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Lateral bracing in steel framed residential structures

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Abstract

One of the most critical design components in light framed residential structures is bracing. This includes bracing of the roof system, walls and sub-floor. Designers often have to make several assumptions concerning the behaviour of individual elements as well as subassemblies. They also have a growing suite of diverse bracing materials and techniques to choose from. This paper provides a brief review of bracing requirements for cold-formed steel-framed residential structures. The paper articulates the assumptions which underpin the bracing design for roofs and walls. Areas which require special attention are highlighted such as mixing of different bracing systems for walls.

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1. Introduction

While design of light framed residential structures is relatively simple, the load transfer mechanics are indeed complex. This is particularly evident in the way houses resist lateral loads due to wind or earthquakes. The complexity is due to the fact that there are usually several bracing elements made of different materials, utilizing many connections, which are combined to transfer the loads from the roof to the foundations. For example, lateral resistance provided by the walls could be available through a combination of strap cross bracing and cladding. This is complicated further by the presence of so-called non-structural elements, such as plasterboard lined partition walls, which may assist in resisting lateral loads.

In conventional bracing design, designers track the lateral loads from the roof to the foundation and provide bracing to the roof, walls, floor and subfloor as required. The paper discusses some of the assumptions which are often made during the analysis and design process and aims to provide advice where appropriate. Due to space limitation, the paper will focus on roof and wall bracing only.

2. Roof bracing

Roof bracing is required to ensure that the roof acts as an integral unit and transfers the imposed loads to the appropriate supports. One of the most common forms of roof construction is a truss system. For roof trusses, bracing for the top and bottom chords needs to be considered. Some trusses may also require web bracing if the web members are slender. Web bracing is normally considered as part of the truss design.

Design loads on cold formed steel houses are well covered by the new NASH Standard for Residential and Low-rise Steel Framing (NASH, 2005). The main function of the roof bracing is transfer the roof load acting perpendicular to the span of the trusses to the supports. This is clearly illustrated in Figure 1 which shows the distribution of wind load acting on a gable roof.

Top chord bracing is required to transfer the horizontal loads perpendicular to the span of trusses to the supports. Wind and earthquake loads are transferred to the top chords by the roof battens or purlins. The top chord bracing also provides restraint to the roof battens or purlins which act as lateral buckling restraints to the top chords of the trusses when they are in compression.

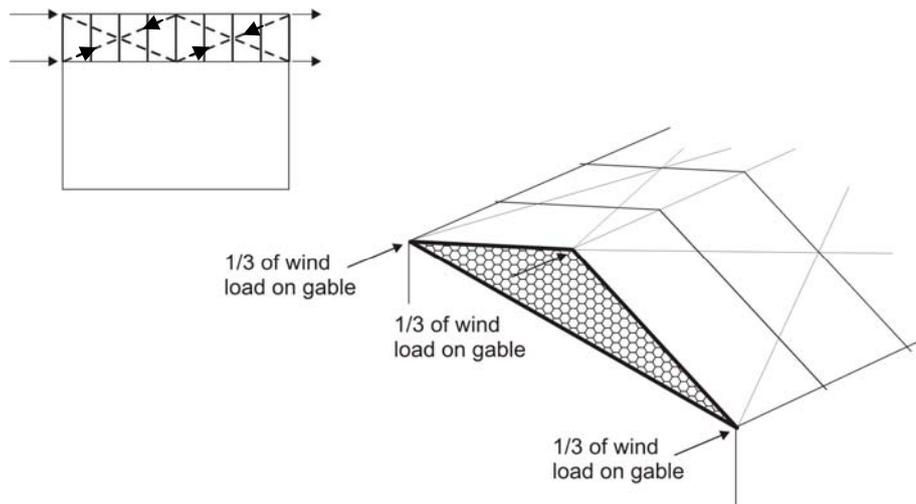


Figure 1: Typical distribution of wind load at roof gable end.

Similarly, bottom chord bracing is required to provide restraint against lateral buckling to the bottom chords of trusses when they are in compression due to wind uplift. If ceiling battens are directly fixed to the bottom chords and do not allow movement, these battens may provide adequate restraint. For suspended ceilings, exposed ceilings or ceiling battens which allow movement of bottom chords, specific bottom chord restraint may be required.

2.1 Diaphragm behaviour

It is often assumed that continuous ceiling lining, such as correctly fixed plasterboard, combined with the braced roof system can act as a rigid diaphragm. While the ceiling and roof may have some flexibility, they can be assumed to be effectively rigid compared with the stiffness of the walls. This is particularly evident when the bracing walls start to soften under ultimate load and become much more flexible compared to the stiff elastic diaphragm. This assumption of rigid diaphragm is consistent with experimental results from full scale testing of a steel-framed house conducted by the Cyclone Testing Station (Reardon, 1990).

It should be noted that in the USA, historically timber clad diaphragms were considered to behave in a flexible manner. This design model simplifies the analysis as the diaphragm can be simply assumed to act as a flexible beam supported by bracing walls. The load on each wall is then determined using tributary area approach. However, in recent years, the American International Building Code (IBC, 2000) has explicitly allowed designers to adopt either a flexible or rigid diaphragm assumption depending on the relative stiffness of the diaphragm to the walls. The definition of a flexible diaphragm is when the diaphragm deflection is two or more times the average shear wall deflection. When the diaphragm deflects less than twice the average story drift (shear wall deflection), then the diaphragm is assumed to be rigid. Based on research presented by Thompson (2000) it was found that for most light framed timber buildings, the diaphragms would be considered as rigid due to the significantly larger shear wall deformations as compared with the diaphragm deflection. The relatively rigid nature of diaphragm behaviour in typical light-frame timber buildings has been further observed and documented both experimentally and analytically (Kasal et al, 2004).

2.2 Top chord bracing

Under gravity load, the top chords of roof trusses are in compression. Subsequently, the top chords would have the tendency to buckle laterally (out of the plane of the truss). Without top chord bracing, lateral buckling could take place as shown in Figure 2. To prevent this buckling mode, the roof battens or purlins should be designed to resist a proportion of the compressive force in the top chords. The resulting forces in the roof battens or purlins should be transferred to the roof bracing.

As the roof trusses are generally parallel, the roof battens or purlins should be designed to resist a force equal to the sum of 0.025 times the maximum compression force in the top chord of one truss plus 0.0125 times the sum of the chord forces in the connected trusses beyond, except that no more than seven top chords (trusses) need be considered (AS/NZS 4600, Cl4.3). If there are seven identical trusses or more in the roof, the abovementioned force spread between the battens or purlins from the ridge to the eave can be taken as 10% of the maximum top chord force of one truss only (i.e., $0.025 + 6 * 0.0125 = 10\%$).

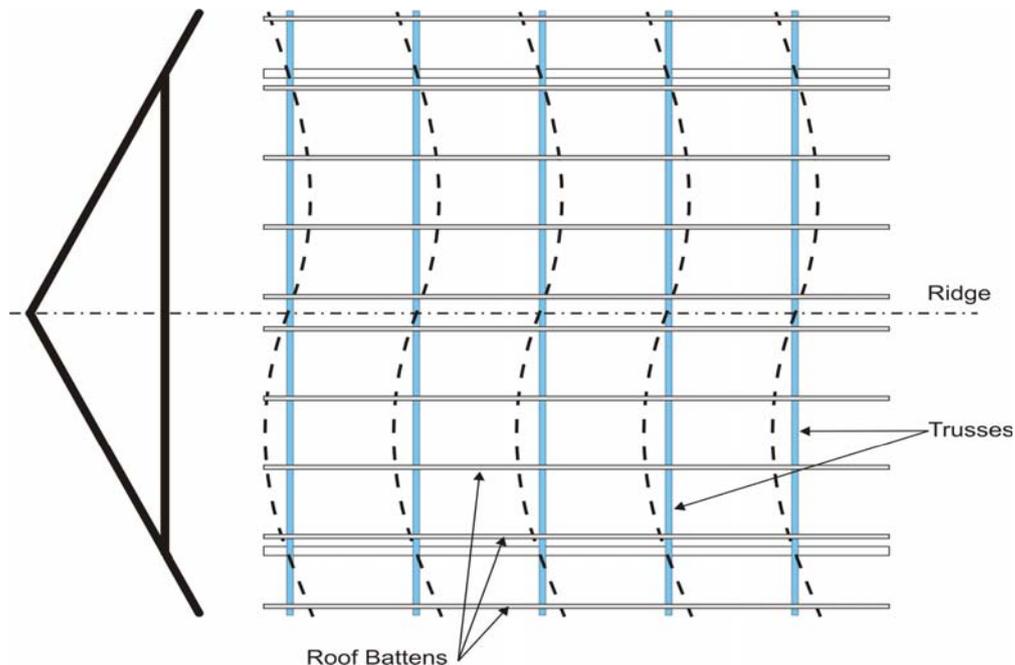


Figure 2: Potential lateral buckling mode for top chords of roof trusses.

The associated roof bracing is normally provided by cross strap bracing. The angle between a strap brace to supporting wall frame should be between 30° and 60° for optimum performance. Strap bracing are required to be fixed to intermediate trusses to assist in resisting lateral buckling of the top chords between the ridge and end supports. The strap braces should be tensioned to remove any slackness before intermediate connections are installed. It should be noted that while steel roof sheeting can provide significant bracing, during construction the roof trusses need to have temporary bracing which may be provided by strap bracing.

Design capacities of strap bracing in tension can be determined using the standard for cold formed steel (AS/NZS4600). Capacities of typical strap braces are presented in Table 1. The ultimate capacity that can be provided by strap braces is dependent on:

- The cross sectional area of the strap brace and grade of steel.
- The presence of holes required for installation of tensioner units which would reduce the net cross sectional area.
- The capacity of end connections. This is often the governing capacity when screws or rivets are used as there is normally limited space to install sufficient number of fasteners to achieve the full capacity of the brace. For example the design shear capacity of 10 gauge screw connection between two 1mm thick plates of G300 steel is 1.6kN. In accordance with Table 1, at least four such screws are required to achieve the full capacity of a 30x1.0 G300 strap with a hole for a tensioner unit. It would be rather difficult to fit that many screws and satisfy the minimum spacing between screws and edge distances. If screws are aligned to be side by side, the reduced net cross sectional area need to be considered in calculating the tension capacity of the strap.

Table 1: Capacity of typical strap braces in tension

Strap brace	Maximum design capacity in tension (ϕN_t) (kN)*	
	Brace with no holes	Brace with 6 mm hole for tensioner bolt
30x0.8 G300	6.5	5.0
30x1.0 G300	8.1	6.2
30x1.2 G300	9.7	7.5

* This table does not include the capacity of end connections.

2.3 Bottom chord bracing

Similar to the top chords, to prevent lateral buckling of the bottom chords, the ceiling battens or other suitable members need to be designed to resist a proportion of the compressive force in the bottom chords. As the roof trusses are generally parallel, ceiling battens should be designed to resist a force equal to the sum of 0.025 times the maximum compression bottom chord force from one truss and 0.0125 times the sum of the bottom chord forces in the connected trusses beyond, except that no more than seven chords (trusses) need be considered (AS/NZS 4600). This total force is distributed between the ceiling battens (i.e., if there are 10 battens each batten would take a tenth of the force calculated above).

If the ceiling battens are directly fixed to the bottom chords and do not allow relative movement, they may provide adequate restraint. For ceiling battens which allow movement of bottom chords, additional specific restraints need to be provided. Clip on battens may be assumed not to provide adequate restraint unless proven otherwise by testing.

In typical residential structures, the ceiling lining is normally assumed to provide adequate bracing to the battens. If specific design is required, stress skin design approach may be utilized to assess the performance of the ceiling lining. In situations where specific bracing to the bottom chords is required, strap bracing could be an appropriate solution.

3. Wall bracing

Wall bracing is required for each storey to transfer the horizontal shear forces generated by wind and earthquakes to the appropriate supports. All in-plane walls in the structure provide varying levels of resistance, but when walls are specifically designed to resist racking forces they become 'designated bracing walls'. Other in-plane walls which are not specifically designed for this purpose are known as 'nominal bracing walls'. There could also be some contribution from bending of transverse walls, however, their contribution is neglected.

There are several types of wall bracing. These include K-bracing, cross strap bracing, sheet bracing (e.g. that provided by fibre cement, hardboard and plasterboard). It is also becoming common to use portal frames in providing lateral bracing where no walls are available.

3.1 Nominal bracing walls

It has been long recognized that light framed walls with nominally fixed lining have some bracing capacity. Tests on isolated walls (Gad et al, 1999) and a full scale house (Reardon, 1990) have clearly demonstrated that typical non-structural walls with plasterboard lining and conventional fixing can provide considerable bracing capacity.

The load paths to both designated bracing walls as well as nominal bracing walls can be complex. The lateral loads from the roof can be transferred to the walls via the frame and/or ceiling cornices if they are present. Two example load paths are diagrammatically shown in Figures 3 and 4.

In Figure 3, the lateral load (assuming wind load) is transferred from the roof (1) to the bottom chord of the truss (2) and then to the top plate of the wall (3). The load along the top plate is then transferred to the wall cladding or lining (4) via the connecting fasteners. This is the most common mechanism used in wall testing procedures where the racking load is applied directly to the top plate.

Figure 4 shows a distinctly different load path to a partition wall. In this case the wind load is transferred from the roof (1) to the ceiling diaphragm (2) and then to the ceiling cornices (3). The cornices would then transfer the load to the lining (such as plasterboard) (4) which in turn transfers the load to the wall frame (5) via the fasteners connecting the lining to the frame. Finally the load is then transferred from the wall frame to the floor (6).

It is possible that combinations of the load paths presented in Figures 3 and 4 could occur. The interaction of the structural system (e.g. frame and designated bracing walls) and so-called non-structural components (e.g. cornices and plasterboard lining) is often referred to as "system effects".

In recognition of the contribution of lining to lateral bracing, the Australian Residential Timber Framed Construction Standard (AS1684) permits the inclusion of contributions from nominal bracing walls to the total bracing as long as such walls do not contribute more than 50% of the required bracing capacity.

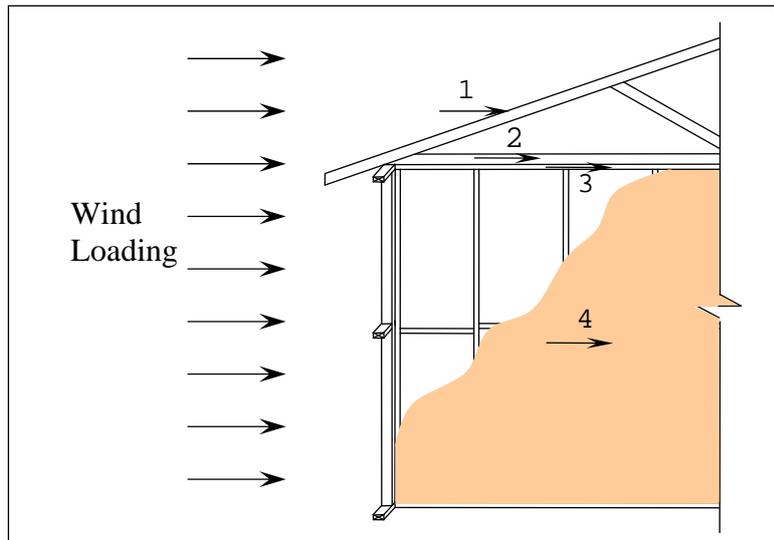


Figure 3: Load path to a wall connected to roof trusses. The numbers indicate the sequence of load transfer.

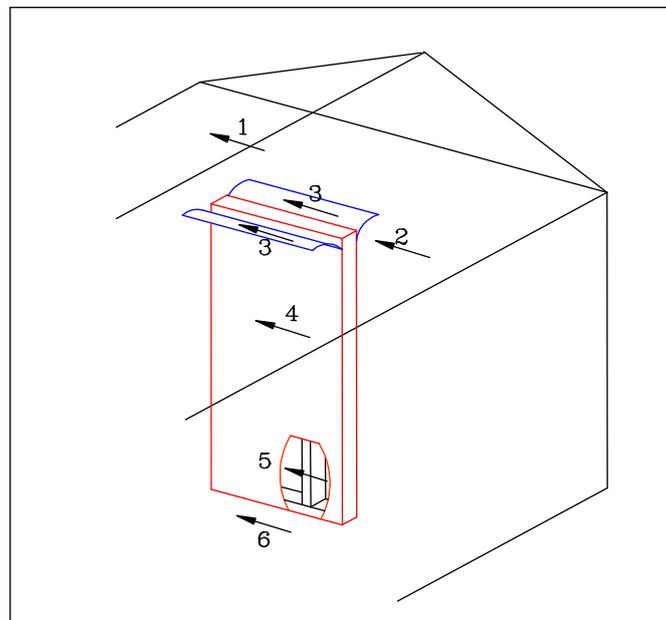


Figure 4: Schematic diagram showing the lateral load path of a non-bracing (partition) wall with no adjacent walls.

3.2 Combination of bracing systems

In steel and timber framed houses, the total bracing capacity of the structure is simply calculated by adding the capacities of individual walls including nominal bracing walls. The capacities of individual walls are typically obtained by testing. Manufacturers of different bracing materials, such as fibre cement, steel sheets and plywood, provide design capacities for various products and fixing details.

In order to simply add the ultimate capacity of all bracing elements to obtain the full resistance of the structure, an important assumption must be satisfied. For contribution of different bracing elements to be additive, all elements should have compatible deformation capacity or sufficient ductility. This concept is illustrated in Figure 5 which shows the racking load versus deflection relationships for two walls with different bracing types. In this figure, walls I and II are shown to

have ultimate capacity of about 7kN and 5kN, respectively. These ultimate capacities are cumulative if the structure is designed or assessed at lateral deflection between about 8 and 12mm. However, at higher levels of deflection, for example 15 to 20mm, the contribution of wall II is very limited and the ultimate capacities of the two walls are not cumulative.

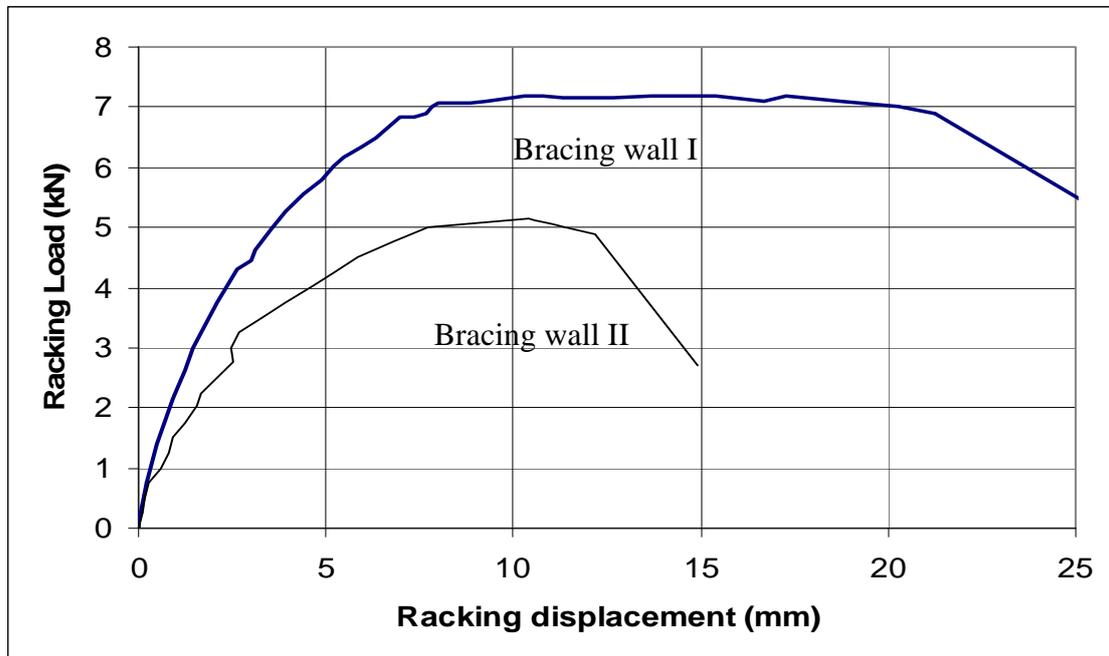


Figure 5: Illustration of the importance of deformation compatibility or ductility in assessing the cumulative effects of different bracing type.

The ultimate capacity and ductility of bracing systems depend on several factors including the type and mechanical properties of the bracing material, the type and number of connections between the bracing and frame as well as the properties of the frame itself. In general strap bracing, plasterboard, plywood, fibre-cement and steel-sheet bracing can be assumed to be compatible at low levels of deformation and hence the resistances can be additive. Typical cross strap bracing and plasterboard lined walls would fail at a racking displacement in the order of 15-20 mm which is lower than that for plywood and steel-sheet bracing which can sustain deformations in excess of 50 mm before ultimate failure occurs.

3.3 Anchorage of designated bracing walls

For bracing walls to be effective they must be correctly anchored. Significant uplift forces could be generated at the ends of bracing walls. For walls with aspect ratio (height/length) of more than 1, the uplift forces are greater than the imposed racking loads. In order to transfer the imposed uplift forces to the supports, stud to plate connections should have adequate capacity and bottom plates should be correctly anchored to prevent uplift.

It is also important to locate the bottom plate anchorage points as close as possible to the end studs to avoid excessive bending moments and potential buckling of the bottom plate. Some proprietary anchorage hardware are in the form of angle brackets which reinforce the connection between the end stud and bottom plate and also provide the means of connecting the bottom plate to the support underneath. For other details where simple bolted connections between the bottom plate and the support are utilized, it is common to use a large and thick washer as shown in Figure 5.



Figure 6: Well detailed bottom plate anchorage showing heavy washers located as close as possible to the end studs.

In addition to the fasteners between the end studs and bottom plate and between the bottom plate and its supports, some additional anchorage at the ends of bracing walls may be available through system effects. These include connections to other framing members (e.g. intersecting or return walls), shear transfer through corner plasterboard joints and continuity of top and bottom plates. The load sharing between all of these load paths is dependent on their relative stiffness. The significance of each load is difficult to determine analytically because of the numerous and varying connections between different materials and members. However, the significance of these interactions has been demonstrated through testing of full scale houses (Reardon, 1986; Reardon 1990; and Reardon and Mahendran 1988) and subassemblies (Golledge et al, 1990).

The additional anchorage available due to the system effects has been recognized and documented in New Zealand since the introduction of the test method for bracing walls known as P21 which was developed by BRANZ (Cooney and Collins 1988). This test method allows the provision of a supplementary end stud restraint at each end of the wall with a capacity of 6 kN to account for typical additional anchorages available through the system effects. While the 6 kN supplementary restraint in the P21 method was quantified for timber framed houses, comparable effects can be demonstrated in typical steel-framed houses.

For bracing walls adjacent to large openings such as garage doors with no intersecting walls, the abovementioned contributions could be minimal and the end anchorages should be fully provided by specific end restraints.

4. Concluding remarks

This paper highlighted some of the basic assumptions often adopted in analyzing and designing bracing systems for light-framed residential structures.

For roof design it has been highlighted that a rigid diaphragm approach is appropriate particularly when a mix of different wall bracing types is often used. In the actual roof truss design, the importance of both top chord and bottom chord bracing has been highlighted. In particular, the

battens need to be designed to provide lateral restraint to the chords of the roof trusses. Typical capacities for strap cross bracing which could be used for either the roof or walls have been tabled.

While it is common to use different wall bracing systems (e.g. clad walls and cross strap bracing) it has been highlighted that such systems should have comparable levels of ductility so that the designer could add the ultimate capacities of different systems. This is an important underlying assumption in wall bracing design. The paper emphasized the importance of correct wall anchorage detailing and also the possible additional anchorage contribution available through system effects.

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