The contractor did not follow the contract requirement to limit the advancement of the uppermost lifted slabs to not more than three levels above the level of completed shear walls. Also, he did not provide guys or bracing for the lateral support, an alternative provision in the contract documents if the shear was installation was to be below the required minimum height (www.engineering.com, Kaminetzky 1991).

Lessons learned:

1. Temporary lateral bracing must be provided at all construction stages.
2. Contract requirements must not be ignored while accelerating the construction schedule.

3.2.Stability concepts

Stability is one of the primary concerns in designing a structure for any load condition. When load is applied, internal forces will be generated causing the structure to deform. In a stable structure, this deformation is usually small and after the load is removed the structure will restore its original shape. In an unstable structure the deformations are massive and the structure does not produce internal forces that tend to restore the original shape of the structure (Schodek, 2004) Stability failures are often sudden and catastrophic. During the construction process builders need to be especially wary of instabilities in the structure being erected, since it will pass through phases where critical permanent stabilizing and bracing members may not be in place. Temporary structures used to provide stability are themselves susceptible to instability and must be designed to meet this critical condition.

Consider (Figure 1). The simple (pin connected) column-beam frame appears to be stable. However, under any lateral load such as wind load, this frame will undergo deformation and collapse due to ability of joints to rotate and lack of members to resist lateral loads (Figure 2).

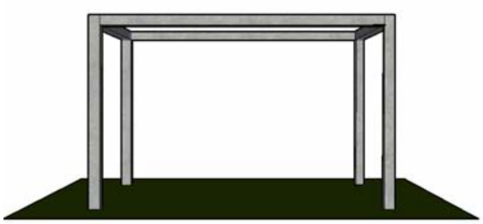


Figure 1: Column beam frame

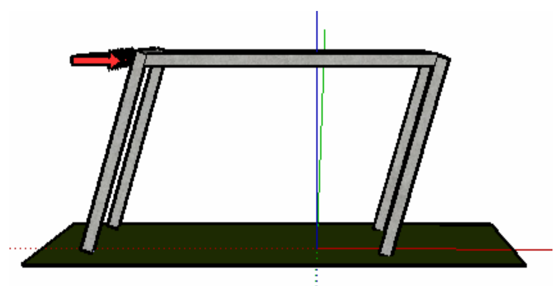


Figure 2: Instability of the frame under lateral loads

The pictures below demonstrate the deformation caused due to inadequate lateral load resisting system.



There are three ways to prevent the collapse of this frame. These are:

1. Additional diagonal members, commonly referred as “Bracings”
2. A stiff diaphragm plane such as a wall used as “Shear Wall”
3. Moment resisting connections or rigid joints.

When a diagonal member (bracing) or a block wall (shear wall) is inserted or when rigid frame connections are used, the structures becomes stiff and capable of transferring the load, thus preventing the collapse (Figure 3). The term “Shear Plane” is used to describe any of these methods that provide the stiffness and load transmittal capabilities (Schodek, 2004).

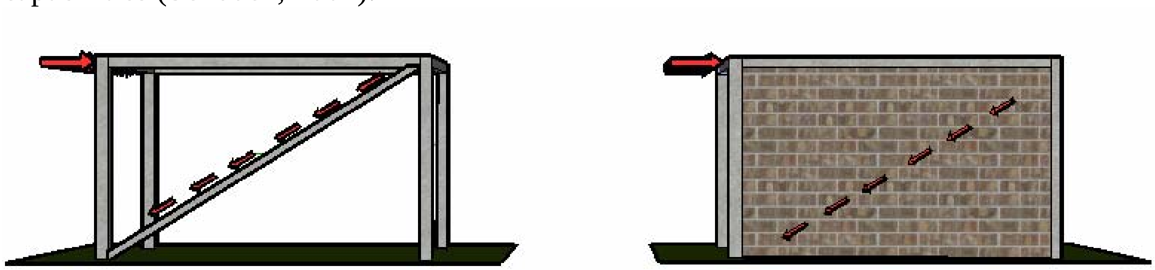


Figure 3: Systems offering lateral resistance (a) Bracing (b) Shear wall

1. Bracing: Bracing is one of the most widely used lateral resisting systems. When bracing is added, the structure can not undergo the deformation under the lateral load; refer to Figure 2) if the bracing is adequately sized. Following are the different types of bracing:

(i) *Single Diagonal Bracing:* As the name suggests, only a single diagonal member is used. This member is designed to resist both, tension as well as compression caused by lateral forces acting in both directions on the frame (Figure 4 and 5)

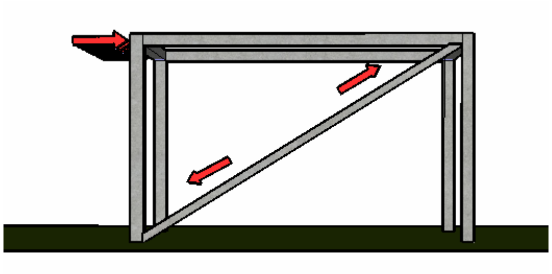


Figure 4: Brace in tension

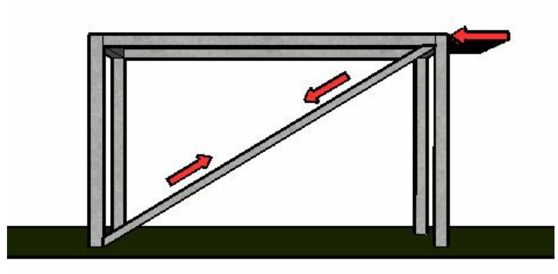


Figure 5: Brace in compression

(ii) *X Bracing/Cross Bracing:* This is the most economical and efficient forms of bracing. When the cross bracing is used, lateral force from one direction induces tension in one member while the other brace is in tension when the force is reversed (Figure 6).

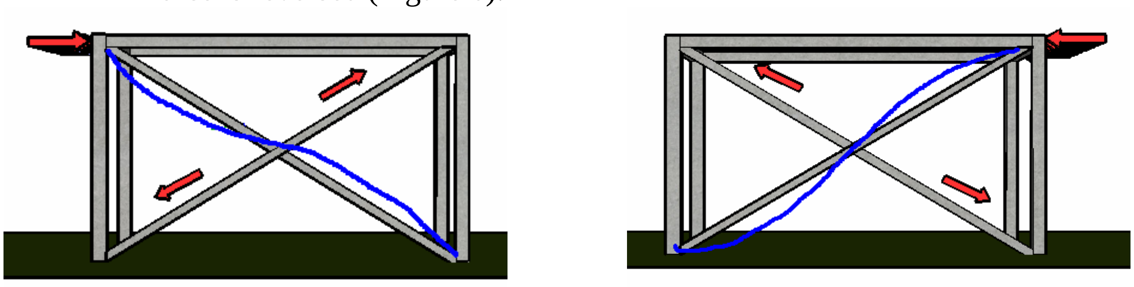


Figure 6: One brace in tension, other goes in slack

Therefore, if two diagonals are used, in the form of cross-bracing, they only need to resist *tension*. When one brace is in tension, compression is induced in the other. However, the slender compressive brace immediately sheds this compression by buckling out of plane to avoid the force. Thus, the other brace then has to take 100% of the lateral force in tension. Therefore, the compressive brace may be ignored. Steel cables can be used for cross-bracing, as they can be stretched, but not squashed (http://www.ideers.bris.ac.uk/resistant/strength_brace_cross.html).

(iii) *Inverted V bracing:* Though the X-bracing is the most efficient and economical type of bracing, many times it is not used. X-bracings run across the entire wall area and it becomes impossible to accommodate required openings such as for windows and doors. In such instances, inverted V-bracing is used that allows for the opening, such as a window or a door (Figure 7)

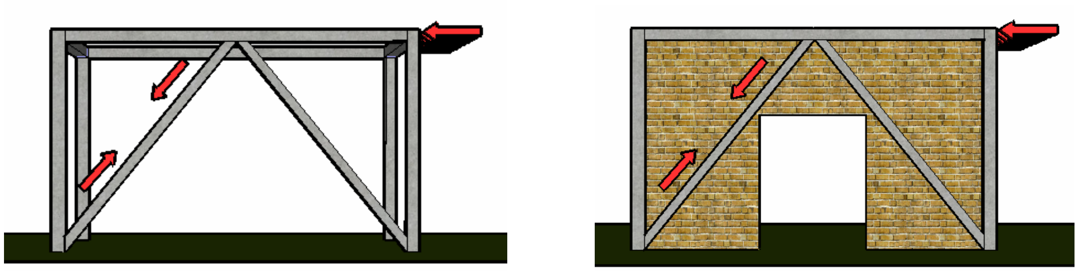


Figure 7: Inverted "V" Bracing

(iv) *Corner/Knee Bracing:* This is another type of bracing that is used as the same purpose as V bracings, to allow for an opening. (Figure 8)

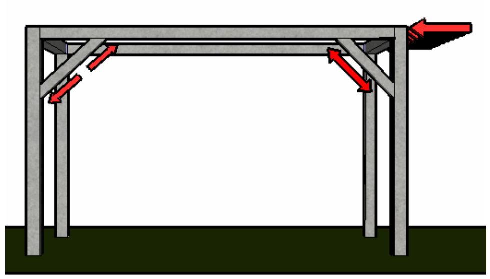


Figure 8: Knee Bracing

(v) *K-Bracing:* K-bracing is used where full height openings are required. However K-bracing is not as efficient as X-bracing (Figure 9)

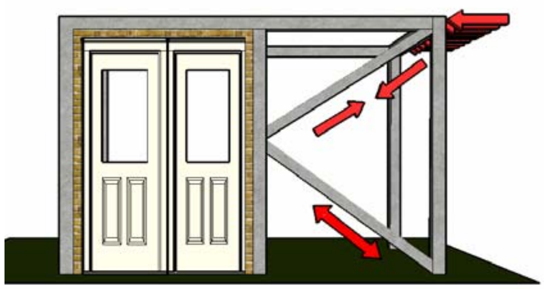


Figure 9: K-bracing

2. Shear wall: Shear walls are rigid planer surface elements that inherently resist any change in the shape. A concrete block wall, or reinforced concrete wall can be used as a shear wall. Depending upon the magnitude of the forces either a full or partial wall may be used. (Figure 10)

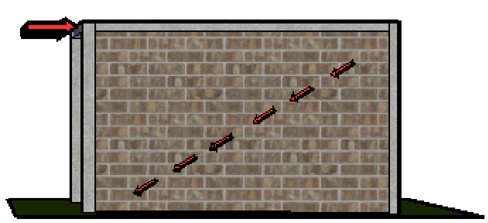


Figure 10: Shear Wall

3. Moment connections/ rigid joints: Under lateral forces, a structure collapses due to large angular deformations in the members. One method to prevent such angular deformation is making connections between the members rigid. Rigid joints prevent any angular deformation that could take place under lateral loading. (Figure 11)

Moment connections offer the frame action that can be used to resist lateral loads, however these are less efficient than shear walls or braces. Moment or rigid connections induce high bending moments in structure resulting into large member sizes. Thus, rigid connections are not generally used for larger buildings.

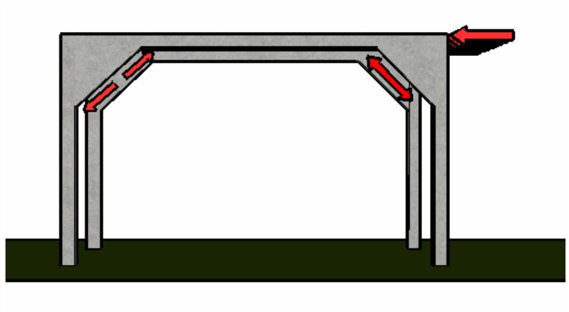


Figure 11: Rigid Joints

Horizontal shear planes/ Diaphragms (roofs, floor etc)

Along with diagonal bracing, shear walls, moment connections, roof and/or floors also play significant roles in resisting lateral forces. Non rigid roofs and floors deform considerably under lateral loads. Lack of in-plane stiffness or a rigid connection prevents the roof and/or floor from transferring the laterally acting forces to resisting vertical shear planes like shear walls.

The stiff or rigid roofs or floors that facilitate such transfer are called horizontal shear planes or diaphragms and the process of load transfer is referred to as a diaphragm action. Diaphragm action can be induced in a roof or floor plane via cross bracings, trusses, frame action, shear connectors, etc. Cast-in place reinforced concrete systems inherently provide diaphragm action while roofs with large glass areas or standing seam roofing require bracings to add the stiffness.

Bracing that provides stiffness and lateral force transmitting capabilities to the glass roof.

The main function of the floors and roofs in carrying lateral loads is to transfer these loads to vertical bracings, shear walls, or frames.

Load Transfer

A. **Loadings on Transverse faces:** Figure 1 shows how the lateral forces on the transverse face are transferred to the shear planes on the longitudinal side. In this case the edge beam is designed for gravity loads as well lateral loads. Since beam size increases with span, this method is typically not used for larger buildings.

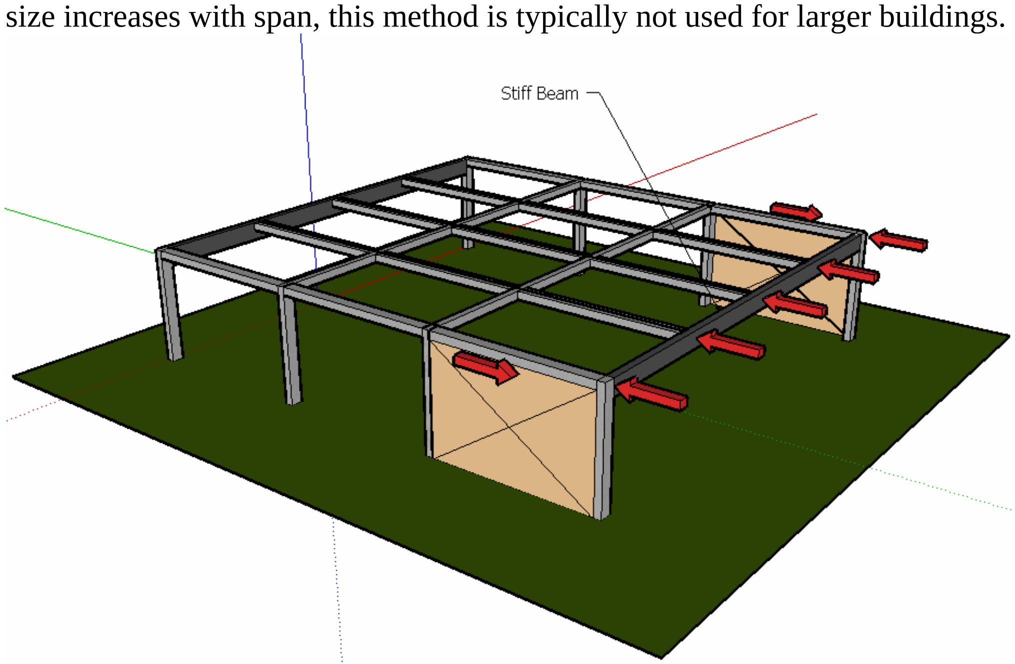


Figure 4: Lateral forces are resisted by an edge beam with high lateral strength and rigidity and directly transferred to the shear walls/bracings, normally used for small structures only.

Consider Figure 2. For larger structures part of the roof and /floor plane is stiffened to transfer the loads. An entire bay may be cross braced to provide adequate in-plane stiffness for a larger building. However, the whole system needs to be organized such that the rigid horizontal plane both receive lateral forces and transmit them to side shear planes. In any size building with either plywood or concrete floor diaphragms this would be the case.

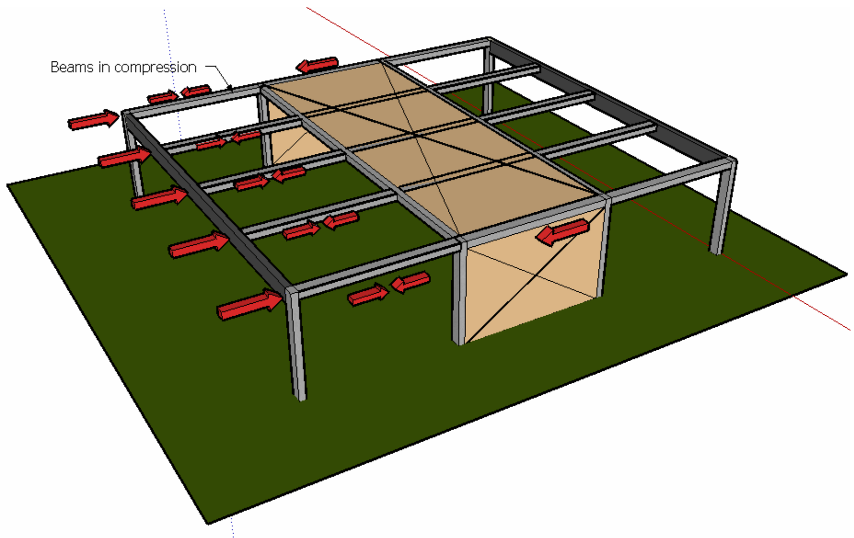


Figure 5: Lateral forces are transferred through roof members to roof diaphragm to side shear walls/bracings

The rigid horizontal plane offering diaphragm action can be anywhere in the overall plane. However, if the horizontal diaphragm is removed from the exterior wall planes, roof or the floor beams must be designed (braced) for transmitting the lateral forces to it. These beams would then have to transfer both normal bending due to gravity loads and to act as columns in compression.

B. Loadings on Longitudinal faces: Figure 3 shows how the lateral forces on the longitudinal face are transferred to the shear planes on the transverse side. An entire bay may be cross braced to provide adequate in-plane stiffness for a larger building.

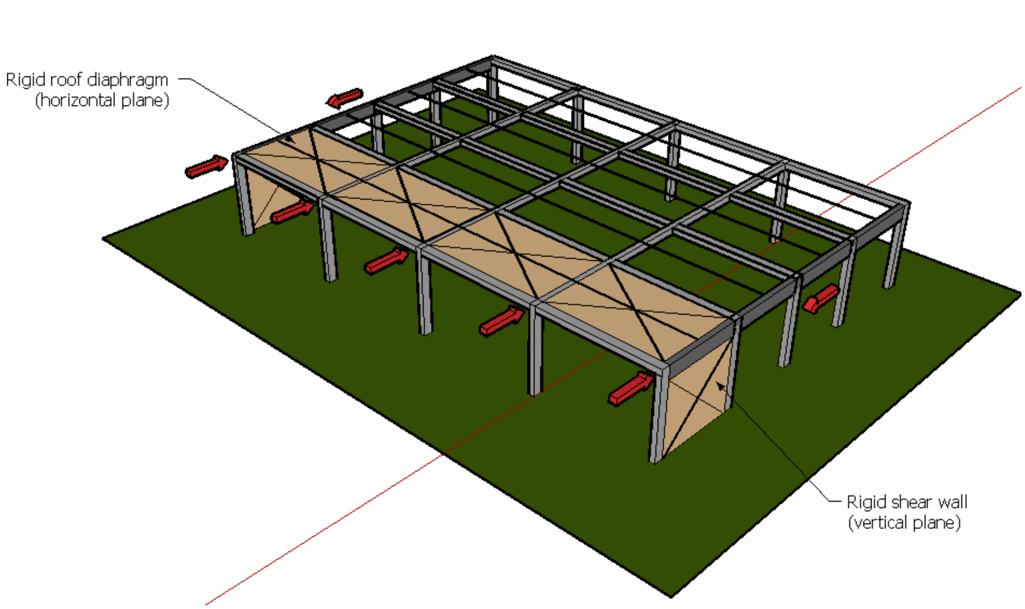


Figure 6: Forces are transferred from the secondary framing on to the rigid shear planes and in turn on to the side shear planes

The rigid horizontal plane offering diaphragm action can be anywhere in the overall plane (Figure 4). However, if the horizontal diaphragm is removed from the exterior wall planes, roof or the floor beams must be designed for transmitting the lateral forces to it. These beams would then have to transfer both normal bending due to gravity loads and to act as columns in compression.

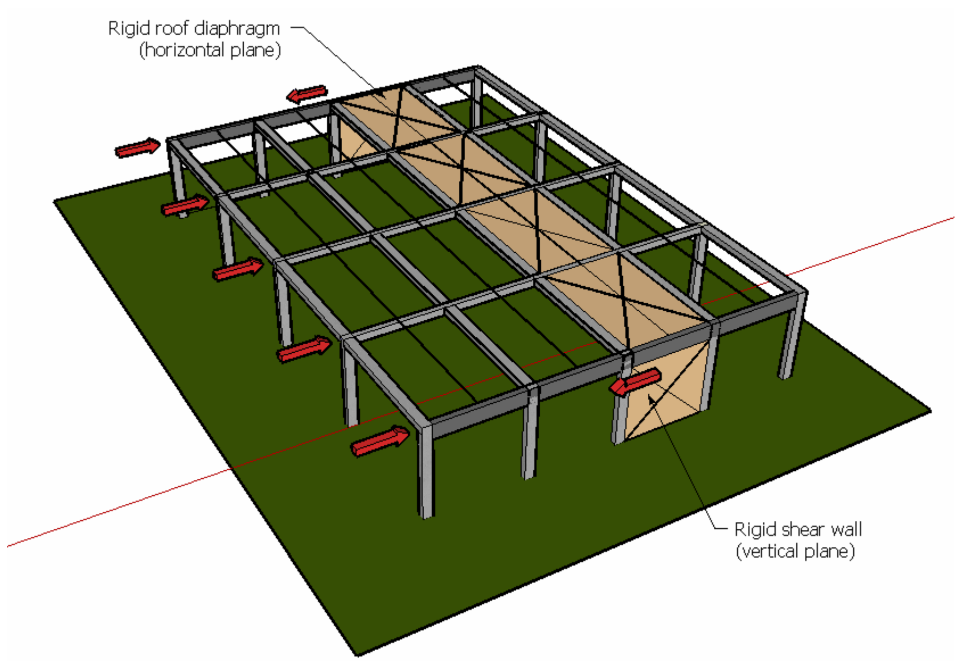


Figure 7: Horizontal and vertical rigid planes can be anywhere as long as load is transferred to them

Typical Lateral Load Resisting Systems

For common square and rectangular buildings, frames, bracings or shear walls must be in a series of mutually perpendicular planes through out the building. Figures 5 and 6 demonstrate the typical lateral load resisting mechanisms.

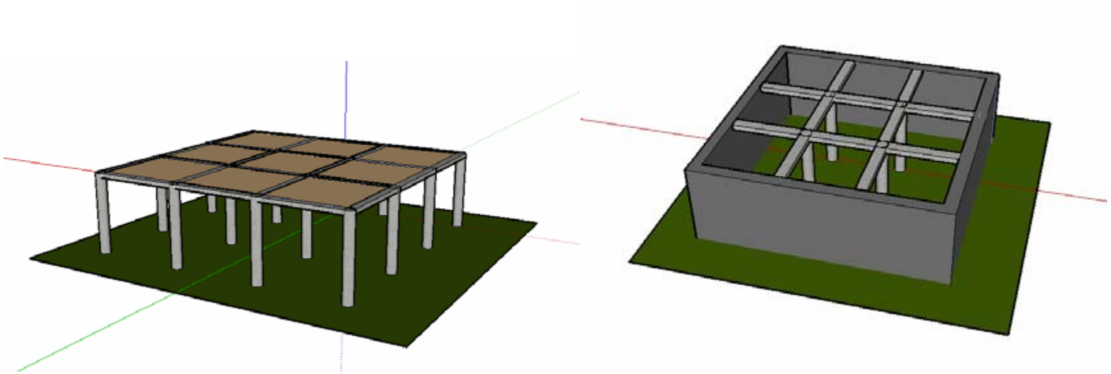


Figure 8: (1). Common rigid frame system, e.g. two way beam and slab system; (2.) Lateral bracing around periphery only.

Cast-in place concrete systems have inherent in-plane stiffness. The system shown in figure 5(1) is the most common rigid system, where the slab and beams are designed for both vertical loads (gravity loads) and horizontal loads (wind loads). When the roof structure cannot be made into horizontal rigid diaphragm, a system of rigid walls is designed around periphery (Figure 5 (2)). Figure 6 shows the common lateral load resisting system for symmetrical buildings, central core (figure 6(1)) and end walls (figure 6(2)).

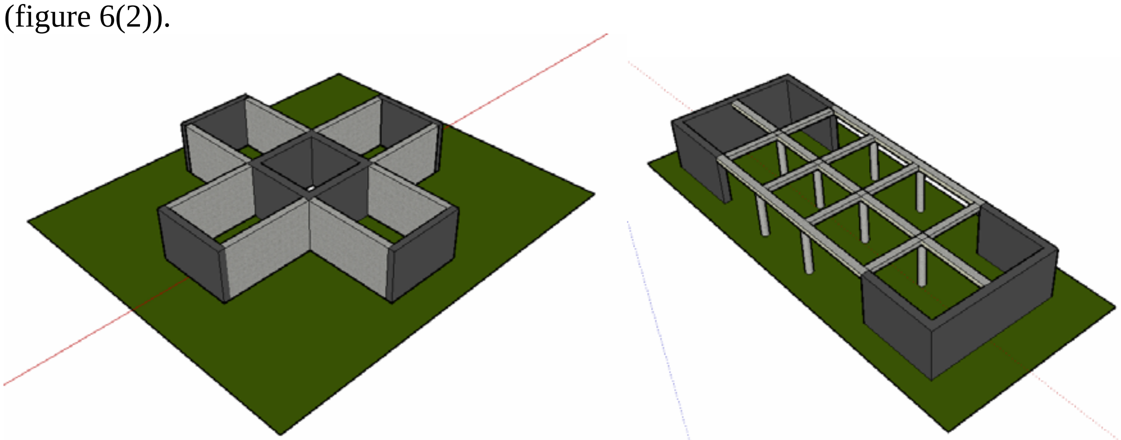
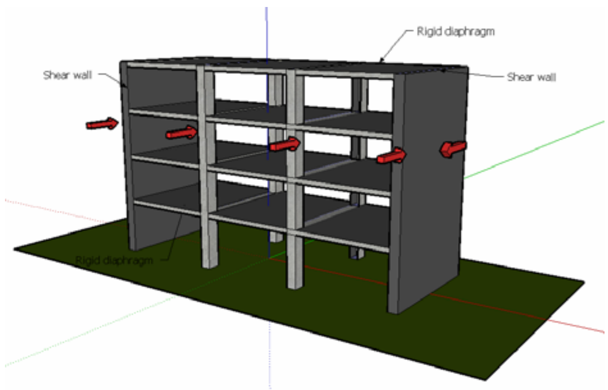


Figure 9: (1). Symmetrically placed shear walls; (2). Shear walls/bracing placed at the end.

For low or medium rise structures any of the above illustrated systems can be used. However, in some buildings shear walls or diagonal bracing systems create functional problems and cannot be used freely. Hence, sometimes a combination of rigid frame that is further stiffened by shear walls and/or diagonal bracings at the building ends or around the service cores is used.

When vertical planes can not be designed to carry lateral loads e.g. pin-connected steel-beam-and-column systems, the floor and/or roof planes are designed to serve as rigid horizontal diaphragms that act as thin horizontal beams spanning between shear planes (see Figure 7).



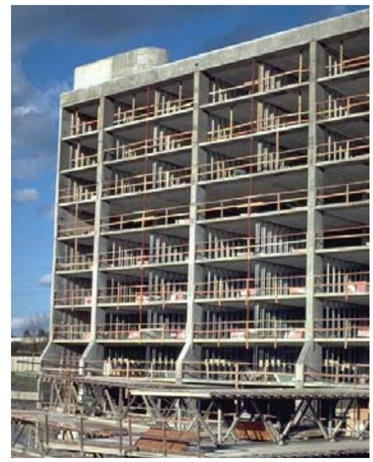


Figure 10: When the horizontal forces are transferred by shear walls, the horizontal floor planes are usually` designed as rigid diaphragms where the floors act like deep thin beams in horizontal direction and carry forces from the face of the building to vertical shear walls.

If shear walls or diagonal bracing systems are placed unsymmetrical in plan, torsional forces can develop due to no coincidence between center of rigidity of the building and the centroid of the applied lateral load. Symmetrical placement of stiffening elements becomes critical for tall buildings or in seismic zones.