floors timber joists
  - 5th floor timber I-beams and metal webbed beams
- Roof – trussed rafters

Disproportionate Collapse Testing Results

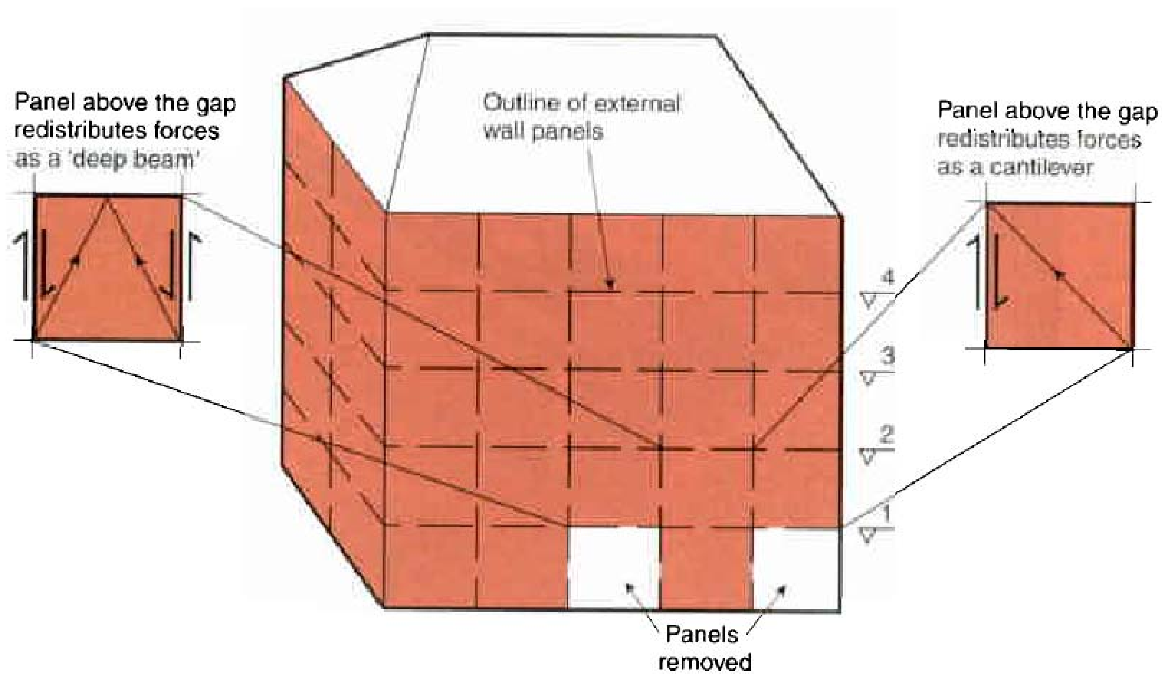
- **Wall panels were found to have sufficient strength created by the plasterboard/timber board sheathing to span unsupported**
  - **Walls with no openings can be regarded as deep beams with vertical shear taken in panel to panel connections and tension taken out through the sheathing**
- **Standard platform frame detail to build floor such that floor is supported on all sides demonstrated that floor has additional strength through the transverse capacity of the floor that is supported on the walls parallel to the span**
- **For removal of internal load bearing wall, floors spanning 3.6 m and 4.2 m wide deflected at the unsupported edge 24 mm.**
- **For removal of the external wall, the unsupported floor deflected 4 mm.**

Alternate Load Paths

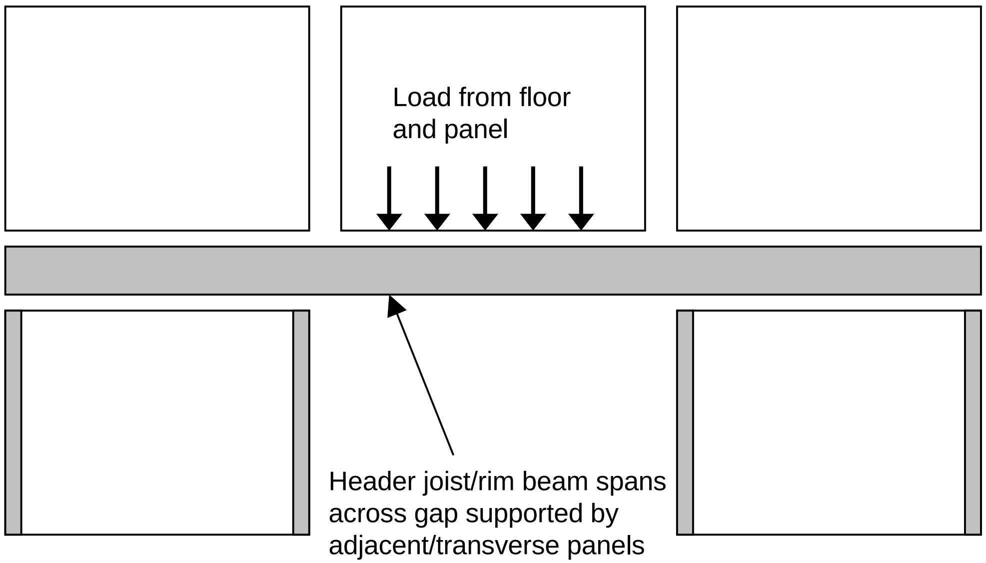
- **Testing in U.K. showed that wall panels above removed sections can act as a “deep beam” redistributing forces over the missing wall section**

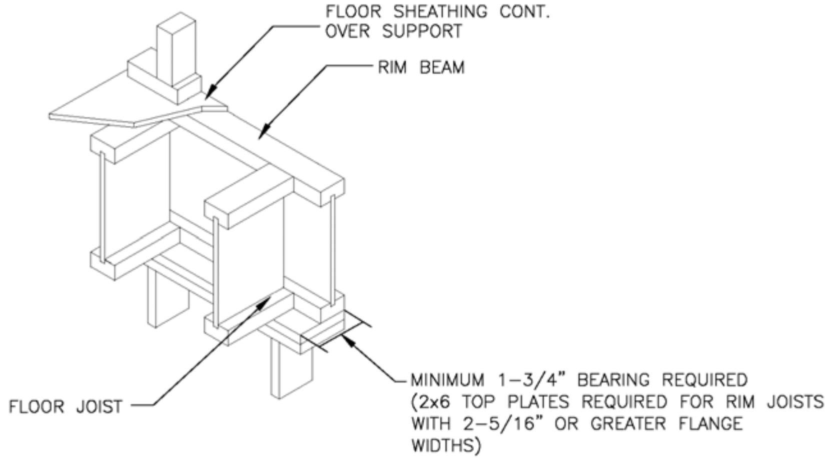
The following diagrams summarise other observations and conclusions drawn from the tests.

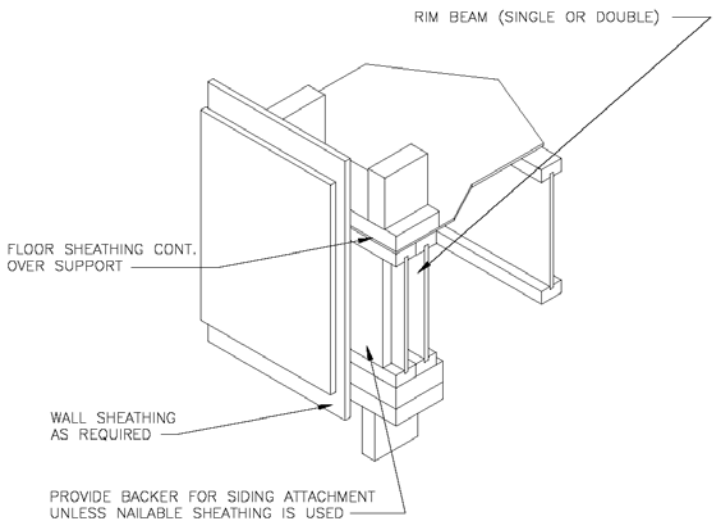
Diagrammatic elevations on panels spanning over a gap for a typical five-storey timber frame



- The use of rim beams to redistribute loads was also investigated

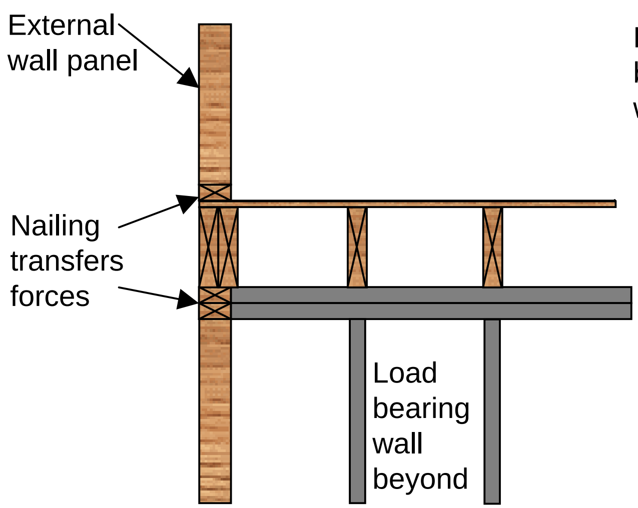






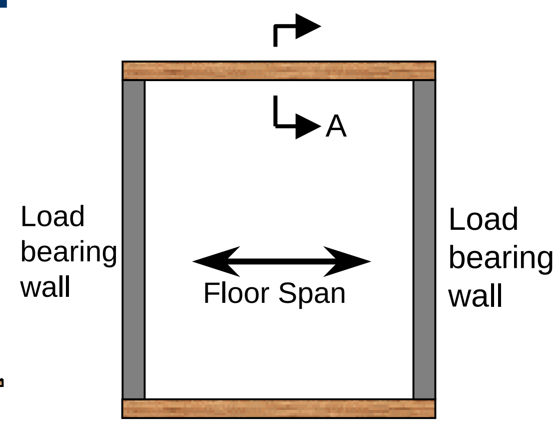
Alternate Load Paths

- **It was also shown that when properly detailed, a floor system designed to span one-way can redistribute loads in the perpendicular direction when support is lost**

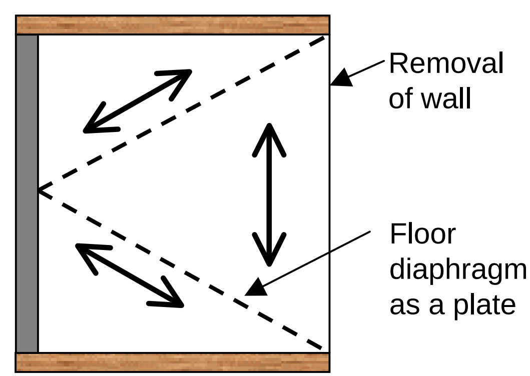


Section A-A

Floor decking continuous into wall section



Floor Plan as designed



Floor Plan after load bearing wall removal

Building Structural Elements

- **Structural elements given for example structure**

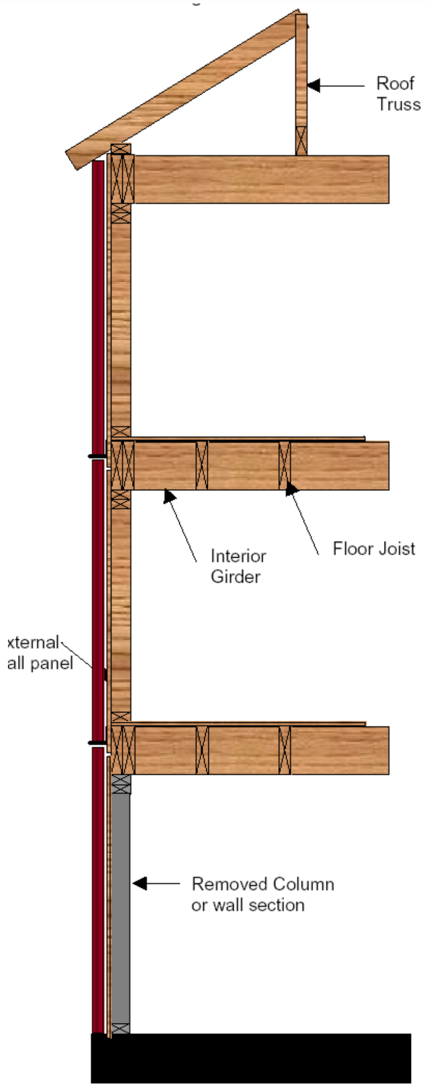
Element	Section	Material
Walls (int and ext)	2x6 @ 16" 0.C.	Southern Yellow Pine (SYP) No. 2
Columns	4 – 2x6	SYP No. 2
Rim Beam	8x12	SYP No. 2
Girder	8x12	SYP No. 2
Floor Joists	11.9" engineered I-Joists	Engineered Wood

Building Loading

- **Unfactored loads as specified previously or assumed for this part of the example**

Level or Element	Dead	Live
Roof	20 psf	20 psf
3rd Floor	15 psf	55 psf
2nd Floor	15 psf	55 psf
Exterior wall section including sheathing	6.5 psf	
Brick Cladding (supported at ground, 2nd , and 3rd floor levels)	40 psf	
Rim Beam / Girder (est.)	25 plf	

Case 1 – Exterior Column Removal



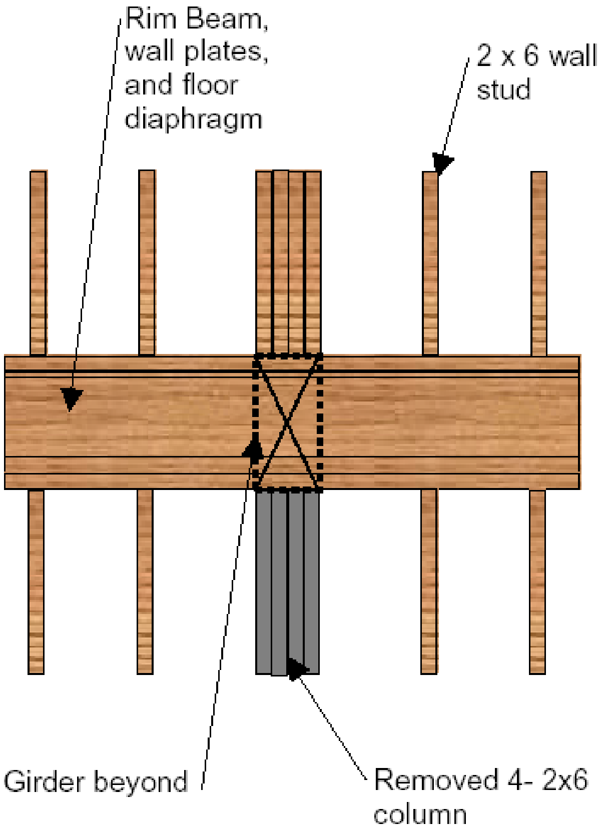
- Proposed bridging mechanism is for rim beam supporting the column and girder reaction to redistribute the loads to adjacent wall studs
- Wall and rim beam is parallel to span of floor joists
- Floor sheathing is continuous over the top of the rim beam
- Rim beam at each level carries the loads at that level, including weight of the brick cladding, wall section, tributary floor load, and girder reaction

Elevation of Framing at Column Removal

- **Rim beam will have to span 32 inches to adjacent 2x6 studs**
- **Loads supported by column are calculated based on Section 3-2.3.2**

  2((1.2 or 0.9)D + 0.5L) + 0.2W
- **Loads adjacent to unsupported area are calculated based on Section 3-2.3.**

  (1.2 or 0.9)D + 0.5L + 0.2W
- **Wind not analyzed for simplicity in example and reduction in lateral force capacity to an unstable level is extremely unlikely for shear wall type building**



Elevation showing area of column removal (cladding not shown for clarity)

Acceptability Criteria for Rim Beam

Table F-5 Acceptability Criteria Check for 8 x 12 S.Y.P. No. 2 Rim Beam

Structural Behavior	Demand	Capacity	Notes
Element Flexure	M_u- = -38.1 k-in M_u+ = 33.8 k-in	$\phi\lambda M'$ = 303.5 k-in	OK, size could be reduced to 4x12, however other load cases may govern
Combined Axial and Bending	NA	NA	Minimal Axial Load Effect
Shear	V_u = 5.3 k	$\phi\lambda V'$ = 12.5 k	OK
Connections	NA	NA	Not designed for this example
Deformation	Δ = negligible	θ = 3.7° or 1.03"	OK

- **Rim Beam is capable of bridging over the removed column as specified**
- **Deformation calculated using load combinations of Section 3-2.3.2 and 3-2.3.1 as appropriate**

Acceptability Criteria for Wall Studs

Table F-6 Acceptability Criteria Check for Wall Studs

Structural Behavior	Demand	Capacity	Notes
Element Flexure	NA	NA	Assumed for example as compression member
Combined Axial and Bending	P_u = 13.6 k	2 – 2x6 wall studs - $\phi\lambda P'$ = 25.25 k	OK. Assumed bending load is negligible for example
Shear	NA	NA	OK - Assumed shear load is negligible for example
Connections	NA	NA	Not designed for this example
Deformation	NA	NA	

- **Two adjacent 2x6 studs on each side of lost column can support the redistributed load from the removed column**

Case 2 – Removal of Interior Column

- **Proposed mechanism is girder bridging over the removed column**
- **Column must be detailed to be continuous and splices designed since any interior column location could be removed**
- **Tributary area to column is approximately 11'-0" x 13'-6"**
- **Load case specified in Section 3-2.3.2 is used for bays adjacent to the removed column for the full height of the building. Other locations are loaded using combination specified in Section 3-2.3.1.**
- **Same Load cases used for deflection calculations**
- **Wind not analyzed for simplicity in example**
- **Since rotation restraint is not quantified, span modeled as simply supported**

Acceptability Criteria for Rim Beam

Table F-7 Acceptability Criteria Check for 8 x 12 S.Y.P. No. 2 Girder

Structural Behavior	Demand	Capacity	Notes
Element Flexure	M_u = 893 k-in	$\phi\lambda M'$ = 303.5 k-in	N.G., 6.75" x 12.375" 26F SYP Glulam O.K. $\phi\lambda M'$ = 952 k-in
Combined Axial and Bending	NA	NA	Minimal Axial Load Effect
Shear	V_u = 13.5 k	$\phi\lambda V'$ = 12.5 k	N.G., 6.75" x 12.375" 26F SYP Glulam O.K. $\phi\lambda V'$ = 23.6 k
Connections	NA	NA	Not designed for this example
Deformation	Δ = 5.68" 8x12 Δ = 4.35" Glulam	θ = 3.7° or 8.54"	N.G. (Deflection estimate invalid since beam fails)

- **Rim Beam as specified is insufficient**
- **Glulam of smaller dimensions would be sufficient**
- **Splice detailing and location critical to performance**

Acceptability Criteria for Columns

Table F-8 Acceptability Criteria Check for Columns (4 – 2x6 SYP No. 2)

Structural Behavior	Demand	Capacity	Notes
Element Flexure	NA	NA	Assumed for example as compression member
Combined Axial and Bending	P_u = 46.5 k (adjacent span load using 3-2.3.1)	4 – 2x6 wall studs - $\phi\lambda P'$ = 50.5 k (braced in weak dir.)	N.G., 6x8 SYP No. 1 column sufficient if studs not braced in weak direction $\phi\lambda P'$ = 49.1 k
Shear	NA	NA	OK - Assumed shear load is negligible since shear walls take lateral loads
Connections	NA	NA	Not designed for this example
Deformation	NA	NA	

- **4 – 2x6 column specified is insufficient if unbraced**
- **6x8 Southern Yellow Pine No. 1 column would satisfy strength requirements**

Case 2 - Summary

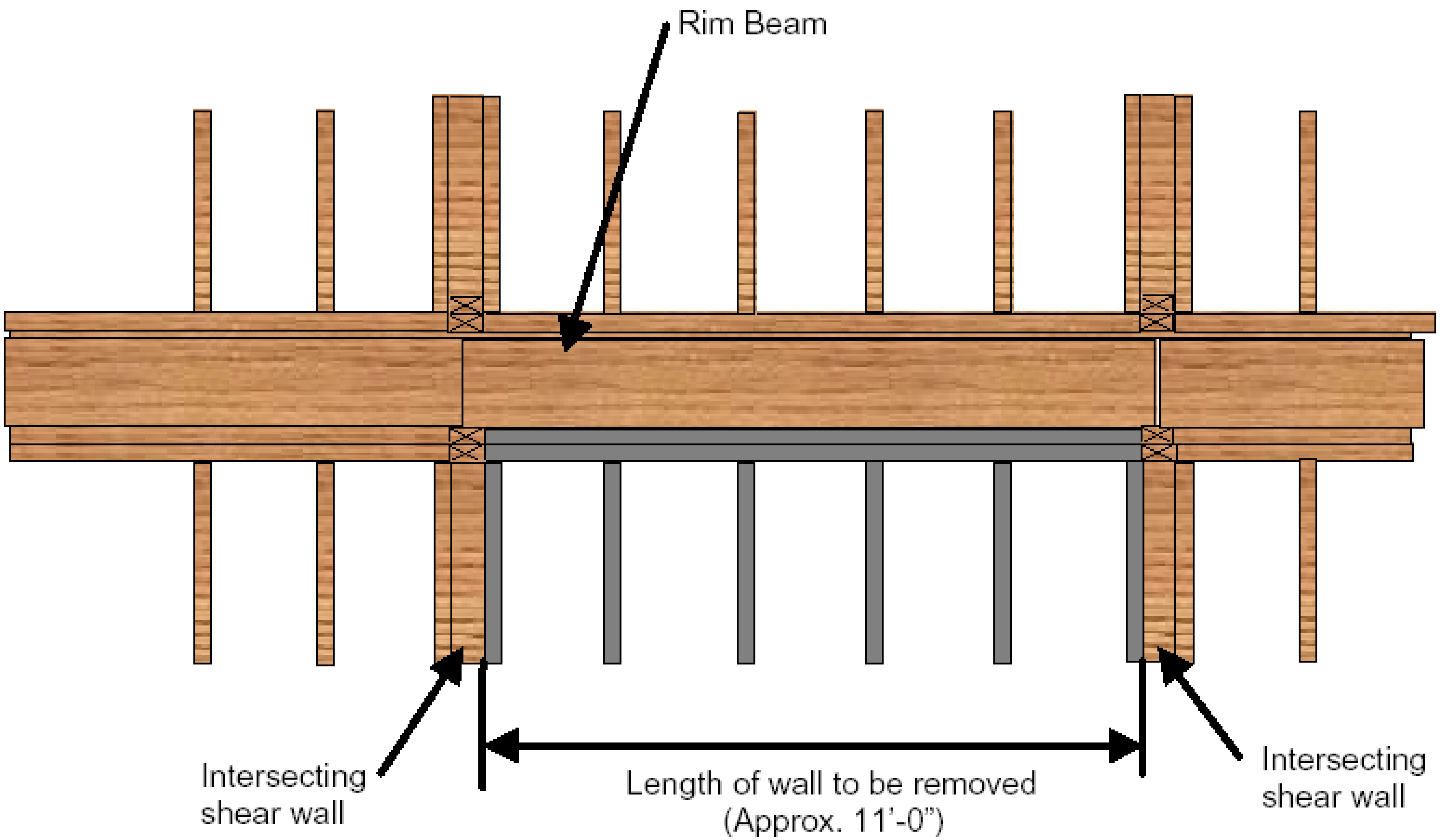
- 8 x 12 girder N.G. and 4-2x6 columns may be insufficient
- Options
  - Increase size of girder and use glulam
  - Increase size of column
  - Use less “frame” action using cellular layout instead of post and beam construction for interior sections of facility

Case 3 – Exterior Load Bearing Wall Removal

- **East-West exterior walls directly support floor joists, with tributary width of 6'-0"**
- **Removed element is section of wall**
- **Proposed bridging mechanism is for rim beam supporting the floor system to redistribute the loads to adjacent wall studs**
- **Rim beam at each level carries the loads at that level, including weight of the brick cladding, wall section, and tributary floor load**
- **Load case specified in Section 3-2.3.2 is used for bays adjacent to the removed column for the full height of the building. Other locations are loaded using combination specified in Section 3-2.3.1.**
- **As case with British building, rim beam is continuous between intersecting walls and modeled as simply supported**

Elevation of Framing at Removed Wall Section

Figure F-6 Notional Exterior Load Bearing Wall Removal



Acceptability Criteria for Rim Beam

Table F-9 Acceptability Criteria Check for 8 x 12 S.Y.P. No. 2 Rim Beam

Structural Behavior	Demand	Capacity	Notes
Element Flexure	M_u- = 443.2 k-in	$\phi\lambda M'$ = 303.5 k-in	N.G., 5-1/8" x 12-3/8" 20F SYP Glulam O.K. $\phi\lambda M'$ = 551 k-in
Combined Axial and Bending	NA	NA	Minimal Axial Load Effect
Shear	V_u = 11.1 k	$\phi\lambda V'$ = 12.5 k	O.K., (5-1/8" x 12-3/8" 20F SYP Glulam $\phi\lambda V'$ = 17.8 k)
Connections	NA	NA	Not designed for this example
Deformation	Δ = 0.42" Glulam	$\theta = 3.7°$ or 4.27"	OK

- **Rim Beam as specified is insufficient**
- **Glulam of smaller dimensions would be sufficient**
- **Detailed to be continuous between intersecting walls**

Acceptability Criteria for Wall Studs

Table F-10 Acceptability Criteria Check for Wall Studs (2x6 SYP No. 2)

Structural Behavior	Demand	Capacity	Notes
Element Flexure	NA	NA	Assumed for example as compression member
Combined Axial and Bending	P_u = 26.7 k (per side of removed wall including upper floor reactions)	2 – 2x6 wall studs in end of shear wall - $\phi\lambda P'$ = 25.25 k (braced in weak dir. by sheathing)	N.G., if SYP select structural instead of No. 2 OK.
Shear	NA	NA	OK - Assumed shear load is negligible since shear walls take lateral loads
Connections	NA	NA	Not designed for this example
Deformation	NA	NA	

- **2 – 2x6 column specified is insufficient**
- **Providing additional studs under rim beam support or providing structural select material in lieu of No. 2 would be acceptable**

Summary of Example - Results

- **Cases 1 through 3 represent only some of the elements that would be removed to verify the capability to develop alternate paths in lieu of developing vertical tie capacity**
- **Another areas include corner sections where the rim beam or wall section must cantilever to redistribute the loads from a removed element**
- **Since elements were only examined on the first floor level, it is possible to optimize the member sizes at the various levels of the structure to achieve greater economy**
- **The analysis presented showed that the proposed framing scheme and member sizes were insufficient in some cases to develop alternate paths, however, reasonable modifications could be made to the members to provide an alternate path**

Summary of Example – Mechanisms Not Used

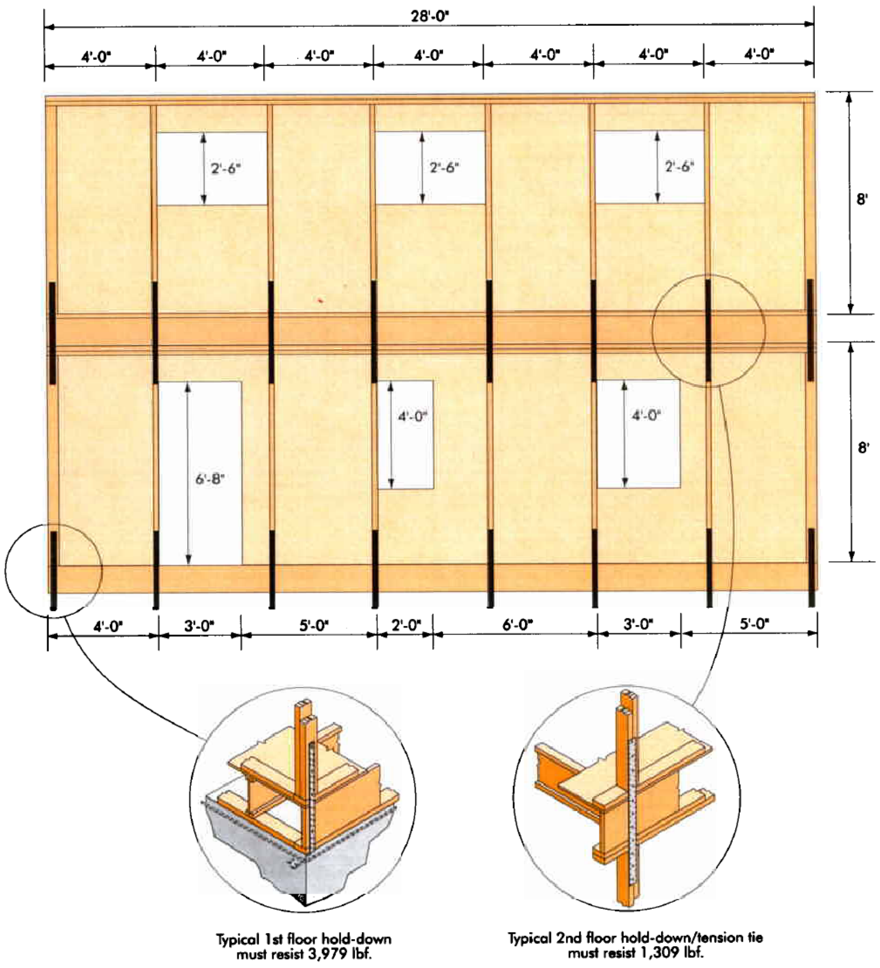
- "Deep" beam action of the wall panels
  - Properly detailed, rated structural sheathing can carry the shear, while rim beams can act as chords of the beam carrying only tension or compression
  - For example, when this mechanism is examined for Case 3 using a two story "deep beam", the factored chord demand is 3.35 kips and the factored shear demand is 1200 plf
  - Allows reduction in section for rim beams and tension/compression splices in lieu of moment splices
- Redistribution of floor loads
  - When the floor sheathing is supported on the walls parallel to the span of the floor system
  - If this redistribution can be shown, the demand on the rim beam or other resisting elements can be reduced

Other Considerations

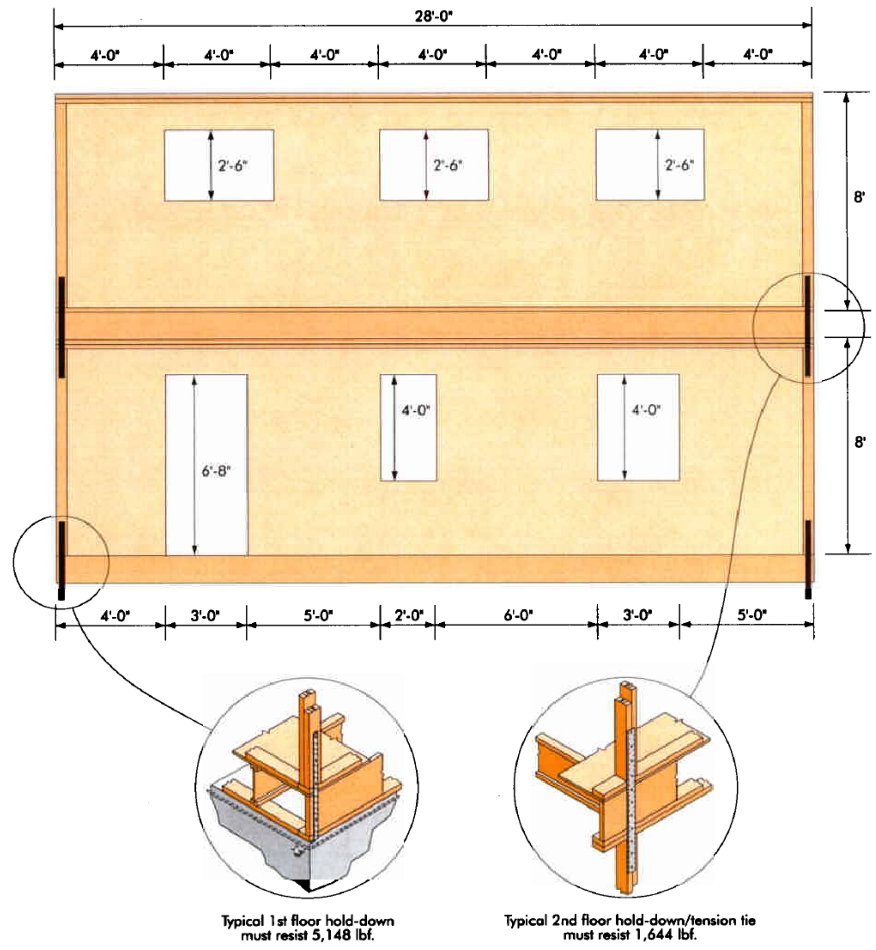
- **Structural Panels - Alternative to horizontal ties at each joist**
  - **Consider diaphragm or sub-diaphragms to provide horizontal tie to wall connection requirements**
  - **Consider if diaphragm is capable of providing internal horizontal tie capacity**
- **Shear Wall Type**
  - **Shear walls with openings typically designed with one of two methods**
    - Force transfer around openings (common for narrow shear walls)
    - Perforated shear wall
  - **Where a force transfer is designed around openings vertical continuous tie-down systems may be utilized**
  - **May be possible to use Continuous tie-down systems or hold-down systems required by lateral force design to provide vertical tie capacity**

Force Transfer Around Openings vs. Perforated Shear Wall

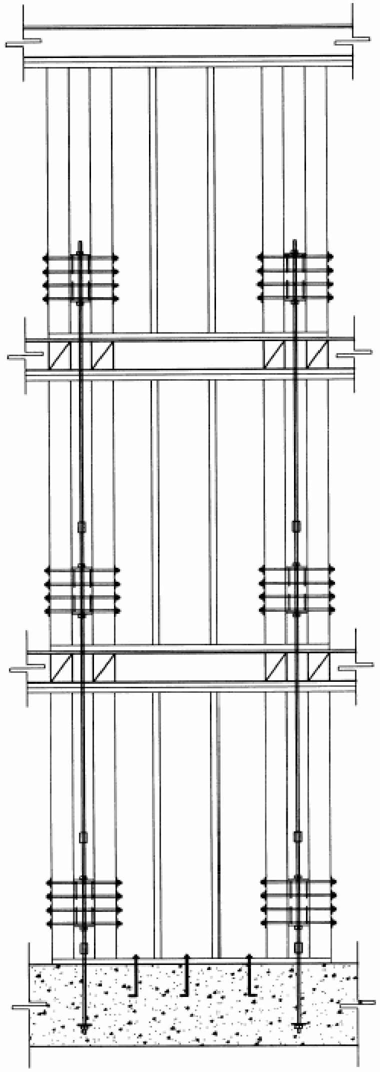
HOLD-DOWN PLACEMENT OF TRADITIONAL ENGINEERED SHEAR WALL

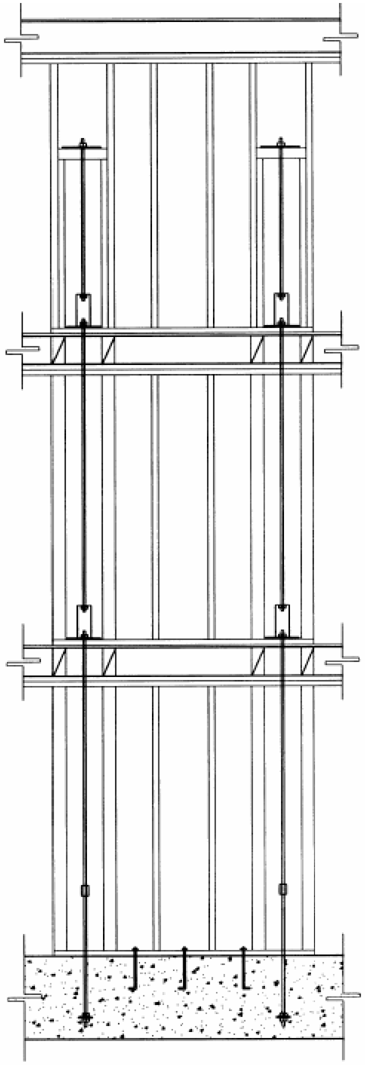


HOLD-DOWN PLACEMENT OF ENGINEERED PERFORATED SHEAR WALL



Narrow Shear Walls / Continuous Tie-Down Systems





Other Considerations

- **Ensure design for preventing progressive collapse is compatible with requirements for other loads**
  - **Continuity and splice considerations for rim beams or girders will be based on both analysis for bridging of deficient vertical members and requirements for horizontal ties or lateral loads**
  - **Even if a simply supported rim beam is sufficient for vertical analysis, the rim beam may still act as a peripheral tie or as the chord for the floor diaphragm and therefore require appropriate continuity and splice detailing**
  - **Detailing of exterior wall framing and sheathing may be governed by “deep beam” action for bridging or by shear wall forces due to lateral loads**

Useful References

- "Design of Wood Structures" Breyer, Fridley, Cobeen
- "Multi-storey timber frame buildings – a design guide", Grantham, Enjily ; BRE/TRADA (UK full scale testing)
- "LRFD Manual for Engineered Wood Construction" with supplements; AFPA/AWC
- LRFD Manual for Engineered Wood Construction – 2001 Supplement Special Design Provisions for Wind and Seismic
- "Diaphragms and Shear Walls – Design/Construction Guide"; APA
- "Lateral Load Connections for Low-Slope Roof Diaphragms"; APA
- "Continuous Tie-Down Systems for Wood Panel Shear Walls in Multi-Story Structures" Nelson, Patel, Arevalo; SEAOC Convention October 28, 2002

Useful References

- "Continuous Tie-Down Systems For Wood Panel Shear Walls in Multi Story Structures" Nelson, Patel in "Structure" Magazine March 2003
- "EWS Data File: Shear Transfer at Engineered Wood Floors", APA
- "Plywood Design Specification", APA
- "Research Report 138: Plywood Diaphragms", APA (includes testing and analysis of diaphragms with openings)

- APA documents available via www.apawood.org