This is an unedited, uncorrected chapter.

The final chapter will be available in time for fall.

NOTE: Figures and tables appear at the end of the chapter.

WEB CHAPTER W3

Structures

W3.1 Lateral Load Resisting Systems in Framed Multistory Buildings

Figure W3.1.1: Some combinations of shear bents.

In general, most building structures include several shear bents in each direction, and they may consist of a combination of one or more of the three different types mentioned in Section 3.3. Some traditional combinations are shown in Fig. W3.1.1.

Wherever physically and architecturally possible (depending upon site geometry, foundation restrictions, etc.), it is recommended to provide structural symmetry in elevation and plan to reduce eccentricity of the building. Also, the shear bents (braced bents, moment resistant frames, shear walls, core walls, and/or core shafts) should preferably be located symmetrically to provide the building with reasonably uniform stiffness.

It would be impossible to discuss all the combinations of lateral load resisting systems used in practice. The designer should feel free to use an arrangement of framing that is best suited for the project at hand. Several common arrangements are described below [Iyengar, 1972;

Schueller, 1977; Taranath, 1988; CTBUH, 1995]:

1. No explicit use of shear bents

For buildings of moderate height, with moderate aspect ratio (below 0.5 to 1.0), the wind forces are generally so small that they can be ignored in the design of the steel frame. In these buildings, gravity load strength requirements dominate the design of the system, as well as in the design of individual members. The inherent stiffness of the standard framed connections produces a skeleton which has the strength to resist lateral forces without the help of special wind bracing. Frames with simply connected girders are economical for buildings up to about six stories high if they have brick or masonry in-filled exterior walls.

2. Use of braced bents or shear walls in end walls

When a building must be braced for wind or other lateral forces, an economical and efficient solution is to use a system of braced bents or shear walls. Since the floors act as rigid diaphragms in their plane, braced bents in the two outside walls may be sufficient, in many cases, to transfer the entire wind load (Fig. W3.1.1*a*). Then only simple connections may be used between the girders and columns throughout the entire structure, inclusive of the braced bents, as the rigidity of the joints is not essential. As the height, and hence the lateral load on the shear bent increases, more panels in the grid line may require bracing. Braced bents of different configurations may be provided in the same system. Up to a certain aspect ratio (the ratio of truss height to truss width), ρ^o, the

braced bent requires little or no increase in the size of beams and columns (beyond that required for gravity loads). The only material required for transfer of lateral loads is the brace material. Above this ratio, additional material will be required in the beams and especially columns to transfer the lateral loads. Above another specific aspect ratio, ρ^*, axial deformations of columns increase rapidly, and additional material will be required to achieve drift control over and above that required for strength. The efficiency of the braced bents could be increased by spreading the truss chords as far apart as possible and by diverting as much gravity load as possible to these chords to prevent or reduce net tensile force. Braced bents are efficient up to about 40 stories.

3. Braced bents in service cores

In low- to medium-rise buildings, lighter structural systems are obtained when the gravity loads and the lateral loads are channeled to two separate structural systems. This simple concept often results in buildings with relatively flexible exterior bents and an inner core of stiff wind bracing frames (Fig. W3.1.1*d*).

Steel moment connections are costly to fabricate and to erect. However, if the inner core using shear walls or braced bents were stiff enough, one could avoid the moment connections between the beams and the columns of the skeleton, and use much less expensive simple connections. The outer hinged bents carry the gravity loads to the foundations, while the lateral loads transmitted to the core, by the roof and floor diaphragms, are carried to the ground by the core. However, the outer hinged frame columns lean on the rigid stiffened core and transfer to the core additional destabilizing

moments known as $P\Delta$ moments as will be seen in detail in Chapter 8. Such columns are known as ***leaning columns***.

For a given floor plan and core dimensions, as the height of the structure, and hence the aspect ratio of the core, increases above a value ρ^o, additional material will be required in the horizontal and vertical members of the cantilever truss over that required for the gravity loads on the core. A tall structure braced in one narrow core may deflect too much. So, as the aspect ratio of the core exceeds another threshold value, ρ^*, additional material over and above that required for strength will be required to achieve drift control.

Core shear wall tubes have generally not been used as the sole lateral force resisting system for buildings over 20 to 25 stories in height because of their limited horizontal dimension.

4. Moment resistant frames only

When conditions prevent the use of braced bents or shear walls, moment resistant frames must be used to resist all lateral loads (Fig. W3.1.1*b*). The moment resistant frame is less stiff and deflects more than the braced bent. The framing in a moment resistant frame may be made with fully rigid or semi-rigid connections. Because of the excessive deflection, moment resistant frames are generally only used for low- and medium-rise buildings. In effect, as the height of the building increases, a stage will be reached when the moment resistant frames require larger member sizes at the lower levels of the building to limit the story drift. In frames over 15 stories, the two main contributing

effects on lateral drift are those due to bending deformation, in both beams and columns, and those due to the axial deformation of the columns. This latter effect becomes predominant for slender frames. Thus, as the height of the frame increases, the axial stiffness of the columns plays a significant role compared to the column bending stiffness. Moment resistant frames are efficient up to about 30 stories, but their economy reduces after about 20 stories.

5. Combination of braced bents and MRFs

Moment resistant frames, braced bents, or shear walls will often be able to resist the lateral loads for buildings up to about 20 stories without a substantial premium of additional material. Moment resistant frames and braced bents, located on parallel grid lines, may be combined in the same structure to resist lateral loads, as shown in Fig. W3.1.1*c*. Such dual systems, in which a combination of braced bents and unbraced bents are used to resist lateral forces, were found to be efficient for buildings of about 40 to 60 stories.

6. Combination of core shaft and moment resistant frames

It is not always possible to completely brace a medium- or high-rise tier building through the braced bents of the core shaft alone. The braced bents of the core, when interconnected with moment resisting frames outside the core, force the two structural subsystems to deflect together and produce a frame-truss interacting system of increased lateral strength. Frame-truss interacting systems have a wide range of application for

buildings up to 30 to 35 stories in height. For heights above 35 to 40 stories even these improvements fail to give economical structures.

W3.2 Lateral Load Resisting Systems in Industrial Buildings

To transfer the wind loads and crane loads in the lateral and longitudinal directions of the building to the foundations, to minimize vibration caused by equipment, to prevent the building from twisting under a diagonal wind, and to provide rigidity and stability under lateral as well as vertical loading on the structure, a system of diagonal bracing (***roof bracing***) is generally included in the upper and lower chord planes of the roof trusses, in the endwalls ***(transverse bracing***), and in the longitudinal walls (***longitudinal bracing***) of the building. The bracing also helps stabilize the structure during erection. Buildings of low height-to-width ratio having heavy continuous walls derive much bracing advantage from the walls. Whether additional bracing is necessary or not must be left to the analysis and the judgement of the designer in each particular case.

A ***transverse bent*** may be designed to resist the lateral wind forces brought to it by the exposed contributing area of each bay, and to resist crane lateral thrust, if appropriate. The wind loads on the longitudinal faces of the building are thus transferred by flexure from the columns to the column bases. However, the resulting bending moments from lateral loads may require heavier columns, depending on the relative values of the gravity and wind loads. Alternatively, the transverse wind forces may be carried by a horizontal truss system, in the plane of the lower

chord of the roof truss. The end walls, or columns and bracing in the end walls, act as end supports of this horizontal truss. The wind loads on the longitudinal faces are transferred, in this case, only to the bases of the columns in the end wall braced shear bent.

The transverse bents are stable against sidesway, but not stable when subjected to forces normal or inclined to the plane of their spans. A stable substructure can be developed, however, by providing bracing between two adjacent bents, in the plane of the longitudinal walls and in the plane(s) containing upper and/or lower chords. For this purpose, diagonal bracing members and longitudinal struts between these bents at the connection points of cross bracing are used. This stable structure is known as a ***braced bay*** (Fig. 3.4.1*a*). Each building structure should have at least two such substructures. When the bracing is placed only in the end bays of a long structure, large internal forces and distortions may develop due to the accumulated temperature movement. Thus, it is customary to brace every fourth or fifth bay in long structures.

The wind acting against the end wall of a building is transferred by horizontal trusses in the planes of the chords to the vertical trusses (concentrically braced shear bents) in the end bay. Thus, longitudinal bracing may be put in three planes. Bracing in the plane of the roof is called the ***roof bracing*** or ***top chord bracing***; bracing in the plane of the bottom chords is referred to as ***bottom chord bracing***; and bracing in the vertical plane between the columns is called ***wall bracing***. When crane runway girders are present, bracing in the walls of the intermediate bays may be needed to transfer the longitudinal forces set up by the starting and the braking of the crane to the foundations.

The longitudinal struts, and in particular the ridge strut R and the two eave struts E, run end to end along the total length of the building and are of constant cross section. Purlins often substitute for struts in the top chord, and girts may also be designed to serve as struts. In the use of wall girts, incorporating one girt (strut, S) along the line of the truss lower chord connection to the column, and another, if appropriate, along the line of the crane girder bracket connection to the column, is considered good practice.

Roofs, in addition to supporting gravity loads applied normal to their plane, may be designed to act as rigid diaphragms in their own plane to collect and transfer lateral loads such as wind to the rigid diaphragms in the vertical plane (longitudinal walls and end walls) of the building, and then to the foundations. Roof diaphragms are generally horizontal but can slope, can be curved (for example, a roof using a bowstring truss), or can include changes of slope (for example, a roof with a ridge). Diaphragms to resist wind loads can be classified as truss diaphragms, plate diaphragms, and stressed-skin diaphragms.

At present, the high cost associated with fabricating and handling the great variety of different elements and the great number of connections required to interconnect the elements make the use of trussed diaphragms in industrial buildings uneconomical. However, older structures that used trussed bracing must sometimes be altered or analyzed for the effect of loading which is different than that for which they were designed. Hence, it will be useful to study trussed diaphragms in detail. Also, the novice designer can easily identify what every portion of a trussed diaphragm (TD) and trussed shear bent (TSB) is doing, permitting him or her to specifically tailor every

element to its special function and gain an understanding of the transfer of wind loads on a three-dimensional industrial building. With this knowledge, the designer should have less difficulty in understanding the behavior of integrated structures that incorporate roof slabs and shear walls or horizontal and vertical stressed-skin diaphragms.

W3.3 Shear Diaphragms

W3.3.1 Plate Diaphragms

The same steel decking or concrete slabs used to support gravity loads of the roof or floor, when adequately interconnected to each other and provided with adequate connections to the framing members, can also function as diaphragms to resist lateral forces. In addition, the steel wall panels, when properly connected to each other and to the end wall columns, act as vertical shear bents to transfer wind loads from the roof level to the foundation, and to provide in-plane stiffness for displacement in the transverse and longitudinal direction.

For most building configurations, the diaphragm acts analogous to a deep, horizontal, plate girder. Thus, the slab or deck acts as the web of the pseudo-girder to resist shear induced by lateral forces. The framing members at the diaphragm edges normal to the direction of the load (such as spandrel beams, eave strut, and ridge purlins) serve as the flanges of the pseudo-girder, resisting the flexural stresses. These flange members are subjected to tensile or compressive forces along the length of the diaphragm edge and are traditionally referred to as ***chords***. Each chord must be designed for both tension and compression since the chord forces reverse with the reversal of wind load direction. Further, the chord members must be made continuous by

splicing and are made more rigid by staggering the splice locations in the two chords.

Shear forces are transmitted from and to the diaphragm via different structural members. The members transferring shear forces from the diaphragm to the vertical shear bents are called ***struts***. Framing members in the interior of the diaphragm that transfer shear forces into the diaphragm are referred to as ***collectors*** or ***drag struts***.

The stiffness of the steel decking, when used as a roof diaphragm, must be sufficient to prevent shear buckling. In addition to the thickness and depth of the rib, the type, strength, spacing, and integrity of fasteners are important parameters that define the shear transfer capacity of the diaphragm. Diaphragm strengths and stiffnesses of the metal deck are generally established by tests. Design of steel deck diaphragms will not be discussed in this text, and it is recommended that the reader refer to [AISI,2001; Yu, 2000; Luttrell, 1987] or to the manufacturers' catalogs. Any large opening or discontinuity in the metal deck will disrupt the transfer of shear forces by the diaphragm and should be avoided. Also, when panels are designed as shear diaphragms, a note shall be made on the drawings to the effect that the panels function as braces for the building, and that any removal of the panels is prohibited unless other separate bracing is provided.

Plate diaphragms, when properly designed, also act as continuous lateral bracing to prevent lateral buckling of the beams, and to prevent column buckling in the plane of the diaphragm.

W3.3.2 Truss Diaphragms in Industrial Buildings

Wind acting on the longitudinal walls of a building (transverse wind loads) is transmitted from these walls to the wall girts G acting as horizontal beams between the columns of adjacent bents (Fig. 3.4.1). The girts, in turn, transfer the wind loads to the truss columns such as C or CB. If a truss is used having some depth at the ends, the columns run through to the rafter, and the transverse wind load tributary to the bent may be transferred to the foundations of these columns entirely by flexure in the columns. However, it is generally more economical to transfer all transverse wind loads to the concentrically braced shear bents (vertical trusses) in the end walls of the building, by means of a horizontal trussed diaphragm (bracing) in the bottom chords of the roof trusses, and then to the foundations in the end walls (Fig. 3.4.1). The wall strut S (line 5 in Fig. 3.4.1*c*), tension member T (line 4 in Fig. 3.4.1*c*), bottom chord members of trusses delimited by S and T, and a system of diagonal members DT form a horizontal truss diaphragm at the truss bottom chord level. This diaphragm transfers the transverse wind loads to the concentrically braced shear bents in the end walls. The bottom chord of the roof truss in the end wall EB is delimited by the corner column CC and the adjacent end wall frame column CS. A system of diagonals, DS, form a transverse concentrically braced shear bent (Fig. 3.4.1*a*) and transfer the transverse wind loads applied by the diaphragm at the bottom chord level to the foundations of the columns CC and CS.

Wind acting on the end walls of the building (longitudinal wind load) is resisted by the siding supported on the girts GS acting as horizontal beams. The girts are, in turn, supported by the end wall framing columns CC and CS. These columns transmit the wind load partly to the

foundation and partly to the bracing trusses in the planes of the top and bottom chords of the roof trusses. The ridge strut R, eave struts E, and roof purlins P, delimited by the top chords TB of the roof trusses A and B in braced bay, and a system of roof diagonals DR in the braced bay form a roof wind bracing truss (roof diaphragm with a change of slope). This diaphragm transfers the longitudinal wind loads, applied by the end wall framing columns CS, to the eave struts, E, of the building. In addition, the wall struts S, the struts SB delimited by the truss bottom chords BB of the braced bay bents A and B, and a system of diagonal bracing DL form another horizontal diaphragm (Fig. 3.4.1*c*). It transfers the longitudinal wind load, applied by the end wall framing columns CS at the lower chord level, to the struts S in the longitudinal wall of the building located at the bottom chord level. Next, the eave strut E, wall strut S, and the wall girts G delimited by the two columns CC and CB of the braced bay AB, and a system of diagonals D form a vertical cantilever truss. This longitudinal concentrically braced shear bent transfers the longitudinal wind loads (transferred by the roof diaphragm to E and by the bottom chord diaphragm to S) to the foundation.

The truss diaphragms can be analyzed in the same manner as vertical trusses with the loads being the tributary lateral forces due to wind loads on the structure. Note that the ridge strut R, eaves struts E, some purlins P, and the bottom and top chord members of the main trusses in certain panels (required to support the gravity loads) will also serve as part of the lateral force-resisting system for carrying the wind loads. Some of these members will be stressed by gravity loads, transverse wind loads, and longitudinal wind loads. So, all of the appropriate load combinations (LC-1 to LC-7 discussed in Section 4.10) should be considered to arrive at the critical load

combination for the design of each member.

The ridge strut R generally consists of two channels or I-shapes tied together by a tie rod (Fig. 3.4.2*b*). They act as a unit to support the roofing and are part of the roof bracing system. The eave strut E consists of a built-up section formed of a channel and an angle combination, which acts as a beam to support the roof sheeting and sidewall sheeting. It also forms part of the wind bracing system. The longitudinal members R, E, P, S, G, and T are unchanged in their respective sections from one end of the building to the other. The diagonal bracing members are usually made up of rods, bars, or single angles. Stresses in bracing members are often nominal and members are selected mainly to provide stiffness and to satisfy the minimum slenderness limitations (L/r values) imposed by the specifications. Today, cold-formed channel sections are used for purlins and girts.

The use of diagonals solely in the end bays, though common, is not recommended for long buildings because of temperature effects. When a long building expands, the column bases do not move; hence, the columns are forced outward at the top, particularly those columns located toward the ends of the building. The diagonal bracing tries to resist this movement and may be over stressed. To avoid this, additional braced bents may be placed near the center.

References

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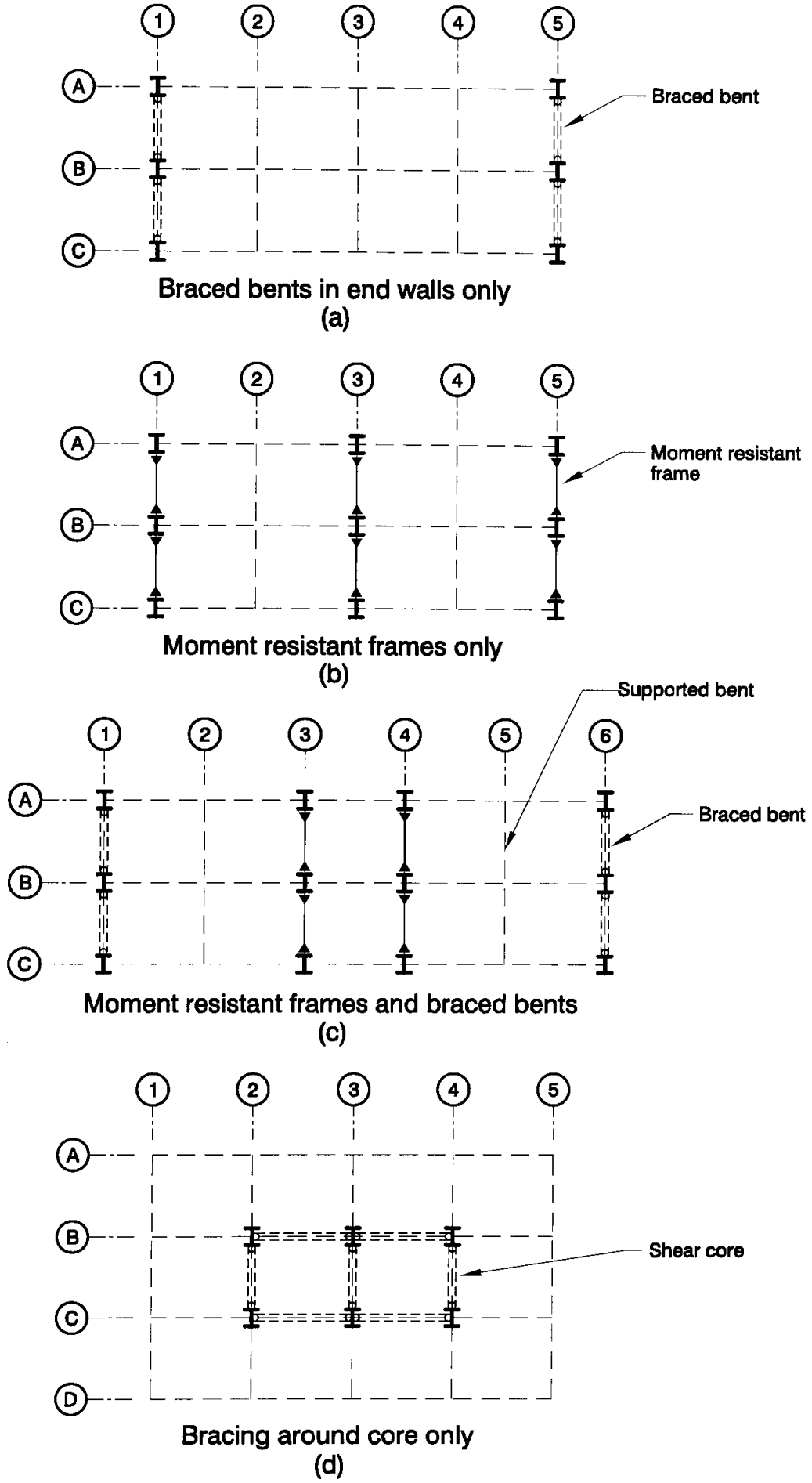

Figure W3.1.1: Some combinations of shear bents.