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## ***1. GENERAL INTRODUCTION***

*Civil engineering represents the set of techniques related to civil constructions. Civil engineering specialists have a forward-looking approach, practicing an interdisciplinary profession that impacts people's daily lives. They are involved in the design, construction, and rehabilitation of structures and urban infrastructure to meet society's needs while ensuring public safety and environmental protection. Engineers must consider structural and functional aspects while preserving the strength, cost-effectiveness, aesthetics, and viability of the building.*

*A building's response to an earthquake is conditioned not only by the characteristics of seismic movement but also by the stiffness of the stressed structure. Relatively flexible structures (such as frames or frameworks) perform better under seismic action. However, the analysis of these structures reveals that they must withstand significant displacements, leading to severe damage to both structural and non-structural elements.*

*During significant earthquakes, it has been observed that many reinforced concrete shear wall buildings have withstood the seismic forces without excessive damage. Besides their role as load-bearing*

elements for vertical loads, properly sized reinforced concrete shear walls can be particularly effective in providing resistance to horizontal forces, thereby reducing risks.

Metal structures are one of the most common choices in the construction of industrial buildings worldwide. Braced frame systems are probably the most favored types due to their minimal skill requirement for assembling structural elements and the use of common and lighter sections for beams and bracing elements. Bracing is a highly effective overall upgrading strategy to enhance the rigidity, strength, and overall stability of steel frames.

A metal structure needs bracing, a term that is extended to most elements ensuring the construction's rigidity and maintaining the main components in their layout. When designing metal structures against horizontal forces, engineers consider nodes as perfectly rigid for their ability to resist these forces with acceptable displacements; these types of nodes exhibit high performance during earthquakes. However, after the North Bridge earthquakes in the United States and the Kobe earthquake in Japan, the performance of several structures was deemed poor based on research results. They showed that semi-rigid nodes have the ability to resist lateral forces, making structures with semi-rigid nodes more economical.

This course on structural bracing systems is intended for Master 1 students in Architecture, Module Structure 1. It explains how to

*arrange bracings for different types of structures (concrete structures, structures with a central core, steel structures). The first chapter covers generalities and definitions about bracings. The second chapter focuses on the classification of bracing systems. The study of truss structural bracing is addressed in Chapter III. Torsion and failure modes of structure walls are examined in Chapter IV. Chapter V is dedicated to seismic design of buildings, while Chapter VI is dedicated to calculations of bracing systems for mixed frames bracing calculations.*

## *CHAPTER I*

### *GENERALITIES ON BRACING*

#### **I.1. Introduction**

The bracing system consists of all structural elements that significantly contribute to the transfer of horizontal actions generated by seismic movement through inertial effects in the structure. Seismic accelerations are applied to all masses in the structure, whether or not they are associated with structural elements, and seismic actions are generally distributed throughout the structure.

They must be transmitted from their point of application to the foundations, which implies local resistances of the elements, including non-structural elements, and the primary resistance of the bracing elements that concentrate efforts to transmit them to the foundations. These force paths must be analyzed and weak points identified to establish the overall coherence for a given level of action [1].

A reinforced concrete structure is braced either with self-stabilizing frames (without the presence of shear walls), with shear walls only (as in the case of wall-slab structures), or with mixed bracing (frame + shear wall) or a central core, which is a tubular shear wall typically positioned in the middle of the floor [2].

#### **I.2. Definition of bracing**

En civil engineering, bracing refers to a static system designed to ensure the overall stability of a structure against horizontal forces resulting from potential actions on it, such as wind, earthquakes, impacts, braking, etc. It also serves to locally stabilize certain parts of the structure (beams, columns) in relation to instability phenomena (buckling or overturning) (**Figure I.1**) [2].



**Figure I.1.** Bracing system [3]

### **I.3. Principle of low bracing structures**

The bracing of a building must be considered from its initial design, as the overall geometry and layout of the most rigid elements largely determine the proper distribution of forces within the structure. Geometries such as U or L shapes should be avoided because they pose problems of stress concentration at the corners and introduce overall torsion. The layout of bracing elements in the plan is also crucial. Poor positioning can lead to torsion in the floor plan, generating additional forces in the bracing elements [2].

### **I.4. Bracing Features**

#### **I.4.1. Description of bracing**

Imagine a frame made of wood or metal (square or rectangular, empty inside). If you press on one of the sides, it deforms. However, if you attach a piece of wood diagonally from one corner to the other inside the frame, it resists. Finally, if you push the frame from the other side, the piece of wood will be just as effective.

In the first case, the piece of wood is used in compression, in the second case in tension. If you apply a twisting force, the piece of wood also prevents deformation.

In conclusion, the wood triangulates or braces the entire frame, which summarizes the principle of bracing.

#### **I.4.2. Utility**

Bracing is a constructive principle used to stabilize and stiffen a structure. It is employed in various applications:

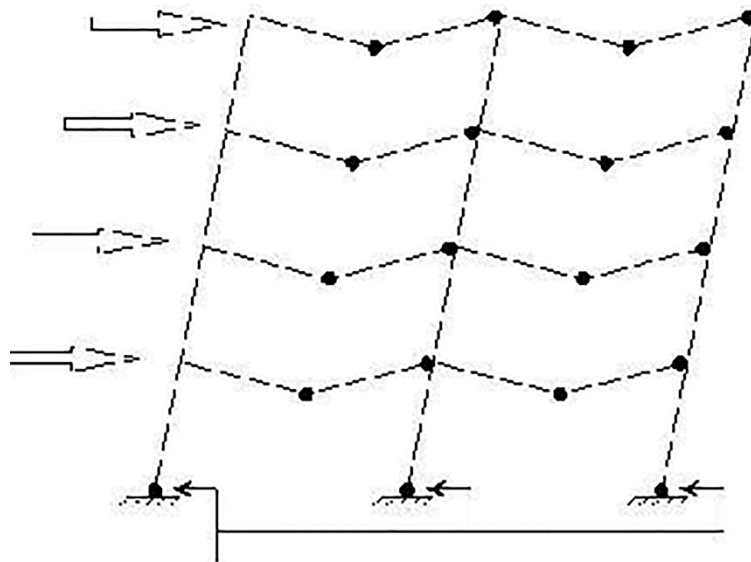
- In sloping roof sections, where it is referred to as wind beams.
- On facades in vertical sections, known as stability braces.

The term "bracing" is utilized across different building trades, including metal framing, carpentry, and masonry [2].

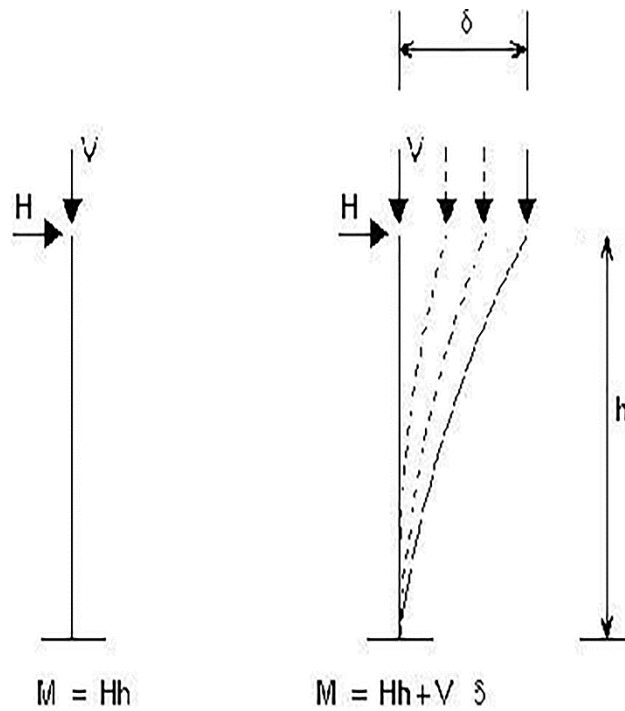
### I.5. The role of bracing

- ✓ The ability that this bracing system must have to transmit horizontal loads to the foundations. (Continuity).
- ✓ The capability that this bracing system must possess to prevent the structure from collapsing – (Rigidity).
- ✓ Furthermore, this bracing system must limit the deformation of the structure to keep it within an acceptable range defined by the current standards and regulations. (Compatibility) [3].

**Figures I.1 and I.2** illustrates, respectively, an example of poor load redistribution and an example of the P- $\Delta$  effect.



**Figure I.1.** Poor load redistribution - Mechanism - imminent collapse [3]



**Figure I.2.** Significant deformation Amplification of the effects of earthquake Effect  $P_{\delta}$  [3]

Thus, the proper design of structures involves the creation of a system formed by reinforced concrete floors and walls or frames, arranged in two directions of the plane, constituting a more or less continuous three-dimensional network achieved by:

- The operation as "diaphragms" of the floors, playing an essential role in the overall seismic behavior,
- The operation as a vertical diaphragm, acting as "bracing" for the walls or reinforced concrete frames, achieved by arranging structural elements with equivalent strength and stiffness in both principal directions and extending straight down (plumb) to the foundations. Their stiffness also serves to protect fragile non-structural elements, unlike frame structures [4].

**Figure I.3** presents an example of a braced framework with columns and beams (portal) that is self-stable and filled with masonry, while **Figure I.4** presents an example of a braced framework with reinforced concrete shear walls.



**Figure I.3.** Frame braced by post-beams



**Figure I.4.** Frame braced by reinforced concrete sails [4]

## **I.6. Area of use**

Bracing is used for:

- Inclined sections for roofing
- Vertical sections for facades

### **I.6.1. Roof bracing**

The bracing of roofs is provided by four beams in isotropic wind. Their role is to bear the wind load acting on the gable and transmit it to the stability braces and then to the foundations, thus ensuring the longitudinal horizontal stability of the structure.

Horizontal bracing is generally achieved through construction arrangements at the floor and roof levels [3].

### **I.6.2. Facade bracing**

The stability brace is a facade bracing element designed to take up the forces coming from the wind beam and transfer them down to the foundations [3].

**Figure I.5** illustrates an example of this type of bracing.



**Figure I.5.** Type of bracing [5]

In order to ensure the overall stability of a building, it is necessary for it to be braced in at least three non-collinear vertical planes and one horizontal plane. Vertical bracing is intended to transmit horizontal forces into the foundations, while horizontal bracing is designed to counteract the torsional effects caused by these forces.

Bracing can be achieved using shear walls (vertical bracing) or plates (horizontal bracing) made of reinforced concrete, masonry, wood, or corrugated steel sheets. It can also be accomplished using trusses made of wood or steel. The terms "walls" or "shear walls" refer to vertical load-bearing elements distinguished from columns by the ratio of their length "L" to thickness "e"; a wall is an element where the L/e ratio is at least equal to 4.

## **I.7. The choice of bracing**

Bracing serves to ensure both the horizontal and vertical stability of the structure during seismic events, which, it is important to note, have components in all three directions.

The role of horizontal bracing is to transmit lateral forces to vertical elements called stability braces. To ensure effective horizontal bracing, floors and roofs acting as rigid diaphragms should not be weakened by excessively large or poorly placed openings that could compromise their strength and stiffness. Flexible diaphragms should be avoided to prevent the tilting of walls, especially in masonry.

Vertical bracing through stability braces should adhere to specific criteria, such as:

- Quantity: At least three non-parallel and non-converging braces per floor.
- Placement: They should be situated as symmetrically as possible in relation to the center of gravity of the floors, preferably at the corners with sufficient width.
- Vertical distribution: Should be regular; the braces are preferably stacked to provide comparable rigidity at different levels in both translation and torsion [5].

## **I.8. The overall bracing of buildings**

The primary concern for a structural engineer should be to anticipate arrangements ensuring overall stability, particularly the comprehensive bracing of buildings. These arrangements aim not only to guarantee resistance to horizontal forces considered in calculations, such as those resulting from wind action but also to potentially allow buildings to withstand certain exceptional solicitations, such as localized explosions, without excessive damage. These issues are particularly acute in buildings with a large number of floors.

**CHAPTER II**  
**CLASSIFICATION OF BRACING SYSTEMS**

**II.1. Introduction**

The purpose of the classification of structural systems is reflected in the rules and calculation methods by assigning a numerical value of the behavior coefficient  $R$  to each category in this classification. The classification of structural systems takes into account their reliability and their ability to dissipate energy in response to seismic action, and the corresponding behavior coefficient is determined based on the nature of constituent materials, the type of construction, the possibilities of redistributing forces within the structure, and the deformation capacities of elements in the post-elastic range.

The primary concern for the structural engineer is to anticipate arrangements ensuring overall stability, especially the comprehensive bracing of buildings. These arrangements aim not only to guarantee resistance to horizontal forces considered in calculations, such as those resulting from wind action, but also to potentially allow buildings to withstand certain exceptional solicitations, such as localized explosions. These issues are particularly acute in high-rise buildings.

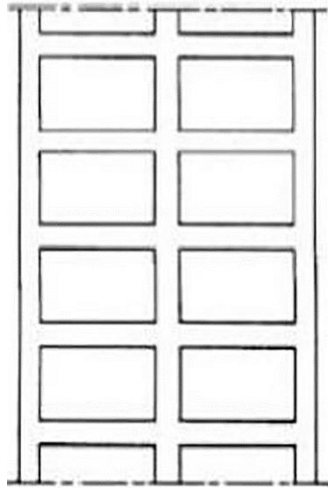
The solutions that can be chosen to ensure the overall bracing of buildings are obviously linked to the constraints imposed by the architectural design; they are also dependent, to some extent, on the materials available to the construction company. These solutions can be classified into three main categories (I.2, I.3, and I.4).

**II.2. Bracing provided by frames**

The frames (**Figure II.1**) must be designed to withstand not only gravity forces but also horizontal forces; this resistance involves the stiffness of the joints. This solution generally leads to larger concrete sections and reinforcements, as well as more complex reinforcement arrangements than those typically adopted in more common building structures.

Unless it is possible to plan frames with a relatively large number of bays in each bracing plane (**Figure II.1**), this bracing solution is expensive and is rarely chosen unless no other option is available. However, it should be acknowledged for its advantage of not creating obstacles to the presence of large openings in the frame plane [2].

The calculation of frame structures can be carried out using various methods, ranging from less sophisticated to more elaborate approaches.



**Figure II.1.**Frame structure [2]

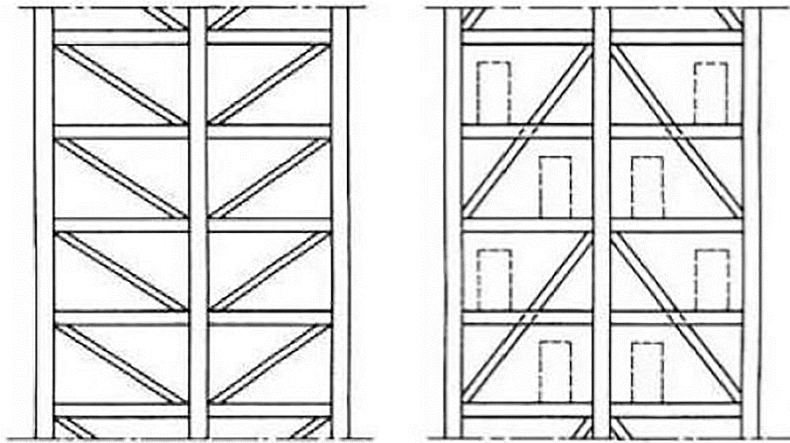
### **II.3. Bracing ensured by rigid panels**

The rigidity of the bracing panels can be ensured by:

- Either reinforced concrete triangulations;
- Or reinforced concrete walls;
- Or, if necessary, by masonry infill's with sufficient strength between elements (columns and beams) of the reinforced concrete framework.

#### **II.3.1. Triangular bracing**

In the first case, the presence of triangulations often creates difficulties for creating openings in the bracing panels. A more satisfactory solution can sometimes be found by arranging the triangulation elements not at the height of one floor but at the height of two floors (**Figure II.2**) [2]. The implementation of masonry in fills is, in any case, made less straightforward.



(a) sur la hauteur d'un étage      (b) sur la hauteur de deux étages:

La solution (b) facilite l'aménagement des baies

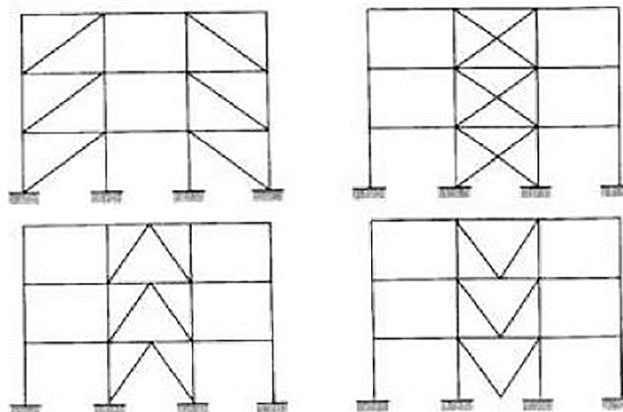
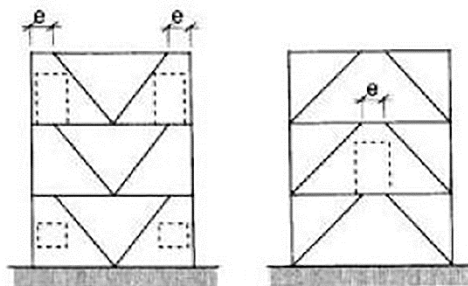
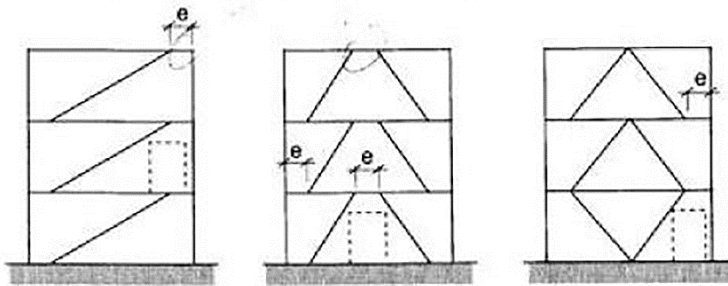


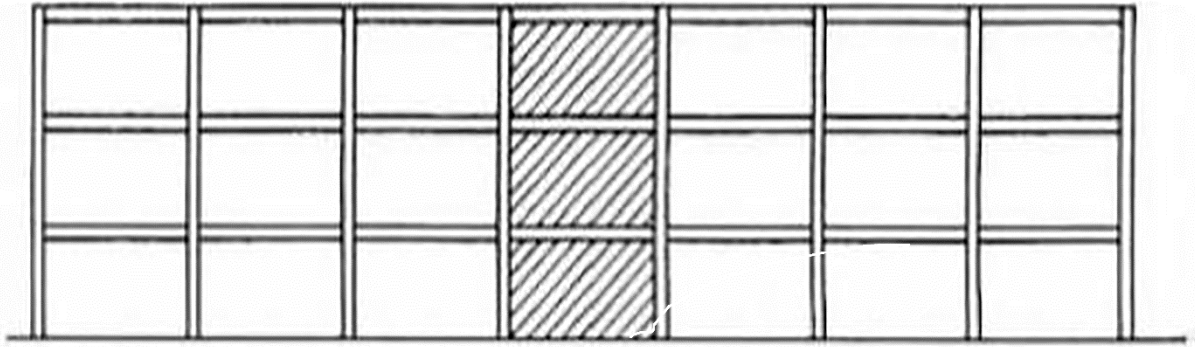
Figure II.2. Triangular bracing panels [2]

The calculation of truss beams, with the members formed by the columns and operating as cantilevers from the foundation level, does not pose any particular difficulties; it is carried out following the usual practices, assuming joints at the nodes.

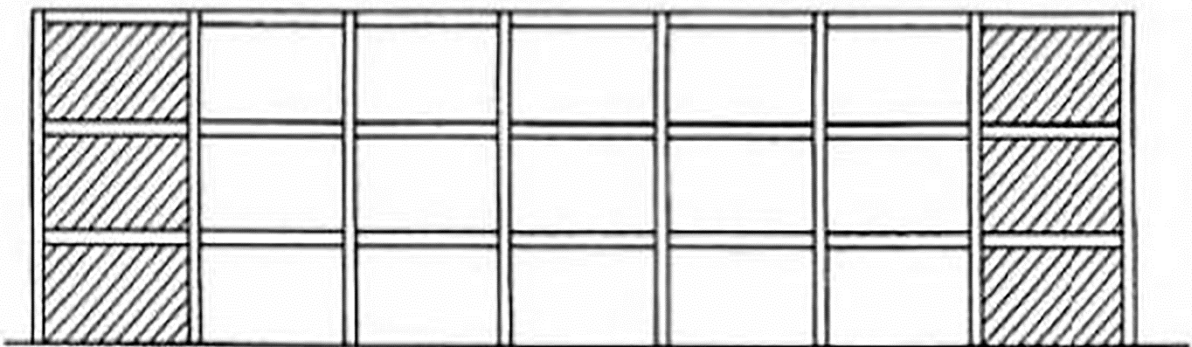
### **II.3.2. Bracing with concrete wall**

The solution of bracing with reinforced concrete walls is currently widespread. Often, these walls, arranged transversely to elongate rectangular buildings, also serve as elements for transmitting vertical loads, without necessarily being reinforced by columns. They thus provide, in economical conditions, both the transmission of gravity loads and bracing in the transverse direction of the buildings. This advantage is particularly pronounced for companies equipped with suitable formwork equipment: formwork panels and tunnel formwork [C 2 316].

As for the longitudinal bracing of the same buildings, it can also be achieved by walls arranged in the planes of the facades and longitudinal partitions. Generally, these walls are only provided in certain bays. To limit the disadvantages resulting from dimensional variations due to shrinkage and temperature effects, it is advisable to place the bracing walls in bays near the center of the buildings rather than at one end, and especially avoid placing them at both ends (temperature effect) (**Figure II.3**) [2].



(a) Rigid section in the middle of the langour of the building



(b) Rigid sections at both ends of the building

**Solution (b) is very unfavorable with regard to the effects of dimensional variation**

**Figure II.3** Longitudinal bracing of a building. Arrangement of rigid sides[2]

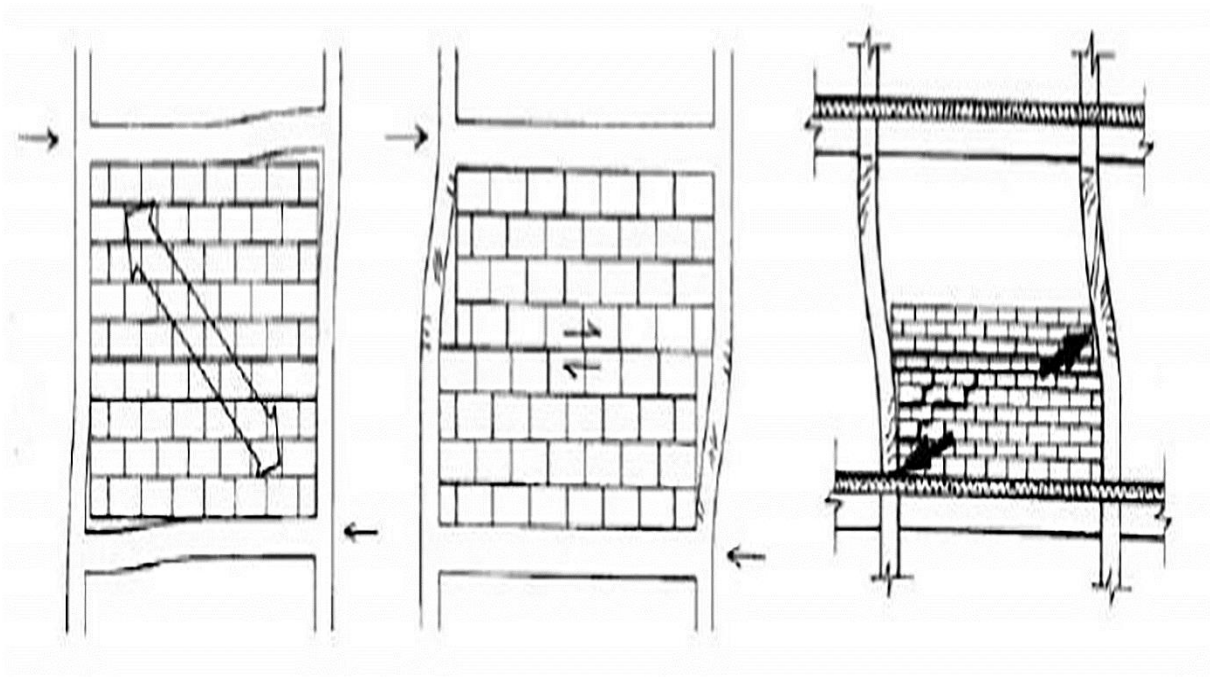
The calculation of bracing with reinforced concrete walls raises, in particular, two issues: a) the general issue of distributing the horizontal forces acting on a building among the various bracing panels; b) the determination of the forces in the connecting elements (lintels) of walls arranged in the same plane.

### **II.3.3. Bracing with masonry infill**

The solution of providing bracing through masonry in fills of sufficient strength is especially suitable for buildings with a limited number of floors (**Figure II.4**). It is crucial to ensure that the relevant masonry is not expected to disappear or be altered (due to future openings). This condition is generally met for certain walls of stairwells, partitions between dwellings, or between building sections at joints, or gables. There is no regulatory calculation method to determine the stresses in masonry panels under the

action of horizontal forces applied at floor levels. Some tests have been conducted in France and abroad, but they have been limited to certain types of frameworks and infill.

One is led to consider fictitious compressed diagonals in the panels, determining their width based on common-sense considerations and verifying that the stress remains below the normally acceptable values for the relevant masonry [2].

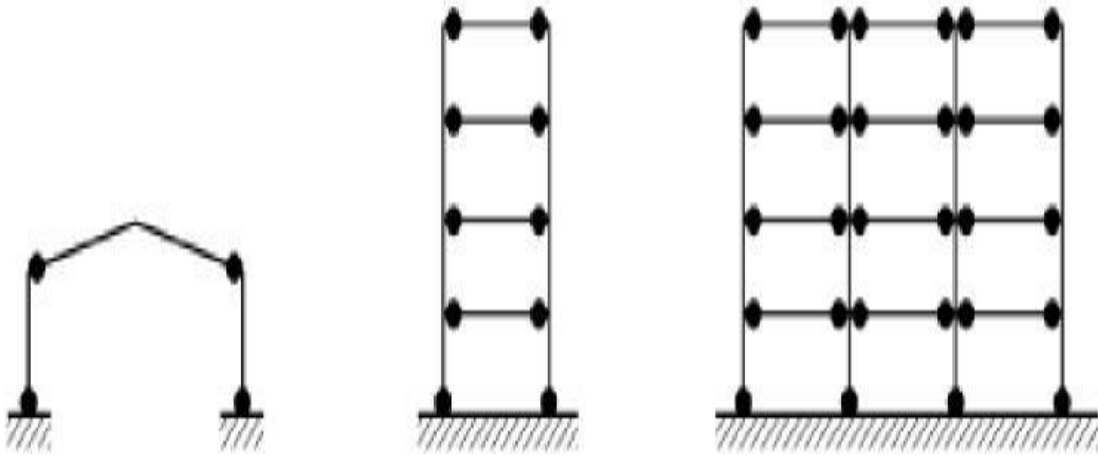


**Figure II.4.**Bracing through masonry infill[2]

in compression; particularly unfavorable if the walls are only partially filled.

#### **II.4. Frame or portal structures**

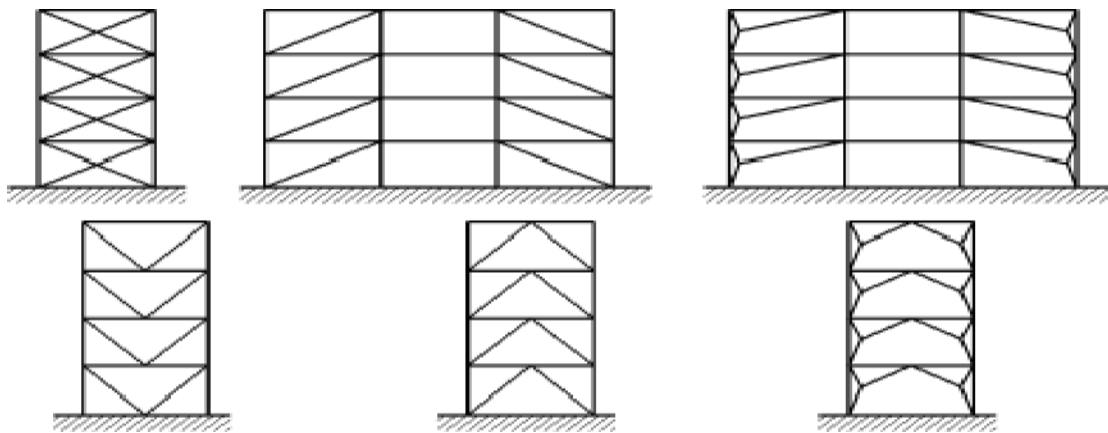
In this type of structure (**Figure II.5**), the resistance to horizontal forces is primarily provided by the bending of columns and beams. It is therefore important that the dissipative zones are mainly located in plastic hinges formed in the beams or in the connections, so that the energy is dissipated through cyclic flexure [5].



**Figure II.5.**Portal structures (dissipative zones in the beams and at the base of columns) [5]

### II.5. Structures with centered bar bracing

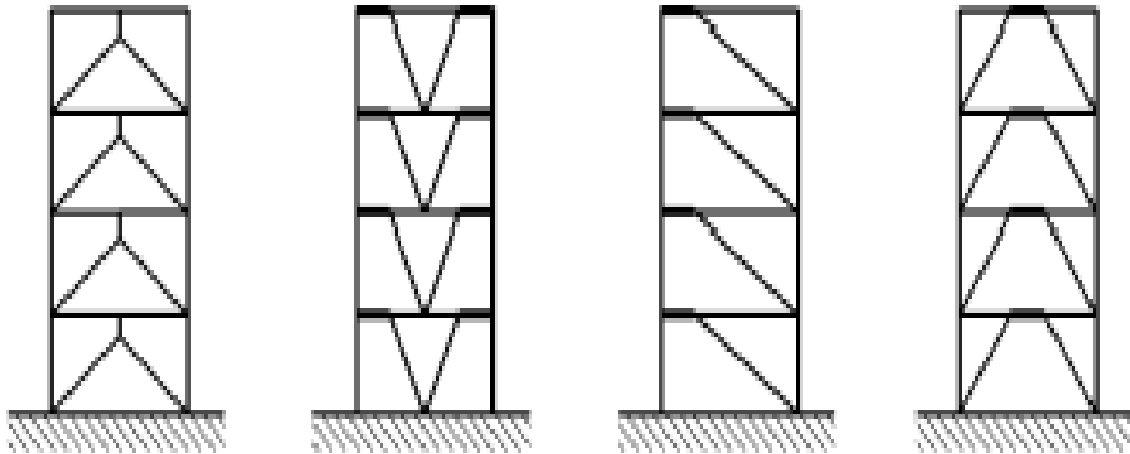
These are structures in which the intersection of the bracing system bars coincides with the midpoint of the load-bearing elements (**Figure II.6**) or with the joint of columns and beams [5].



**figure II.6.**Structures with centered bar bracing [5]

### II.6. Structures with off-centered bar bracing

In this type of structure (**Figure II.7**), the intersection of the bracing bars can be located at any point along the beam depending on the adopted configuration [5].



**figureII.7.** Structure with off-centered bar bracing [5]

## II.7. Core stability of tower buildings

The stability of residential and, especially, office tower buildings is often ensured by a structure located in the central part, consisting of vertical walls in reinforced concrete, arranged in orthogonal planes, along with the floors. This assembly is typically positioned in the area where vertical circulation elements (elevators and emergency stairs) are grouped, as well as in annex spaces without natural light (bathrooms, toilets, dressing rooms, archives, etc.).

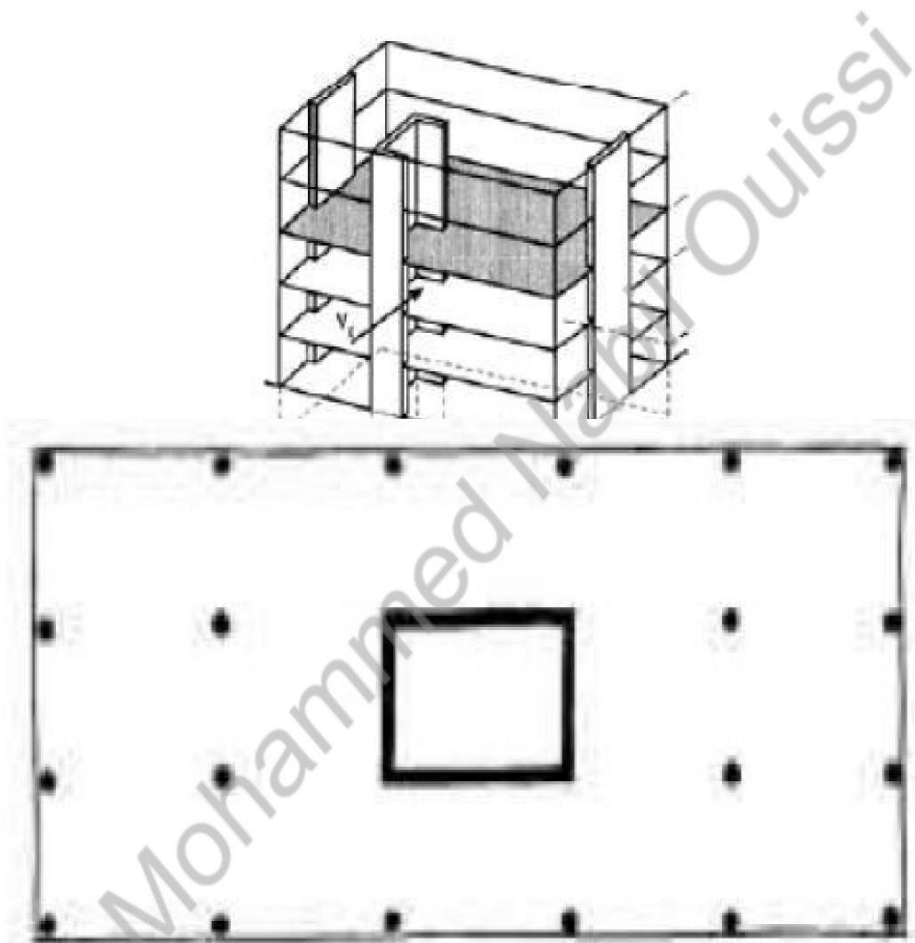
The walls of this core transmit a portion of the vertical loads and, by themselves, resist horizontal forces, particularly wind actions. The vertical elements of the structure around the core typically only bear vertical loads.

In some cases, the stability core has been constructed in reinforced concrete, while the peripheral parts had a framework - beams and columns - made of metal.

It should be noted, however, that in certain tower buildings, the frameworks of the facades were designed to provide stability against wind action.

In the cases mentioned in the first paragraph of this section, the calculations do not differ in principle from those corresponding to the solution of bracing with reinforced concrete walls; one must determine the distribution of forces between the different walls in each direction and study, in particular, the resistance of lintels between elements of walls located in the same plane. The solution mentioned in the fourth paragraph involves calculations for frameworks with a large number of bays and stories, which can hardly be approached without the use of automatic calculation programs.

The **Figure II.8** illustrates an example of bracing for a tower using a central core



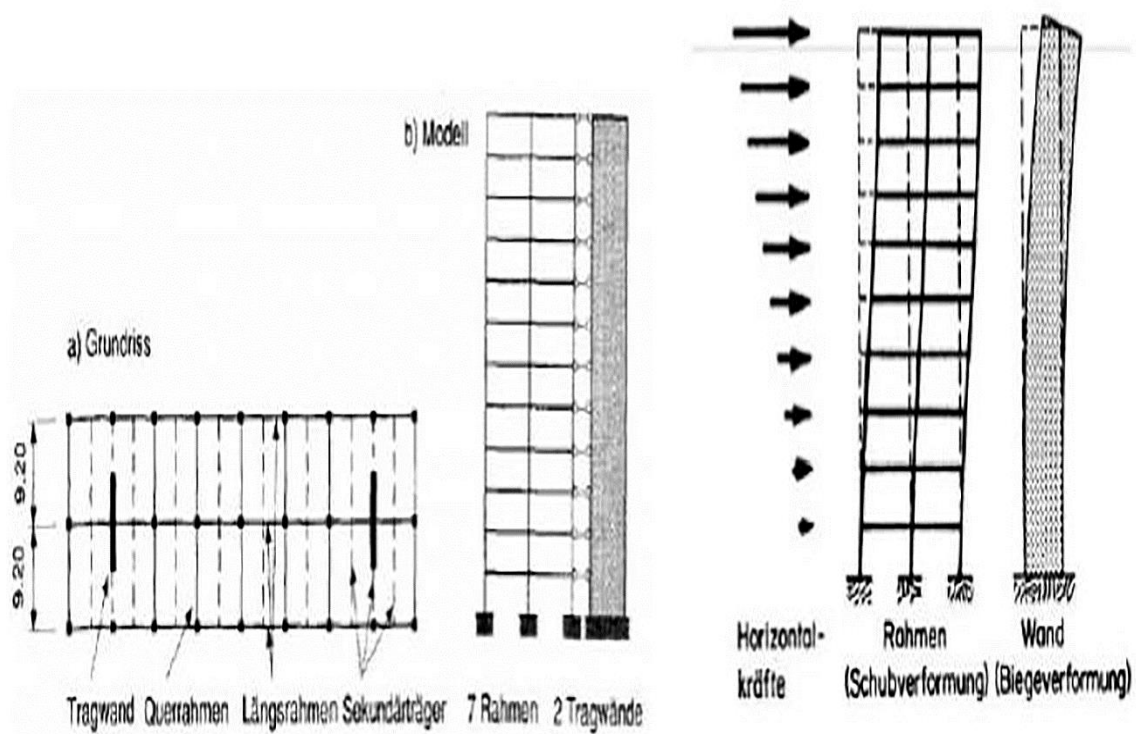
**Figure II.8.**Bracing through a central core [8]

### II.8. Hybrid solutions

One can very well resort to hybrid solutions, simultaneously using several of the solutions mentioned in the preceding paragraphs. The essential difficulty then is to define the distribution of horizontal forces among the various bracing panels, whose deform abilities can be very different due to their dimensions and constitution.

Finally, the longitudinal bracing of an elongated rectangular building can very well be ensured differently from the transverse bracing. For example, the latter by reinforced concrete walls and the former by frameworks, if a significant number of bays can be arranged [5].

The **Figure II.9** illustrates an example of a mixed bracing system.



**Figure II.9.**Example of a mixed bracing system [5]

## II.9. Braced structures and unbraced structures

A frame is classified as braced if its lateral stiffness, in its plane, is ensured by a bracing system that is sufficiently rigid with respect to horizontal loads, so that it can be considered, with acceptable accuracy, that these horizontal loads are taken up by this bracing system alone. Eurocode 3 prescribes that a structure with a bracing system is classified in the braced category if its horizontal displacement remains less than 1/5 of the displacement that would have occurred in the absence of the bracing system [6].

**CHAPTER III**  
**BRACING OF LATTICE STRUCTURES**

**III.1. Generality**

Bracing systems are devices designed to counteract wind forces in a structure and transfer them to the ground. They are either placed on the roof within the plane of the slopes (wind beams) or on the facades (stability bracing) and are intended to resist wind forces on both gables and sides. This type of bracing will be covered in another course. Stability is thus ensured in all three directions of space. Three essential types of bracing are distinguished:

**III.1.1. Triangulation (truss)**

This is the most common type; N-trusses are well-suited when there are no possible reversals of forces. When potential force reversals are present, Saint Andrew's crosses (sometimes K or V trusses may be suitable) are preferred.

**III.1.2. Stiffening of nodes (frame or portal)**

Ils se justifient pleinement lorsque l'on doit laisser le passage libre, ou pour éviter des diagonales inesthétiques, ou bien parfois pour laisser une plus grande liberté pour une modification de la structure.

**III.1.3. Filling (shear wall, diaphragm)**

Concrete shear walls are employed for high loads, while masonry shear walls are suitable for lower loads. When a core or partition wall is present, it can serve as bracing, especially in multi-story buildings. It's essential to note that cladding and roofing elements made of metal sheets, such as steel deck, should not be utilized as bracing elements.

A well-designed structure should ensure stability against any external load, particularly horizontal forces like wind pressure on facades, seismic forces, or vehicle impacts. In other words, the overall design of a structure, as well as each of its components, must facilitate the transfer of horizontal loads from their points of application to the foundations.

## **III.2. Definition**

The set of structural elements designed to ensure the transfer of horizontal loads applied to a building is called a bracing system. Note: in the case of bracing with infill, it is always necessary to ensure that the transfer of forces between load-bearing elements and stabilizing elements is done correctly (Timber-framed houses).

## **III.3. Basic principles of structural bracing**

The bracing of a building must be considered from its initial design phase, as the overall geometry and the plan positioning of the most rigid elements largely determine the proper distribution of forces within the structure. Simple and compact geometries are therefore preferable. Conversely, U or L-shaped forms should be avoided as they pose issues of stress concentration at the corners and introduce overall torsion.

The layout of bracing elements in the plan is also crucial. Poor positioning and/or improper distribution of rigid elements inevitably lead to floor torsion, generating additional forces in the bracing elements. The concept of torsion is, therefore, significant in studying structures concerning horizontal forces, and it can be mitigated by aligning the tensional center with the point of force application. For instance, in a structure subjected to wind forces, adopting a symmetrical bracing system is a good solution to the torsion problem.

### **III.3.1. Origin of efforts**

Horizontal solicitations on structures result from wind forces or seismic forces. Wind forces are influenced not only by the geographical location but also by topography (geographical science of relief), the orientation of the structure, and the building's volume.

Seismic forces, on the other hand, depend mainly on the seismic zone where the building is located, its geometry, plan and elevation regularity, mass, and the nature of the ground it stands on. It is crucial to ensure that the ground has the capacity to support construction under seismic conditions.

Earthquakes produce two types of effects:

1. Direct effects involve earthquakes occurring along fault planes, causing vertical and/or horizontal displacements at the fault line. This can result in surface displacements,

shocks, and the propagation of seismic waves, the amplitude and duration of which are influenced by the quality of the soil beneath the buildings.

2. Indirect effects occur due to ground shaking during an earthquake, leading to a loss of cohesion in the soil. This loss manifests as soil liquefaction (reduction of soil resistance under constructions), subsidence, or settlement of the soil.

As evident, the calculations for wind and seismic forces differ significantly. Seismic forces involve concepts such as period and energy dissipation. A structure well-designed to resist wind forces may not necessarily be adequately equipped to withstand seismic forces.

#### **III.4. Vertical bracing**

There are two main principles for implementing vertical bracing: by core or by shear walls. Vertical bracing by core involves placing a rigid element at the center of the structure to absorb all horizontal loads. Typically, vertical circulations such as elevator or stair shafts fulfill this function. In shear wall bracing, rigidity is provided either by rigid panels (rigid frame walls stiffened by panels, walls in glued laminated timber) or by creating triangulated stability braces or rigid frames.

Vertical bracing must be designed to stabilize the structure throughout its height while minimizing the loads on the foundations. Generally, bracing trusses are designed so that the diagonals are subjected to tension only, requiring two crossed diagonals (St-Andrew's cross). If the bracing covers several bays or the entire width of the building, a second type of vertical bracing is reinforced concrete walls. These walls are arranged on the facade or inside the building and extend the full height of the structure.

As with halls, there are different ways to arrange vertical bracing in plan. Bracing can be symmetrically arranged in both orthogonal directions of the plan. Horizontal bracing located in floors and the roof is considered as simple beams supported by two vertical facade bracings in two directions. Transverse wind forces are balanced by a combination of the two longitudinal facade bracings with the concrete bracing of the gable. The equilibrium conditions are met because the moment created by the wind force eccentricity relative to the gable is balanced by the reactions of two perpendicular metal bracings to the concrete wall.

Figure III.1 illustrates examples of vertical bracing arrangements.

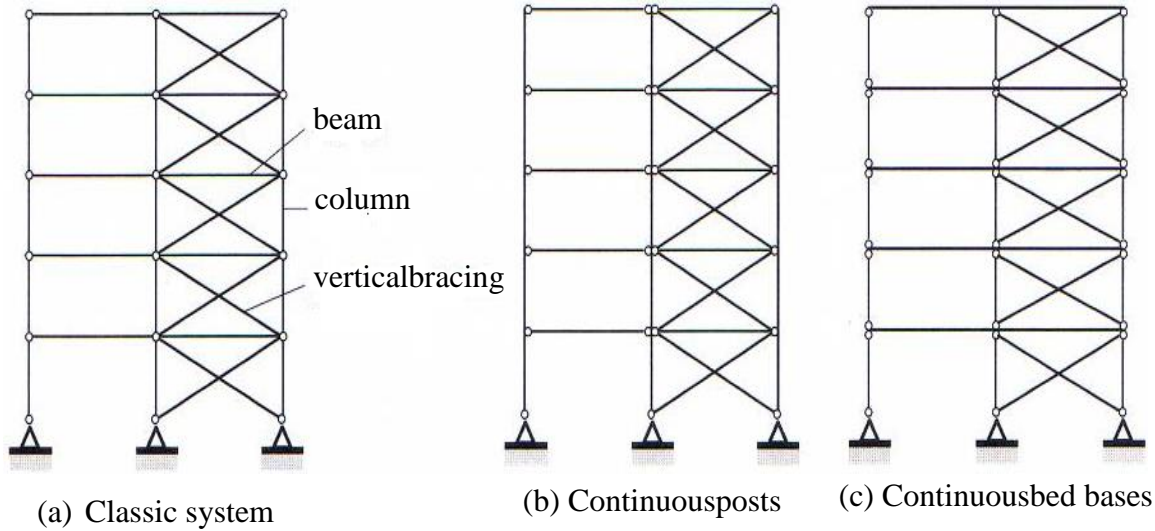


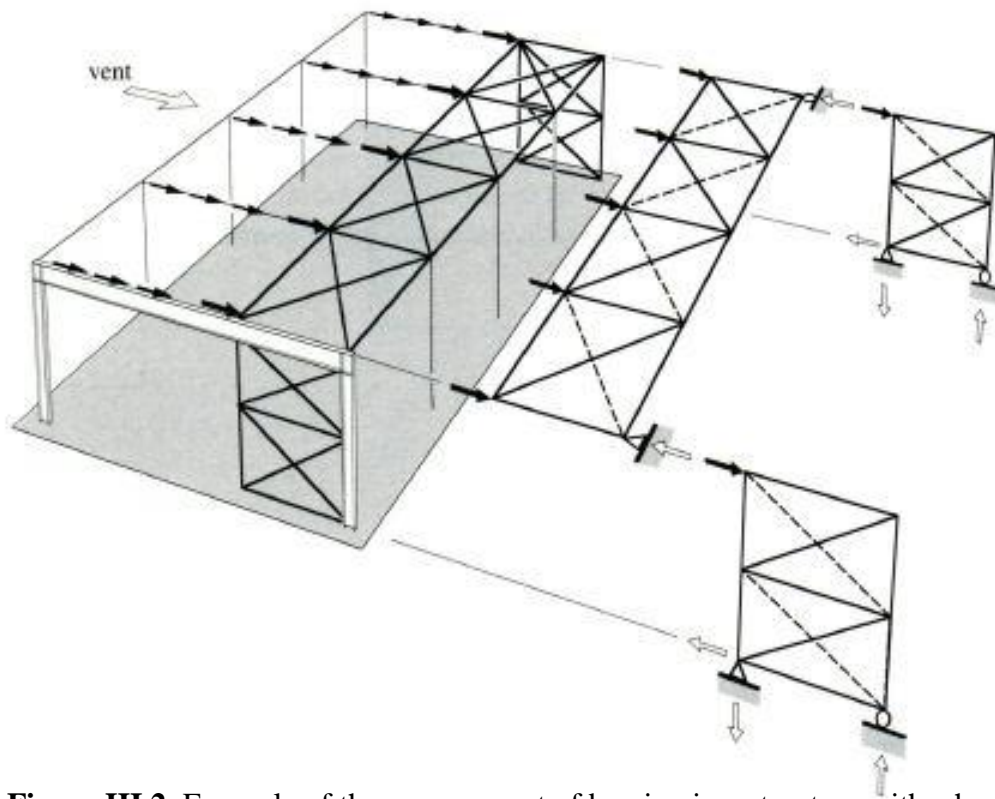
Figure III.1. Examples of vertical bracing arrangements

**III.5. Horizontal Bracing**

Most often, floor and roof slabs provide sufficiently rigid surfaces for the transmission of horizontal forces. If the slabs do not serve this stabilizing function, horizontal bracing is then necessary.

If the columns are continuous, horizontal bracing is only required every two to three floors, as the flexural strength of the columns is generally sufficient to absorb forces from wind and earthquakes at that height. Figure III.2 provides an example of the arrangement of bracing in a structure with a horizontal roof.

Horizontal bracing is typically achieved through construction arrangements at the floor and roof levels. It is ensured by a diaphragm consisting of joists, decking, and possibly a collaborating slab, along with tie elements in the case of multi-story buildings. Alternatively, it can be achieved by creating wind beams, usually obtained by triangulating stability elements.



**Figure III.2.** Example of the arrangement of bracing in a structure with a horizontal roof.

### III.5.1. Principle of the rigid diaphragm

A rigid diaphragm refers to any upper floor (or roof) that is braced in such a way that it can behave like a beam. The supports for this beam will be the stability bracing. Similar to a "classic" beam stabilized by blocking 3 degrees of freedom (1 fixed support OR 1 hinge + 1 sliding support OR 3 sliding supports), it is necessary to block at least 3 degrees of freedom of the rigid diaphragm to ensure its stability. The distribution of forces among the vertical elements depends directly on the nature of the floor. Two types of floors can be defined based on their behavior towards horizontal forces: flexible floors and rigid floors.

### III.5.2. The floors

The choice of the floor type depends on a wide range of factors, including structural, aesthetic, acoustic, fire, thermal, etc. Thus, in wooden constructions, three main types of floors are primarily distinguished: the traditional floor composed of joists and rigid panels, the solid engineered wood floor, and finally, the mixed wood-concrete floor.

For each type of floor, the general composition, construction arrangements, and important points for bracing are presented. This type of floor works very well in the case of a structure entirely made of wood provided it is well-braced (with wood panels or wind beams). It serves the role of a diaphragm, distributing horizontal forces among the elements.

### **III.6. Bracing requirement**

#### **III.6.1. Basic principles**

To balance force acting in any direction on the plane, it is necessary to have at least three lines of forces:

- The action lines of the forces must not be concurrent.
- The action lines of the forces must not all be parallel to each other.

#### **III.6.2. Analogy**

The bracing of a building largely follows the rules of iso-statics. To stabilize a building, it is necessary to eliminate the six possible degrees of freedom, namely the three translations along  $(O, x, y, z)$  and the three rotations around the axes  $(O, x, y, z)$ .

Let's consider a building placed in a coordinate system  $(O, x, y, z)$ , where the elevation corresponds to the height of the building. If this building has a rigid diaphragm, it will resist forces in three degrees of freedom  $(R_x, R_y, T_z)$  since it is a plane. The walls supporting this rigid diaphragm will need to resist forces in  $T_x, T_y$ , and  $R_z$ .

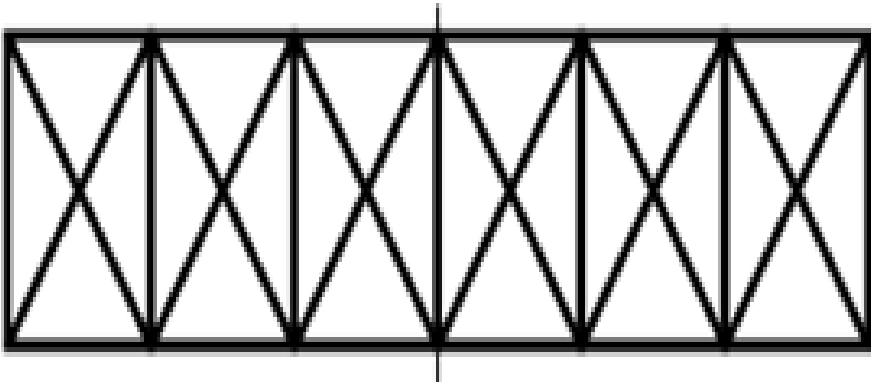
Bracing involves ensuring the longitudinal stability of a structure using "bars" forming a triangulation between structural elements (frames or arches, rafters, purloins, columns...) representing initially deformable "frames."

These bars can be made of wood, handling both tension and compression forces, or metal, handling only tension forces; in the latter case, a systematic arrangement in a Saint Andrew's cross is required.

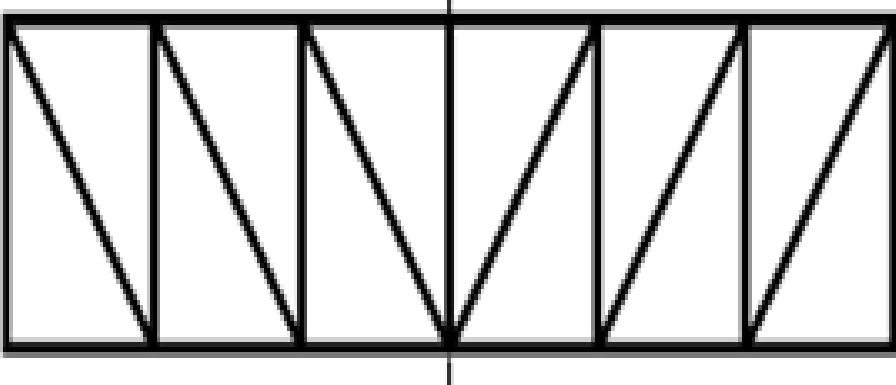
### **III.7. Roof bracing**

#### **III.7.1. The devices**

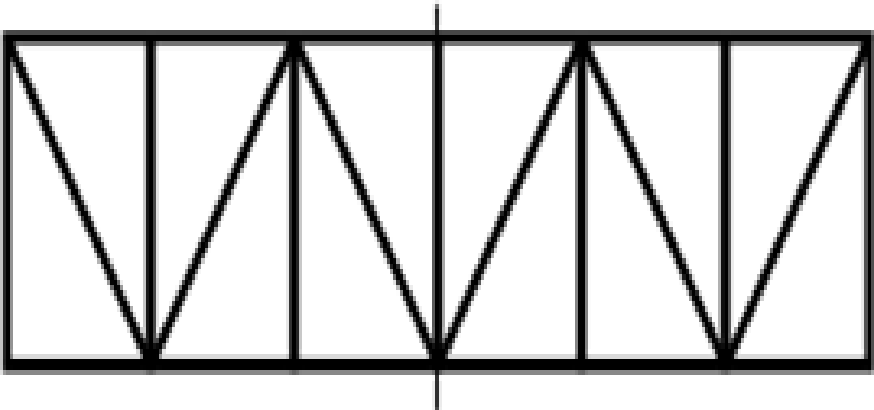
On the roof, the assembly formed by the porticos (or arches), purlins and “bars” is called: “windward” beam; the diagrams below present the main devices:



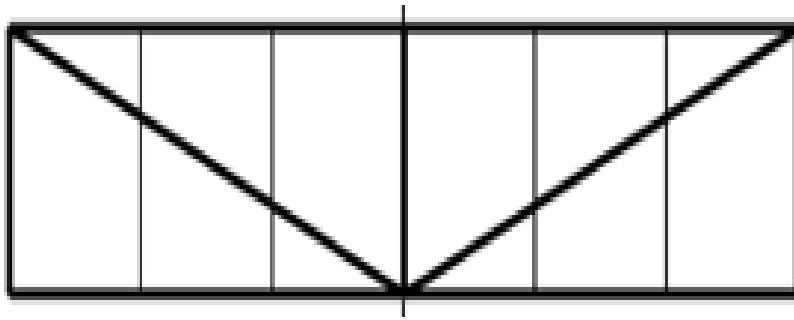
"Saint Andrew's Cross" (often metallic)



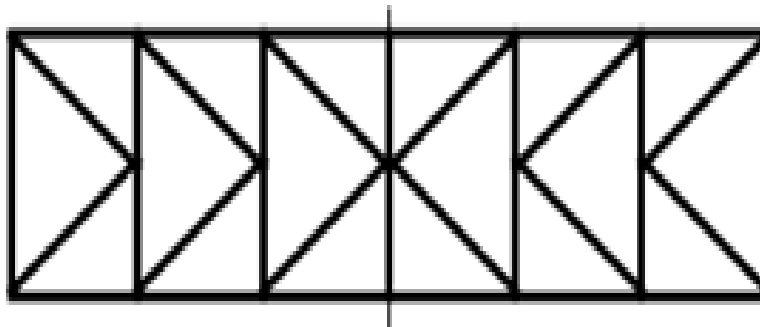
"N-bracing"



"V-bracing"

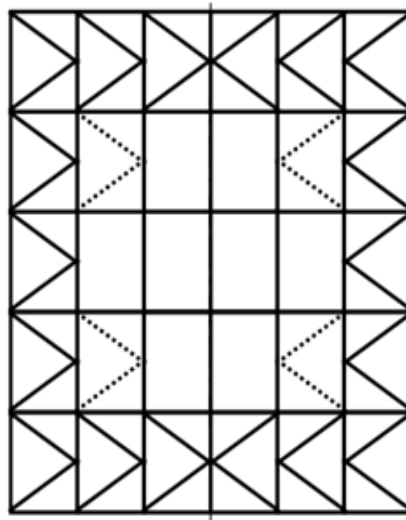


"V-bracing" (under the purlins)



"K-bracing"

For significant wind pressures and/or on large structures, bracing bars are arranged between other bays to evenly distribute the forces. This arrangement forms a system known as an equal resistance beam.



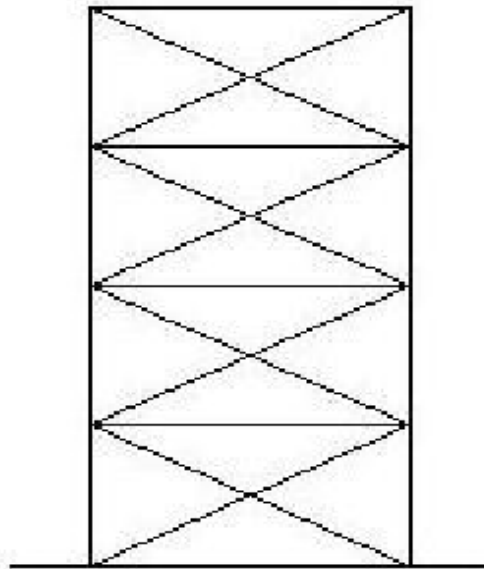
"K-bracing" (for illustration purposes)

**III.7.2. Saint Andrew's cross**

It is a cross shaped like an X. Its name comes from the shape of the cross that tradition says was used to torture Saint Andrew. The bracing with the Saint Andrew's cross adopts this X shape, which is essentially a triangulation of four triangles. This cross can be made using wooden arms or with the help of stays. In the case of stays, the assembly is adjustable.

### III.7.3. X-bracing (Saint Andrew's cross bracing)

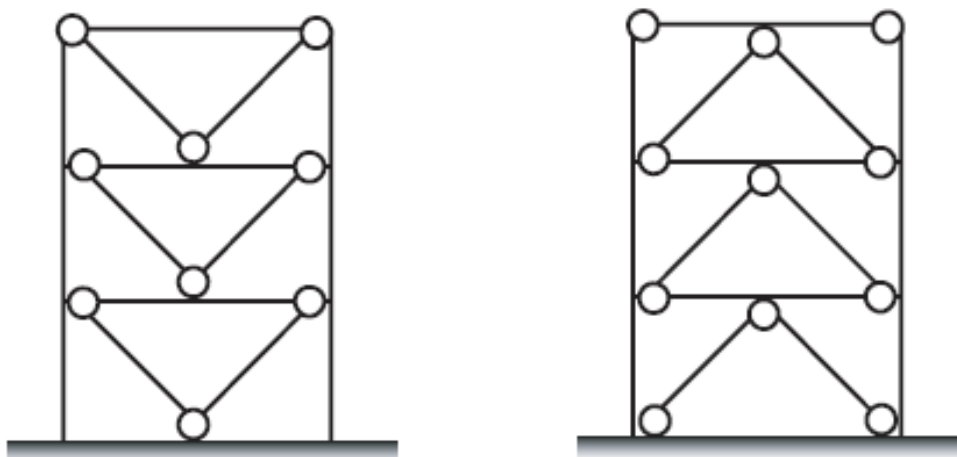
In this type of bracing, it is assumed that the resistance to horizontal forces is provided solely by the tensioned diagonals, while the compressed diagonals are neglected. This bracing system (**Figure III.3**) effectively contributes to energy dissipation only in the case of tensile loading on the diagonals [8].



**FIGURE III.3.X-BRACING** [8]

### III.7.4. V-bracing

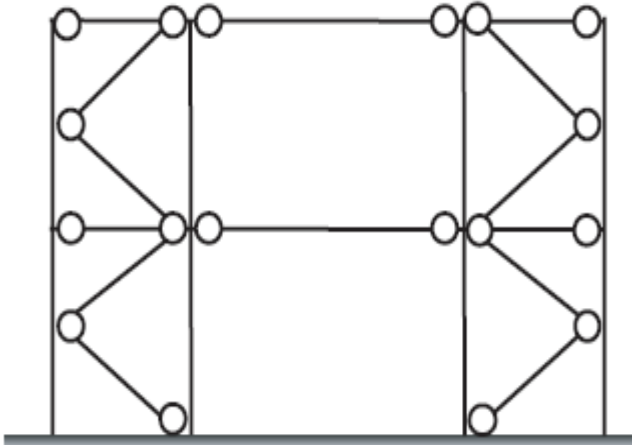
- The purlins and the bracing arms are located at the same level.
- The trusses support the roof on the rafters.
- The rafters form the members of the beam, the combination of purlins and bracing arms forms the web of the beam, and through triangulation ensures the rigidity of the beam.
- The fittings for attaching the purlins can be either U-shaped or in two parts (web + finger) (**Figure III.4**) [8].



**Figure III.4.V-bracing [8]**

**III.7.5. K-bracing**

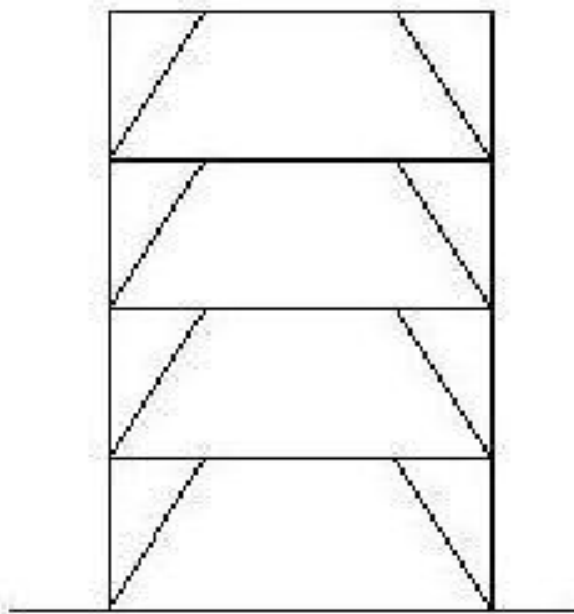
In this bracing system (**Figure IV.5**), the intersection point of the diagonals is located on the axis of the posts. K-bracings should be avoided, especially in seismic zones, as the intersection of the bracing bars occurs at the level of the posts and not the beams, leading to the creation of plastic hinges in the latter. This poses a risk of structural collapse [9]. K-bracings are preferred in cases where there are openings for doors and windows.



**Figure IV.5.K-bracing [9].**

### III.7.6. Trapezoidal bracing

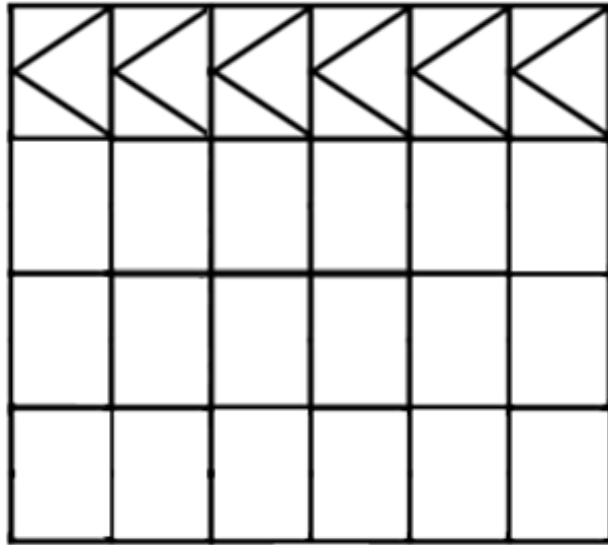
It is a structural component that transfers wind pressures exerted on the side walls and roof of a building to its foundation. Trapezoidal bracings (Figure III.6) are used in seismic regions and allow for the provision of doors and corridors in the braced bays. Eccentric bracing frames may exhibit a more ductile characteristic and higher energy dissipation capacities compared to a concentric bracing frame in the same material. This type of bracing has proven to be very effective when subjected to actual seismic events [7].



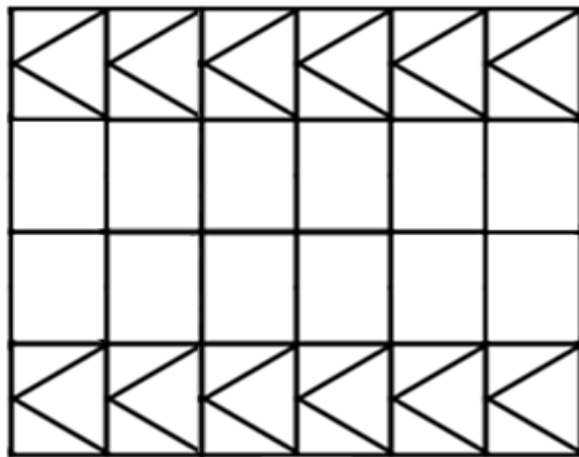
**FIGURE III.6.**TRAPEZOIDALBRACING [7]

### III.7.7. Case studies

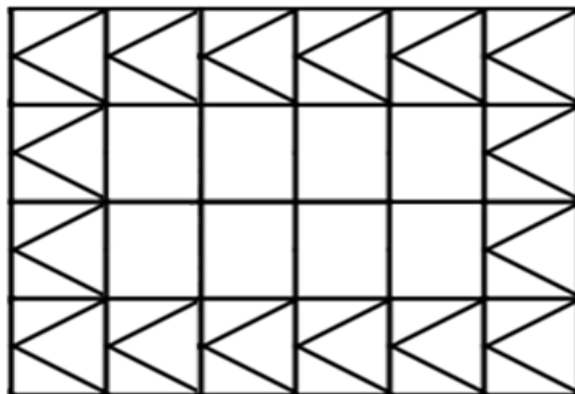
In general, roof bracing forms a belt at the edges; the diagram above illustrates this. However, depending on the circumstances, it is possible to move the beam of equal resistance inside a bay for passage or structural reasons. In the case of heavy loads, it will be possible to reinforce stress zones at the location of the beams.



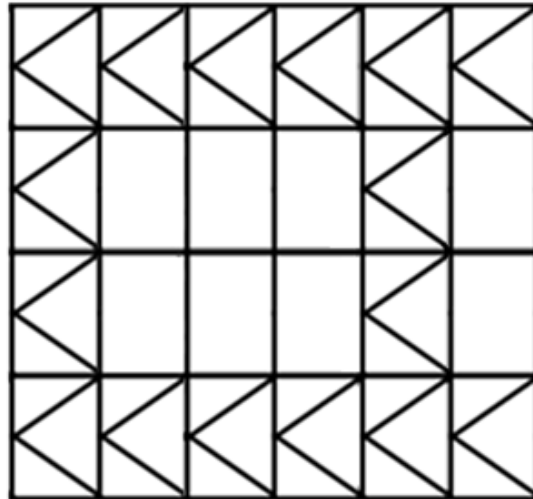
"Principle of a beam of equalresistance."



"Beams on bothsides."



"Belt at the edges"



*Moving a beam*

### **III.8. Stability core of tower buildings**

The stability of residential and, especially, office tower buildings is often ensured by a structure located in the central part, consisting of vertical walls in the form of reinforced concrete shear walls arranged along orthogonal planes, and by the floors. This assembly most commonly occupies the area where vertical circulations (elevators and emergency stairs) are concentrated, along with annex spaces that do not receive natural light (bathrooms, toilets, dressing rooms, archives, etc.).

The walls of this core bear part of the vertical loads and, on their own, resist horizontal forces, particularly wind actions. The vertical elements of the structure, around the core, generally only have to bear vertical loads.

In some cases, the stability core has been constructed with reinforced concrete, while the peripheral parts featured a framework—beams and columns—in metal. However, it should be noted that in certain tower buildings, the facades' frameworks have been designed to ensure stability against wind actions.

In the cases mentioned in the first paragraph of this section, the calculations do not differ, in principle, from those corresponding to the solution of bracing with reinforced concrete shear walls; it is necessary to determine the distribution of forces among the different walls in each direction and study, in particular, the resistance of lintels between shear wall elements located in the same plane.

The solution proposed in the fourth paragraph involves the calculation of frameworks with a large number of bays and floors, which can hardly be approached without the use of automatic calculation programs.

### **III.9. Mounting bracing**

Temporary bracing is necessary whenever stability during assembly cannot be ensured by the elements of the structure already in place. These braces transmit horizontal forces caused by the wind, as well as construction loads, to the foundations or parts of the structure capable of bearing these forces.

Temporary braces are arranged in horizontal and vertical planes and are most commonly made up of diagonal crosses using angles or round bars. It is also possible to use cables, which then also serve as adjustment means, in cases where the slab has not yet been poured and hardened and cannot perform its stabilizing function. Occasionally, the profiled floor sheeting is used as temporary horizontal bracing.

**CHAPTER IV**  
**TORSION AND FAILURE MODES OF SHEAR WALLS IN**  
**STRUCTURES**

**IV.1 Introduction**

The increase in shear force caused by the vertical axis torsion due to the eccentricity between the center of gravity and the center of rigidity must be taken into account. Negative shear forces due to torsion should be neglected. For all structures with rigid horizontal floors or diaphragms in their plane, it will be assumed that at each level and in each direction, the resultant of horizontal forces has an eccentricity relative to the center of torsion equal to the larger of the two values:

1. 5% of the largest dimension of the building at that level (this eccentricity must be considered on both sides of the center of torsion).
2. Theoretical eccentricity resulting from the plans.

**IV.2. Location and twisting of sails in structures**

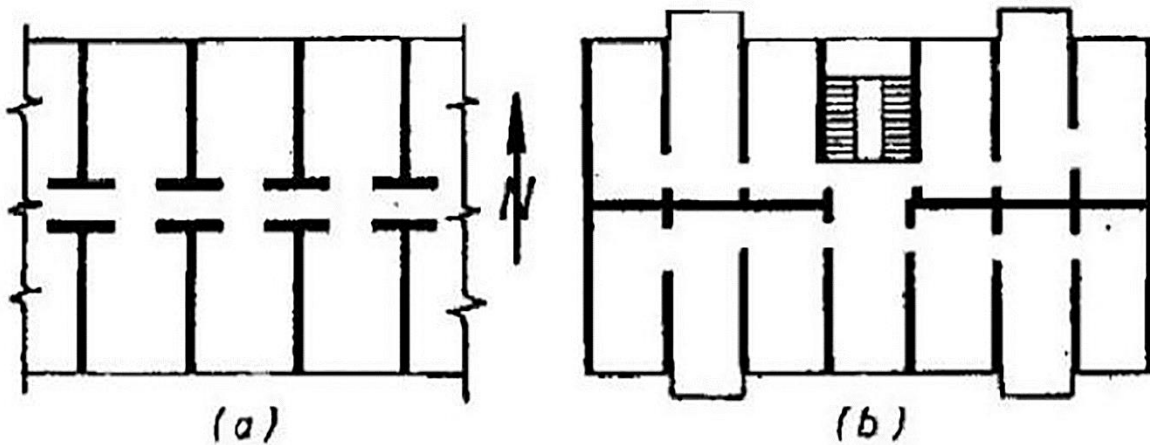
To facilitate the separation of various issues encountered in the design of bracing walls, it is convenient to establish a classification based on geometric configurations [7].

**IV.2.1. Strategies for siting shear walls**

Individual walls can be subjected to axial displacements, translation, and torsion. The extent to which a wall contributes to the resistance of overturning moments, shear forces, and torsion on each floor depends on its plan configuration, geometric orientation, and its location within the building's plan. The positions of bracing walls in a structure are usually dictated by functional requirements. The arrangements of shear walls in a building can be effectively utilized for lateral force resistance.

Structural designers often advise architects on the most desirable locations for bracing walls to optimize seismic resistance. Major structural considerations for the load-bearing wall alone include aspects of symmetry, stiffness, tensional stability, and the available overturning capacity of foundations. The key to the bracing wall layout strategy is the desire for inelastic deformations to be distributed reasonably uniformly across the entire building plan rather than concentrated on just a few walls.

A typical arrangement of walls is shown in **Figure IV.1**. In the north-south direction, the lateral force per wall will be low due to the presence of a large number of walls. The behavior in the east-west direction of the structure in **Figure IV.1 (a)** will be more critical because of the reduced wall area and the need for numerous openings [7].

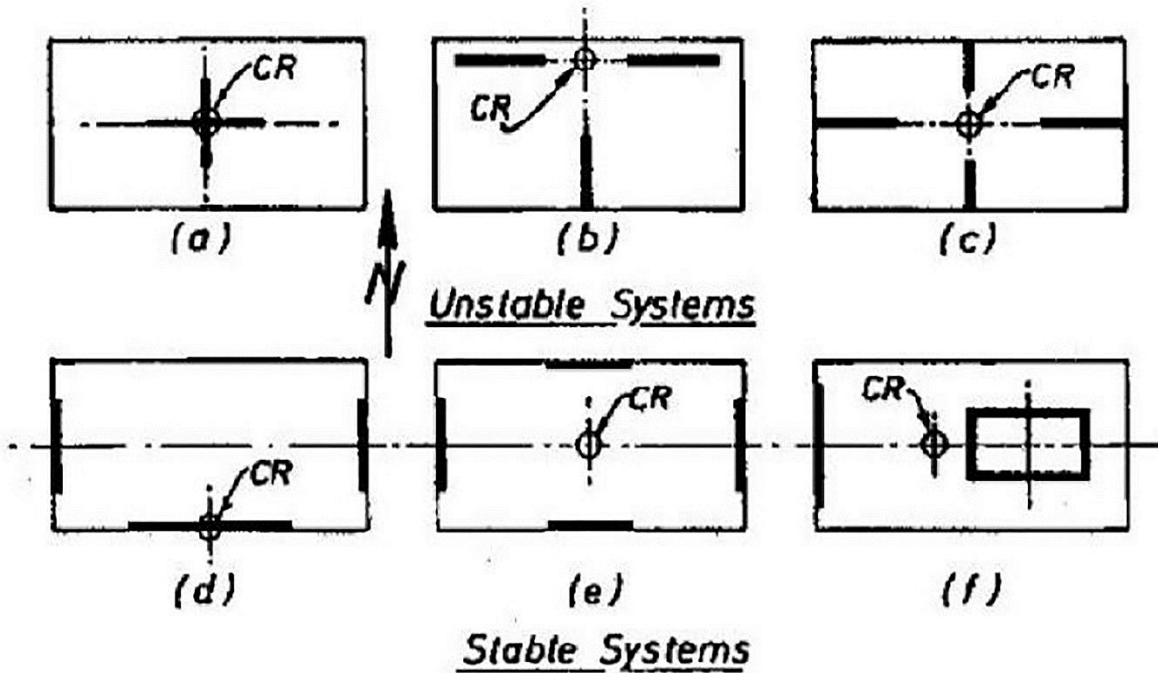


**Figure IV.1.** Wall type arrangements in hotels and apartment buildings [7]

Besides the large number of walls, the adequacy of the systems in **Figure IV.1 (b)** comes from the position of the mass centers, with rigidity being conflated, resulting in a low static eccentricity. When assessing the torsional stability of wall systems, the arrangement of walls, as well as the flexural and torsional rigidity, must be taken into account.

#### **IV.2.2. Effect of torsion on shear wall systems**

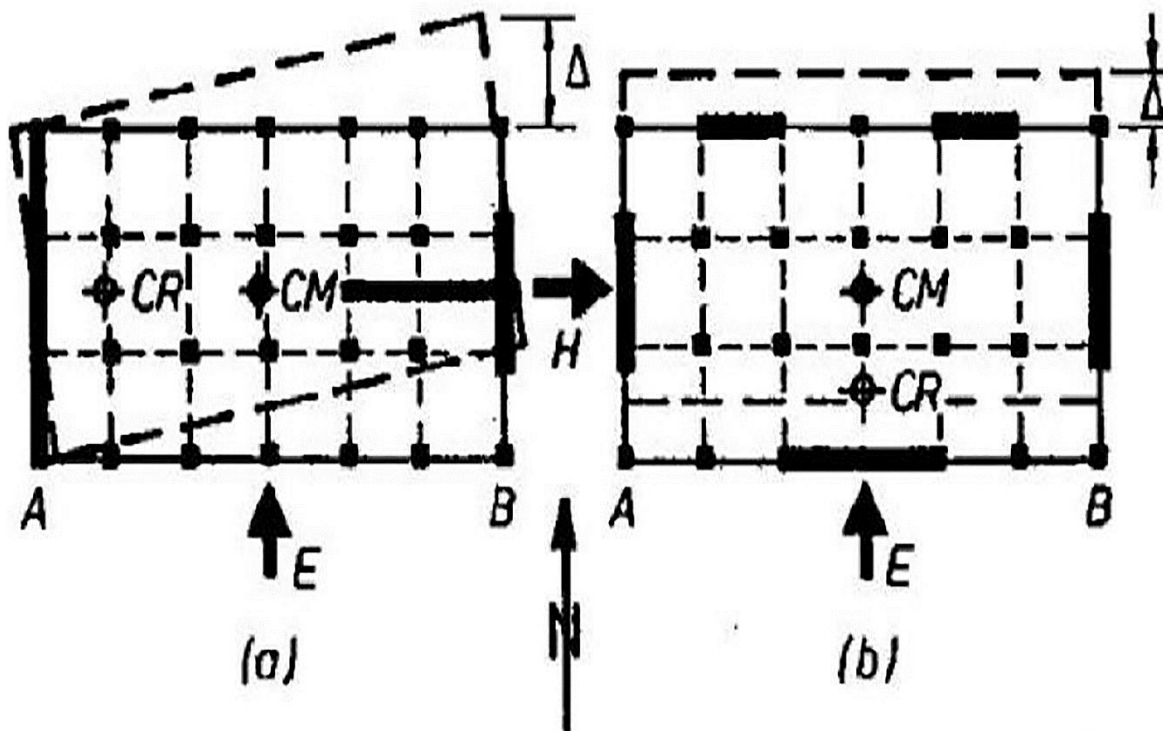
The torsional stability of wall systems can be examined using **Figure IV.2**. Many load-bearing walls are open with thin-walled sections and limited torsional rigidities. Therefore, in seismic design, it is common to neglect the torsional resistance of individual walls, except for tubular sections. It is observed that the torsional resistance of the wall arrangements in **Figure IV.2 (a), (b), and (c)** could be achieved only if the lateral force resistance of each wall about its weak axis is significant. Since this is not the case, these examples represent unstable torsional systems. In the case of the arrangement in **Figure IV.2(a) and (c)** calculations may show no eccentricity of inertia forces. However, these systems will not meet the torsional requirements [7].



**Figure IV.2.** Examples for the torsional stability of wall systems [7]

The **Figures IV.2. (d) and (f)** depict stable torsional configurations. Even in the case of the arrangement in **Figure IV.2. (d)**, where significant eccentricity is presented along the east-west axis of lateral force, torsional resistance can be effectively provided by actions induced in the plane of the short walls. However, eccentric systems, as represented by **Figures IV.2. (d) and (f)**, are specific examples that should not be favored in ductile earthquake-resistant buildings unless additional lateral force resistance systems, such as ductile frames, are also present.

To illustrate the torsional stability of inelastic wall systems, the arrangements shown in **Figure IV.3** can be examined. The horizontal force,  $H$ , in the longitudinal direction can be effectively resisted in both systems. In the case of **Figure IV.3. (a)**, the eccentricity, if any, will be low, and the elements in the short direction can provide torsional resistance, even if the T-section stiffener may undergo inelastic deformations due to seismic shear force  $H$  [7].

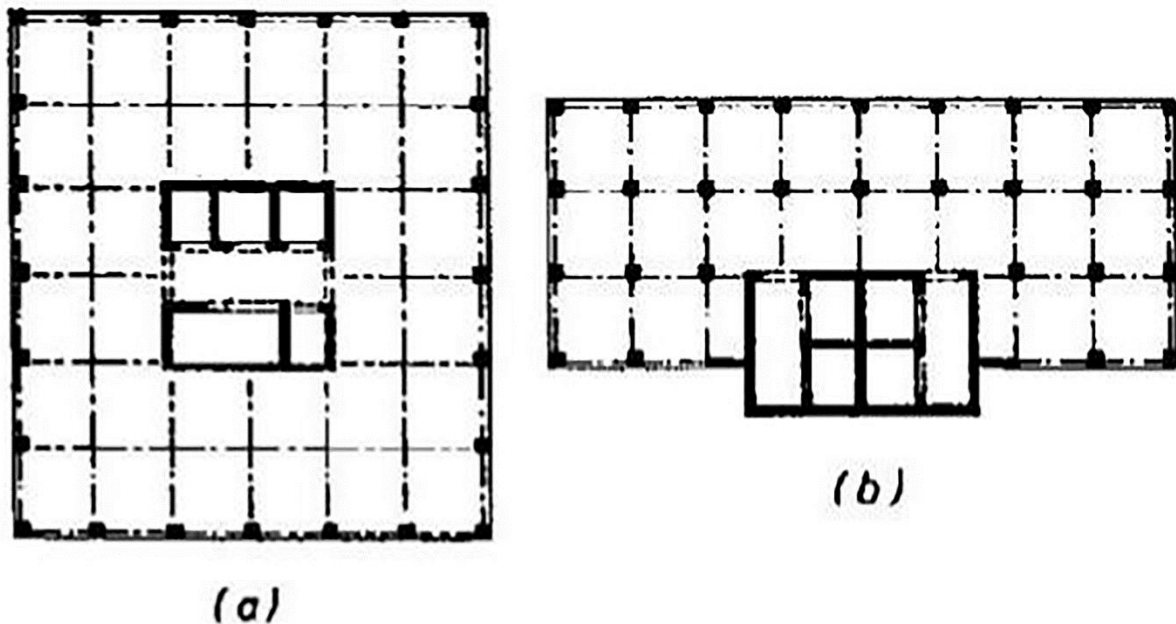


**Figure IV.3.**Torsional stabilities of inelastic wall systems [7]

Under seismic action E in the short direction, the structure in **Figure IV.4 (a)** appears stable despite the significant eccentricity between the center of mass (CM) and the center of rigidity (CR), as shown in **Figure IV.4**. However, regardless of how the resistance of the two walls parallel to E is determined, it will be practically impossible to ensure that both walls simultaneously reach the yield state due to the inevitable uncertainties in mass and stiffness distributions. If one of the walls, says B, fails first, its incremental stiffness will reduce to zero, causing excessive floor rotations as indicated. There are no walls in the transverse direction to E (i.e., the long direction) to provide resistance against this rotation, making the structure torsion ally unstable.

On the other hand, if one of the two walls parallel to E in **Figure IV.4. (b)** Fails first, as is again probable, the walls in the long direction, which remain elastic under action E, will stabilize the tendency of uncontrolled rotation by developing shear in-plane, making the structure torsionally stable.

Elevator and stair shafts lend themselves to forming a reinforced concrete core. Traditionally, these have been used to provide the major lateral force resistance component in multi-story office buildings. Additional resistance can be derived, if necessary, from the perimeter frames as shown in **Figure IV.4.(a)**. Such a central core position can also provide sufficient torsional resistance [7].



**Figure IV.4.**The lateral force resistance provided by reinforced concrete cores [7]

For better space distribution or visual effects, walls can be arranged in non-rectilinear, circular, elliptical, star-shaped, radiating, or curvilinear positions [S14]. While the distribution of lateral forces on elements of such a complex system of load-bearing walls may require special consideration in seismic design, especially those related to torsional balance, they remain the same as those described above for simple rectilinear walls.

### IV.3. Methods of sail breaking

The term "voile" encompasses elements of structure with very diverse mechanical behavior. However, we can consider that the main parameters with a predominant influence on the behavior of a voile are as follows:

- Slenderness, defined as the ratio of the height to the width of the voile,  $h/l$ .
- The arrangement and percentage of reinforcements.

- The intensity of the normal force.

Therefore, from the point of view of their operation, it is appropriate to distinguish between slender walls ( $h/l > 2$ ) and short walls ( $h/l < 2$ ).

### IV.3.1. Modes of breaking of slender sails

#### IV.3.1.1. Bending failures

We observe this mode of failure in very slender sails subjected to a normal compressive force and moderate shear.

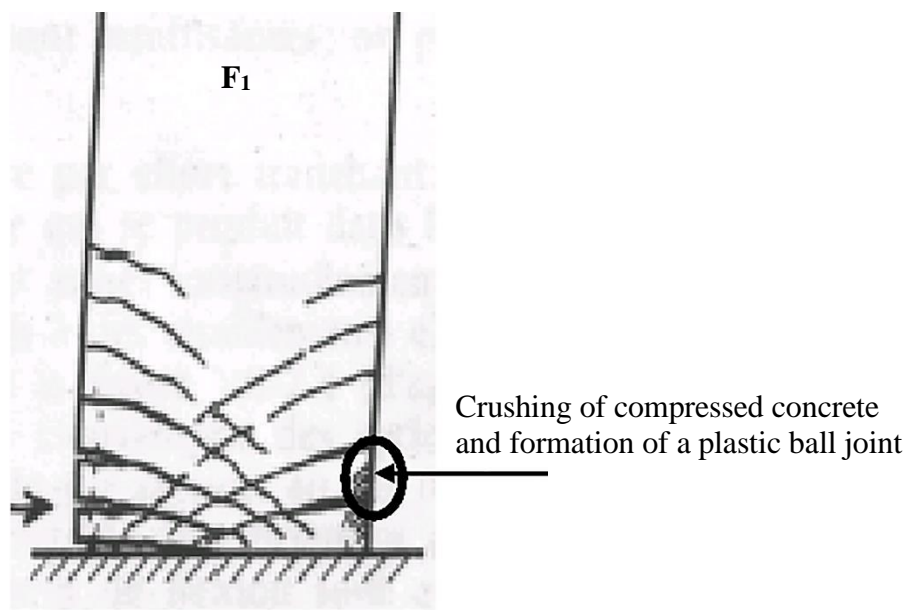
##### F1 Mode

Failure occurs through plasticization of the tensioned vertical reinforcements and compression

crushing of the concrete (**Figure IV.5**). This pattern corresponds to the formation of a plastic

hinge in the lower part of the web with significant energy dissipation. This mode of failure is

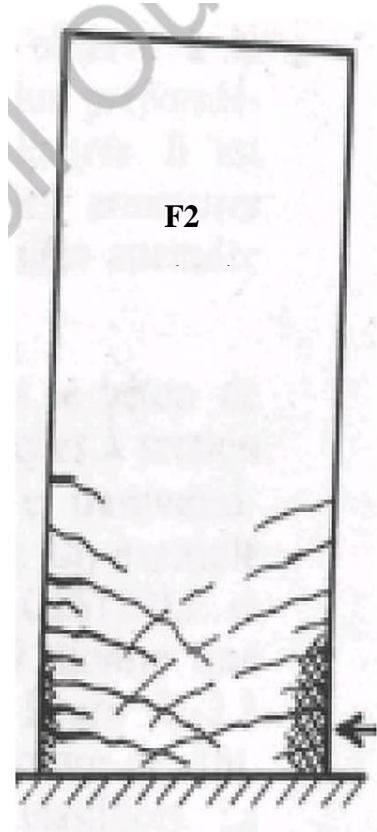
observed in very slender webs subjected to a low normal compressive force and moderate shear [10].



**Figure IV. 5.**Plasticization of coated reinforcements [10]

### **F2 Mode**

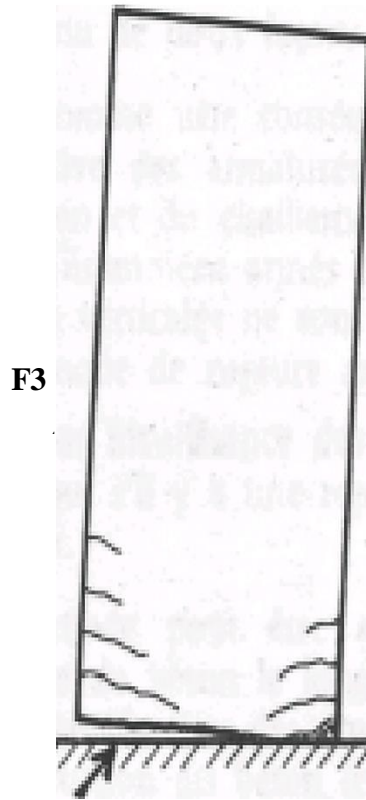
Failure by concrete crushing (**Figure IV.6**), encountered in webs with significant reinforcement subjected to substantial normal compressive force [10].



**Figure IV.6.** Crushing of compressed concrete [10]

### **F3 Mode**

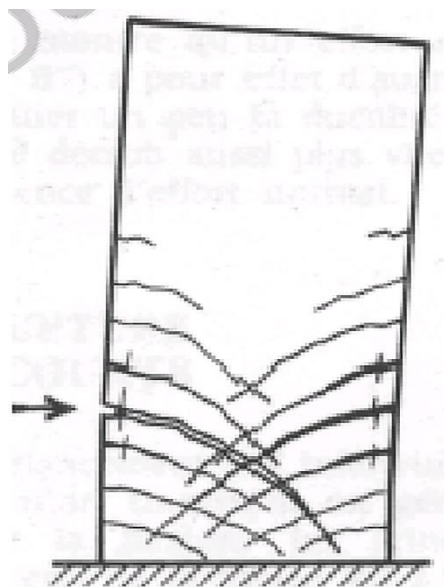
Brittle failure due to fractures in tensioned vertical reinforcements (**Figure IV.7**), observed in thinly reinforced webs when the vertical reinforcements are distributed rather than concentrated at the ends [11].



**Figure IV.7.** Failure of tension reinforcements [11]

**F/T Mode (Flexure/Shear Failure)**

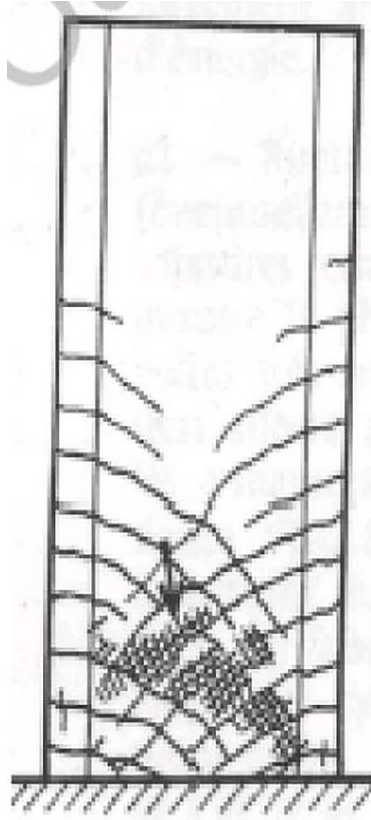
Failure through plasticization of flexural vertical reinforcements and transverse reinforcements (**Figure IV.8**), encountered in moderately slender webs where flexure is no longer predominant, and horizontal reinforcements are insufficient [10].



**Figure IV.8.** Plasticization of transverse reinforcements and Longitudinals [11]

### **Mode T (Rupture by shear force)**

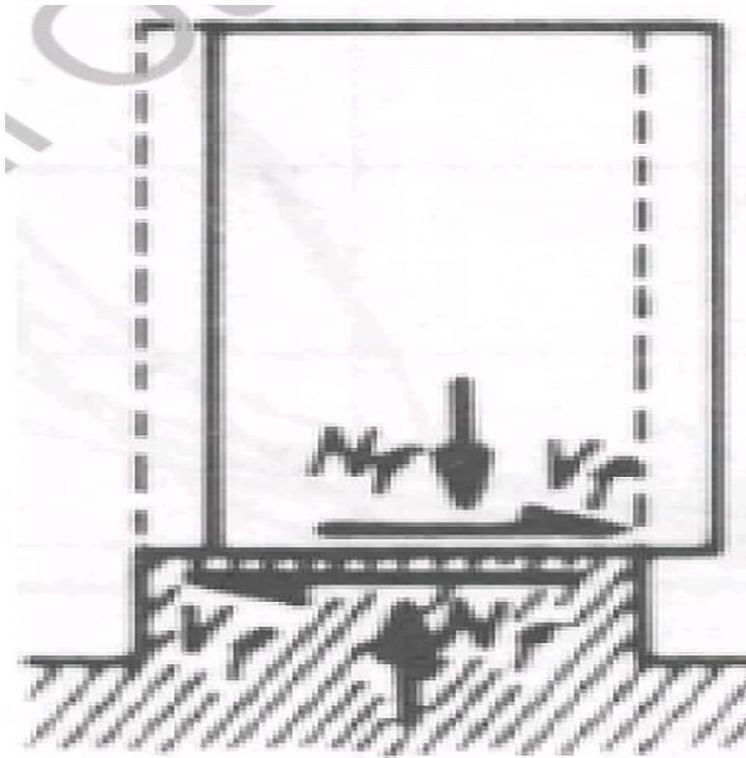
Breakage of the compression rods developed in the web core (**Figure IV.9**), encountered in sails equipped with stiffeners, strongly reinforced longitudinally and transversely and subjected to high shears [11].



**Figure IV.9.** Rupture of the concrete of the soul [11]

### **G-mode**

Failure by sliding at the concrete pour joints (**Figure IV.10**). This type of failure can occur when the distributed vertical reinforcements are insufficient, the quality of the concrete pour joints is poor, and the value of the normal force is low [11].



**Figure IV.10.** Sliding failure [11]

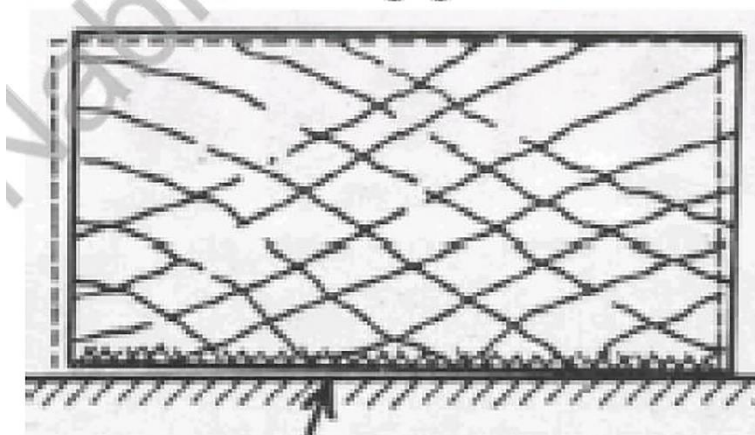
#### **IV.4. Method of breaking short sails**

In this case the shear force is preponderant over the bending.

##### **T1 mode**

Failure by sliding at the anchorage. This mode of failure (**Figure IV.11**), resulting from the progressive plasticization of the vertical reinforcements, is accompanied by significant slips that significantly reduce stiffness [10].

##### **T1**

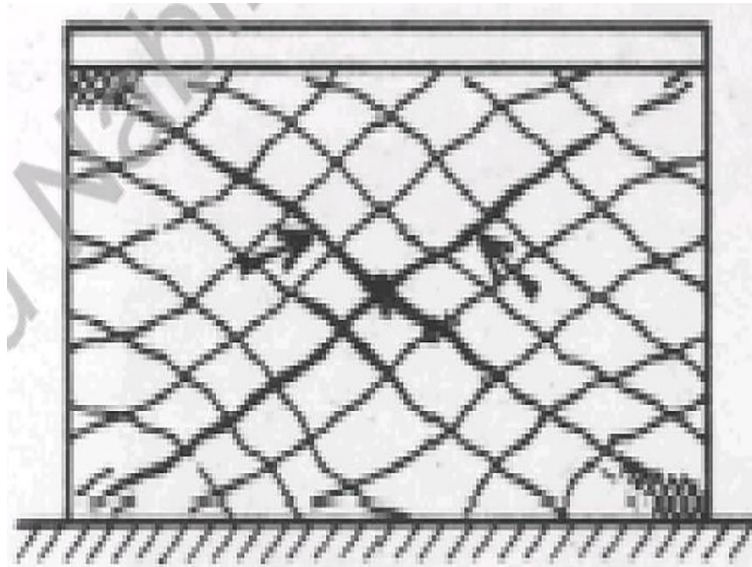


**Figure IV.11.** Failure by sliding at the anchorage [10]

### **T2 Mode**

Diagonal failure with plasticization or rupture of reinforcements along diagonal cracks (**Figure IV.12**), observed in moderately reinforced webs subjected to low normal force [10].

**T2**

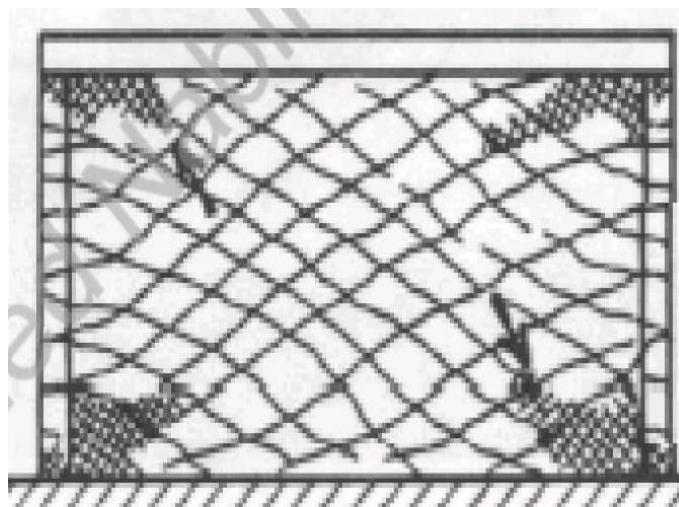


**Figure IV.12.** Diagonal break with plasticization [11].

### **T3 Mode**

Failure by crushing of the concrete of the core (**Figure IV.13**), at the base of the connecting rods transmitting the compressive forces [10].

**T3**



**Figure IV.13.** Crushing failure of concrete [10]

## **IV.5. Earthquake consequences on reinforced concrete structures**

### **IV.5.1. Damage suffered by structures braced by self-stable frames**

The structures braced by self-stable frames are most affected by the earthquake, given that moment and shear are essentially the primary forces the frame must withstand during horizontal loading. We are particularly interested in frames, specifically in the nodal zone, which is the essence of the frame [10].

#### **IV.5.1.1. Plastic ball joint at post-beam nodes**

**Figures IV.14 and IV.15** respectively illustrates an example of rupture in the nodal zone and a section dislocation [10].



**Figure III.15.**Section dislocation [10]

**Figures IV.16 and IV.17** respectively illustrate an example of a hinge in the column and in the beam [10].



**Figure. IV.16** Ball joint in the post (sinking behavior) [10]



**Figure. IV.17.**Ball joint in the beam (Desired behavior) [10]

#### IV.5.1.2. Shearing of posts

Figures IV.18 and IV.19 respectively illustrates an example of short columns due to crawl space and shearing of a column [10].



**Figure IV.18.**Short posts due to crawl space [10]



**Figure IV.19.**Shearing of a Column [10]

**IV.5.1.3. Crush failures**

**Figure IV.20** illustrates an example of concrete crushing and steel buckling in the two posts of the stairwell [10].



**Figure IV.20.** Crushing of concrete and buckling of steel in the two posts of the stairwell [10]

**IV.5.1.4. Buckling of the columns and separation of the concrete cover**

**Figure IV.21** illustrates an example of buckling of columns and flow of concrete cover [10].



**Figure IV.21.**Column buckling [10]

#### IV.5.1.5. Bending failure

Figure IV.22 illustrates an example of failure by bending of beams [10].



Figure IV.22. Failure by bending of beams [10].

#### IV.5.1.6. Dislocation of masonry in fills

Figure IV.23 illustrates an example of dislocation of masonry fillings [10].



Figure IV.23. Dislocation of masonry fillings [10]

IV.5.1.7. image suffered by mixed structures: (gantry + sail)

Figures IV.24 and IV.25 respectively illustrate an example of section failure at the base of the walls and open cracks in the short column wall due to the crawl space and shearing of a column [10].



Figure I V.24. Section breaks at the base the sails [10]

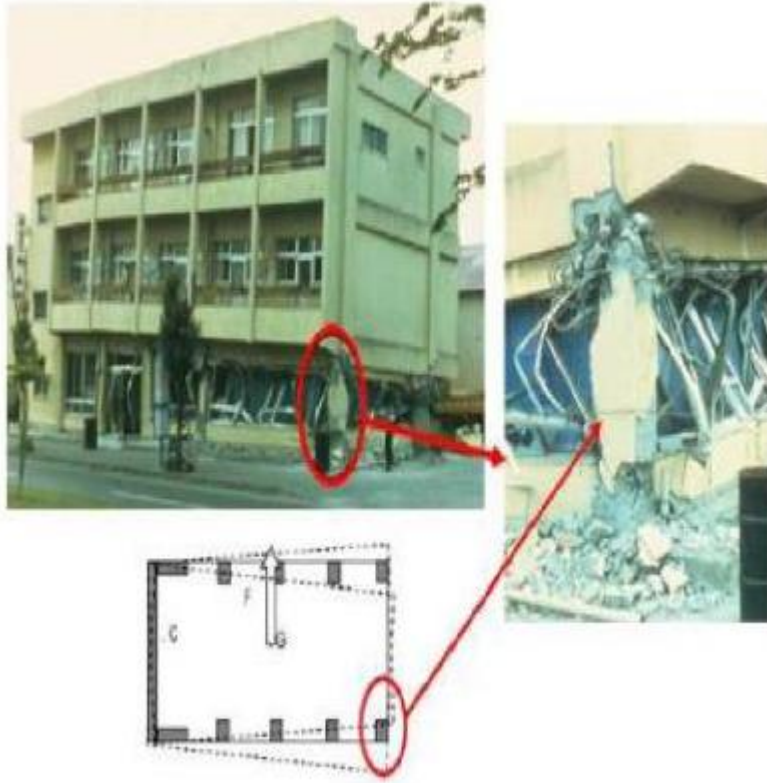


**Figure IV.25.** Open cracks in the veil [10]

**Figures IV.26 and IV.27** respectively illustrate an example of the slender and plastic elements of the corner post [10].



**Figure IV.26.** Slender elements [10]



**Figure IV.27** Plasticization of corner post the asymmetrical position of the sails[9]



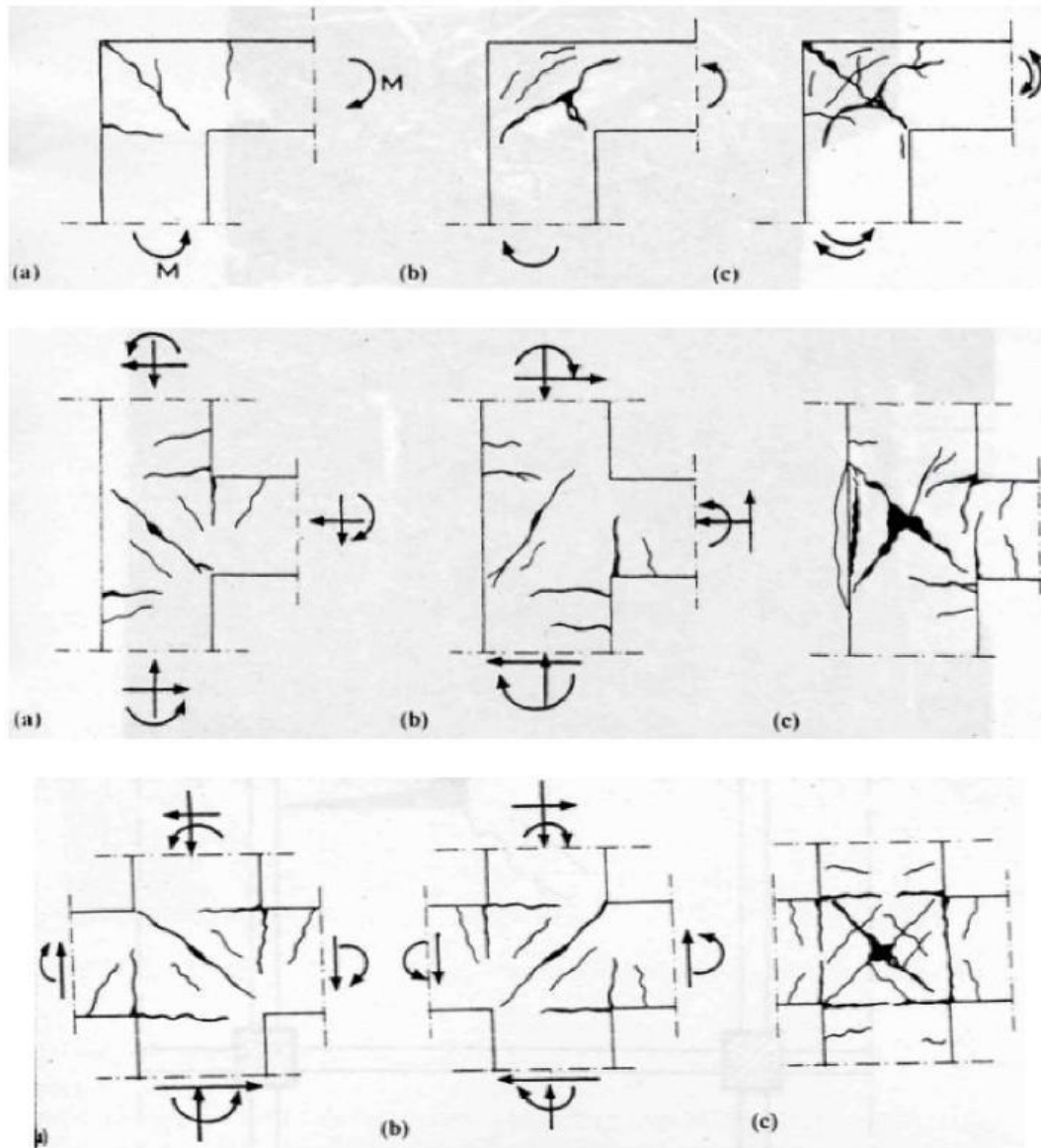
**Figure.IV.28.** Total collapse of unbraced or poorly braced constructions



**Figure. IV.29** Collapse by out-of-plane bending of a portal structure reinforced concrete parking lot during the Northridge earthquake (United States) in 1994[10]

#### **IV.5.1.8. Column – beam junction (nodes)**

Damage to column-beam joints, even at the first cracks, is considered extremely dangerous to the structure and should be treated accordingly. This damage reduces the rigidity of the structural element and leads to uncontrollable redistribution of loads. Common failures in column beam joints (corner joint, multi story structure exterior joint, and interior joint) are shown in Figure IV.30.



**Figure IV.30.** Damage to column-beam joints

**Figure IV. 31** present an example of frame science at the heart of the column-beam intersection node.



**Figure IV.31.** Figure IV. 31 Example of the science of frames at the heart of the node the column-beam intersection

**Figure IV. 32** illustrates an example of Plastic hinge formation 2003 earthquake, Boumerdes, Algeria



**Figure IV.32.** Formation of plastic hinge 2003 earthquake, Boumerdes, Algeria

Figure IV. 33 illustrates an example of knot shearing 2003 earthquake, Boumerdes, Algeria



**Figure IV.32.** Example of knot shearing 2003 earthquake, Boumerdes, Algeria

**Figure IV.34** illustrates an example of very severe structural damage and almost complete collapse.



**Figure IV.34.**Example of very severe structural damage and almost complete collapse.

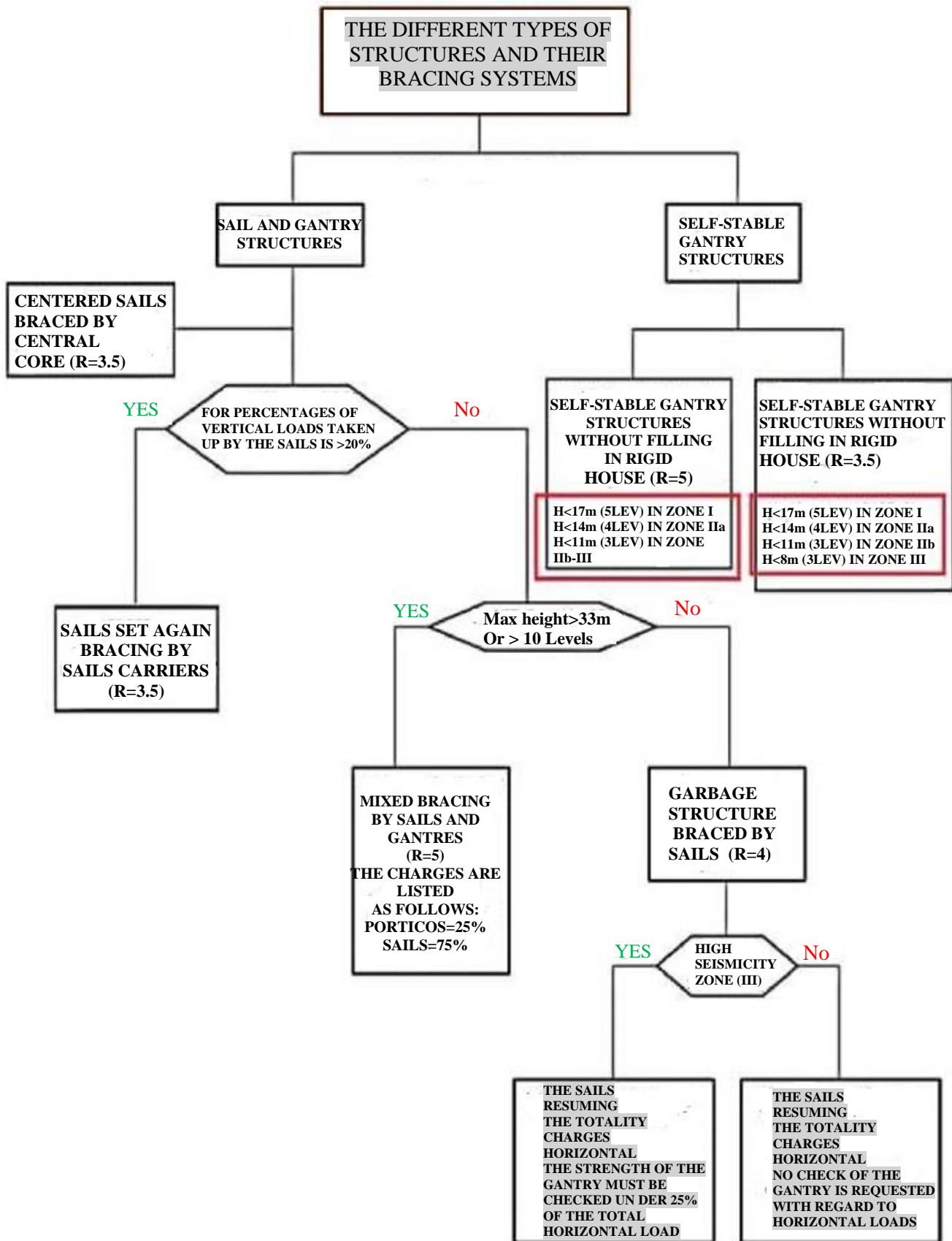


**Figure.1V.35**How a shear wall works



**Figure IV.36** Plastic ball joint at the base of BA post

#### IV. 6. Flowchart of the different types of structures and their bracing systems

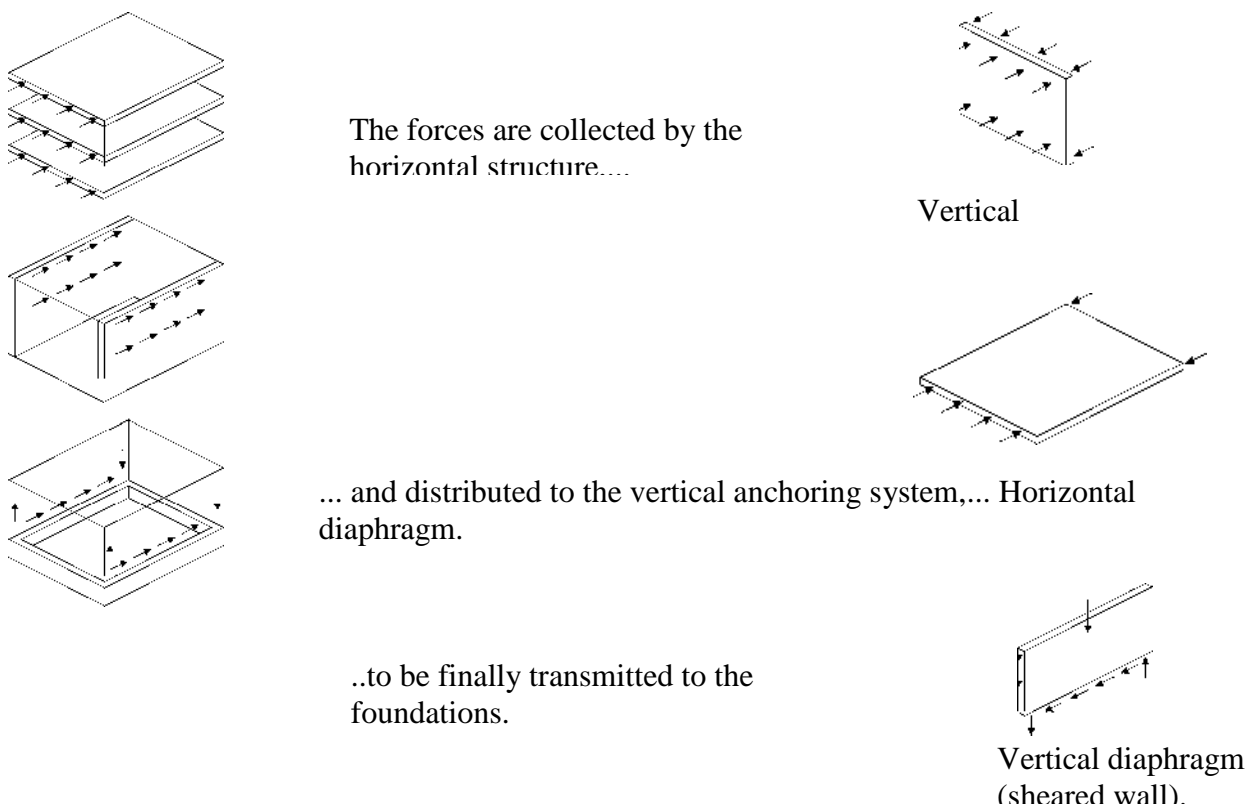


**CHAPITRE V**  
**SEISMIC DESIGN OF BUILDINGS**

**V.1. General Concepts**

**V.1.1. General Concept of Building Stability under Seismic Action**

**Figure V.1** depicts the general operational framework in a "box" for addressing horizontal seismic or wind actions.



**Figure V.1.** General "box" operating diagram for resisting horizontal earthquake or wind actions (after ZACEK, 1996).

All buildings consist of "boxes," the general operation of which is schematically depicted in Figure V.1, and their stability entails adhering to the following three conditions:

1. Adequate resistance of the components constituting the box:
  - Vertical bracing: walls, triangulations, frames
  - Horizontal or sub-horizontal bracing or diaphragms: floors, roofs, windward beams

2. Appropriate selection of these components, ensuring that the overall geometry of the box remains unchanged during seismic movements:
  - Limitation of out-of-plane movements, twisting, etc. This requires:
    - A suitable number of vertical and horizontal bracing components
    - Proper relative arrangement of these components
3. Adequate connections between these components.

### **V.1.2. Overall Objective of Seismic Framework Project**

The overall objective of a seismic framework project is to define a structure capable of enduring, without collapsing, the deformations caused by seismic action. This objective can be successfully achieved through various types of framework projects with different degrees of energy dissipation capacity through plastic deformations (see **Figure V.1**), including:

- Frameworks where deformations are primarily elastic.
- Frameworks forming a significant plastic zone, usually at the base. Example: reinforced concrete core structure.
- Frameworks comprising numerous dissipative zones.

### **V.1.3. Significance of "Seismic Design Principles"**

In the seismic context, the best safety-oriented projects are achieved by adhering to the "design principles" outlined in section V.2. It's important to note three things about these "principles":

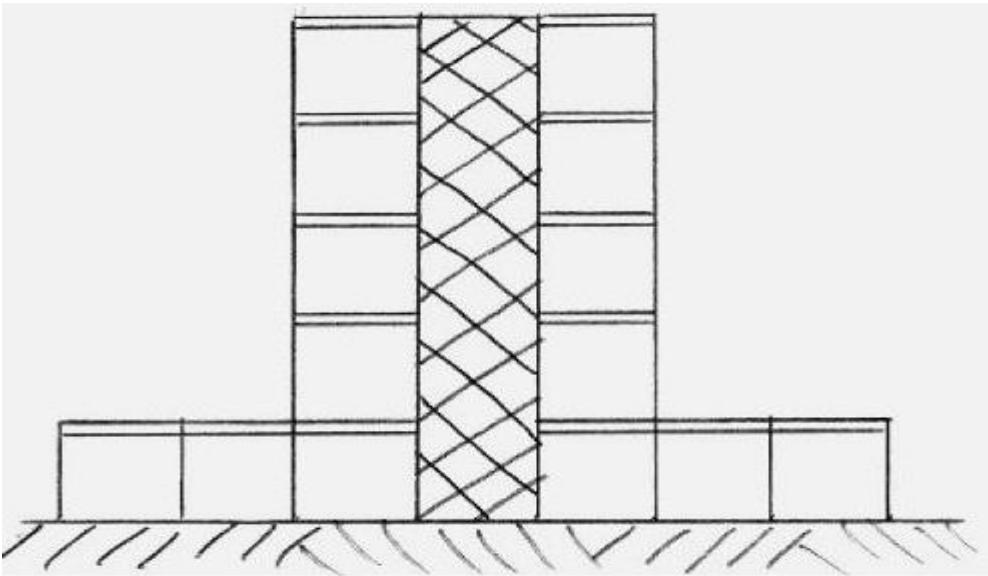
1. It is entirely possible to design structures that do not strictly adhere to the "principles" of seismic design yet are still capable of successfully enduring seismic actions as calculated. Adhering to design principles primarily results in minimizing the additional cost required to transition from a regular structure to a seismic one. Additionally, safety is generally better assured in a well-designed and approximately calculated structure than in a poorly designed one for which complicated calculations are performed. The more complex the calculations, the more uncertainty there is regarding the quality of the representation of the structure and its behavior in a model.

2. The stated principles apply to the actual structural elements of buildings, not merely their appearance. When outlining silhouettes to express certain principles, it's done to provide a

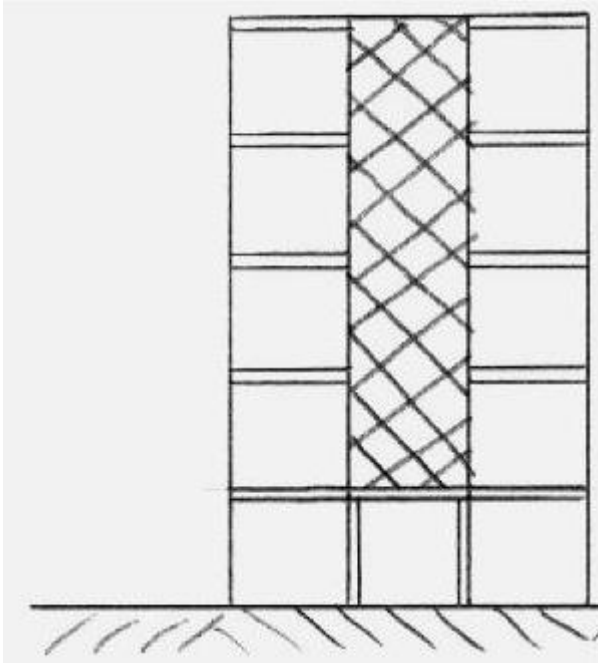
vivid image, but architects have much more freedom than these silhouettes might suggest because the principles pertain to the primary structure of the building. Structural elements (beams, columns) may be chosen to constitute a secondary structure, which is not part of the seismic resistance system (or only marginally, as discussed below). For instance, a building with concrete cores may have these cores as its primary structure and the entire framework, including beams and columns arranged around the cores, as its secondary structure (see **Figure V.1**). The strength and stiffness of secondary elements regarding seismic actions must be significantly lower than those of primary structural elements. Eurocode 8 sets the limit of the contribution of secondary seismic elements to lateral stiffness,  $K_{sec}$ , at 15% of the contribution to lateral stiffness of primary seismic elements,  $K_{prim}$ :  $K_{sec} \leq 15\% K_{prim}$ . However, the secondary structure must still be designed to continue bearing gravity loads when the building is subjected to displacements caused by earthquakes.

3. Adhering to design principles still leaves the project designer with several choices to make at the project's outset, as multiple solutions are possible that all respect the principles of seismic design.

**Figures V.2 and V.3** show the distinction between primary structure and secondary structure of the building. Distinction between structural regularity and apparent regularity.



**Figure V.2.** The primary structure is a wall or veil



**Figure V.3.** Irregular primary structure

- The primary structure consists of a wall or shear wall, as the secondary structure (peripheral frames) contributes minimally to the absorption of seismic action and follows the deformations of the primary structure.
- The primary structure is regular, even if the exterior appearance of the building is irregular.
- The primary structure is irregular because the interrupted shear wall at the first and ground floors acts as a frame.

## **V.2. Seismic Design Principles for Buildings**

### **V.2.1. Simplicity**

The behavior of a simple structure is easier to understand and calculate; the risk of overlooking a particular phenomenon, such as interaction between parts of different stiffness or accumulation of different effects among these parts, is low. Overall simplicity contributes to simplicity in details.

### **V.2.2. Continuity**

Any discontinuity in the design of a structure leads to a concentration of stresses and deformations. A discontinuous structure is always problematic because the failure mechanism it involves is localized. Energy dissipation in the structure should be maximal, achieved by involving the maximum number of elements to form a global failure mechanism rather than a localized one. The non-homogeneous behavior of a structure with major discontinuities always presents issues as it makes the calculation of the structure as a whole delicate and the correct design of crucial nodes where significant deformations occur difficult. The principle of continuity impacts the overall design of structures, as explained in principles 3 and 4. This principle also translates into structural details and site monitoring.

In structural details, it is necessary to:

- Avoid weakening of sections (hollow cores).
- Construct beams and columns with converging axes.
- Avoid abrupt changes in the directions of load-bearing elements.
- Avoid abrupt changes in the widths of load-bearing elements; hence, widths of converging beams and columns should be similar.
- Carefully design connections of prefabricated elements.
- Position assembly joints (steel, industrialized concrete systems) or restraints (reinforced concrete) outside highly stressed zones.

Site monitoring:

This is particularly important to ensure the actual quality of the work performed, especially:

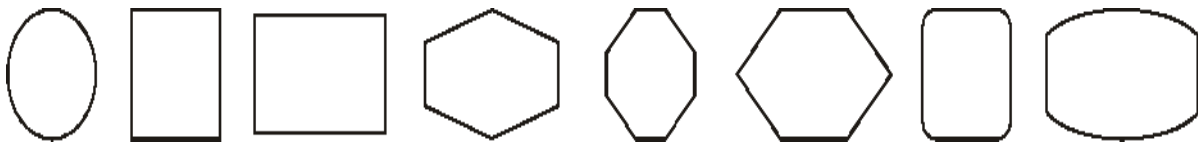
- Positioning of prefabricated concrete elements.
- Pouring of their assembly joints.
- Proper placement of reinforcements, meticulous execution of reinforced concrete restraints.
- Quality of materials used.

Furthermore, even if high statically determinate structures are not always possible, it is essential to avoid the absence of any positive connection. Elements simply placed are held in place only by friction, and once this is overcome, major displacements can occur. This problem can be solved with flexible connections or stops, which only come into play in the event of an earthquake.

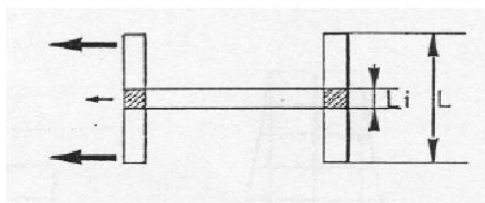
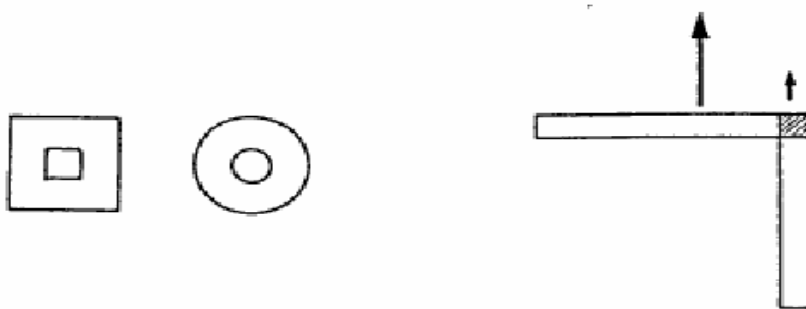
### V.2.3. Plan Regularity

Horizontal seismic motion is a bidirectional phenomenon. The building structure must be capable of withstanding horizontal actions in all directions, and structural elements must possess similar strength and stiffness characteristics in both principal directions, leading to the choice of symmetric forms. The ideal form is not only symmetric along two axes but approaches axisymmetry (see **Figures V.4 and V.5**) because significant damage is often observed at the junctions of segments in structures composed of multiple perpendicular segments.

Purely flexural considerations explain this phenomenon: the flexural stiffness along the principal directions is significantly different in a rectangular building. This results in different natural periods for two perpendicular wings subjected to seismic action of a given orientation, leading to a different response over time and concentration of issues at the junctions of perpendicular wings. This fact was particularly notable in Bucharest after the 1977 earthquake, where all buildings forming street corners collapsed or were significantly more degraded than others. This observation also applies to H-shaped buildings, despite being symmetric in two directions.



**Figure V.4.** Favorable shapes: simple planes with 2 axes of symmetry (AFPS, 2002)



**Figure V.5.** Plan views of buildings. Left: symmetrical and compact in plan. Right: harmful effects of asymmetry or non-compact character

Ce qui est vrai pour la flexion générale est également applicable à la torsion : les éléments chargés de reprendre la torsion doivent être répartis de manière suffisamment symétrique. Le non-respect de ce principe peut entraîner une déformation permanente torsadée de la structure.

### V.2.4. Régularité en Élévation

En vue en élévation, les principes de simplicité et de continuité se traduisent par une apparence régulière de la structure primaire, sans variations abruptes de rigidité. De telles variations entraînent des contraintes locales élevées.

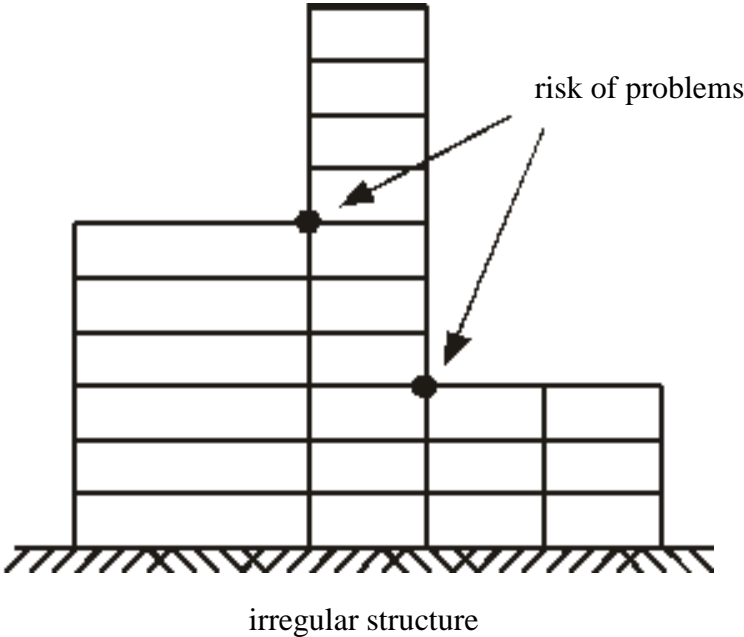
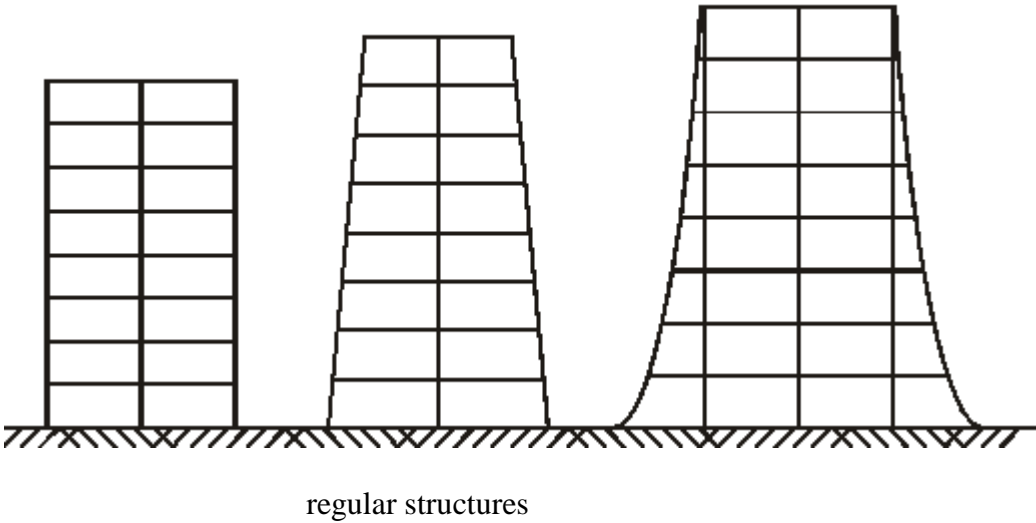
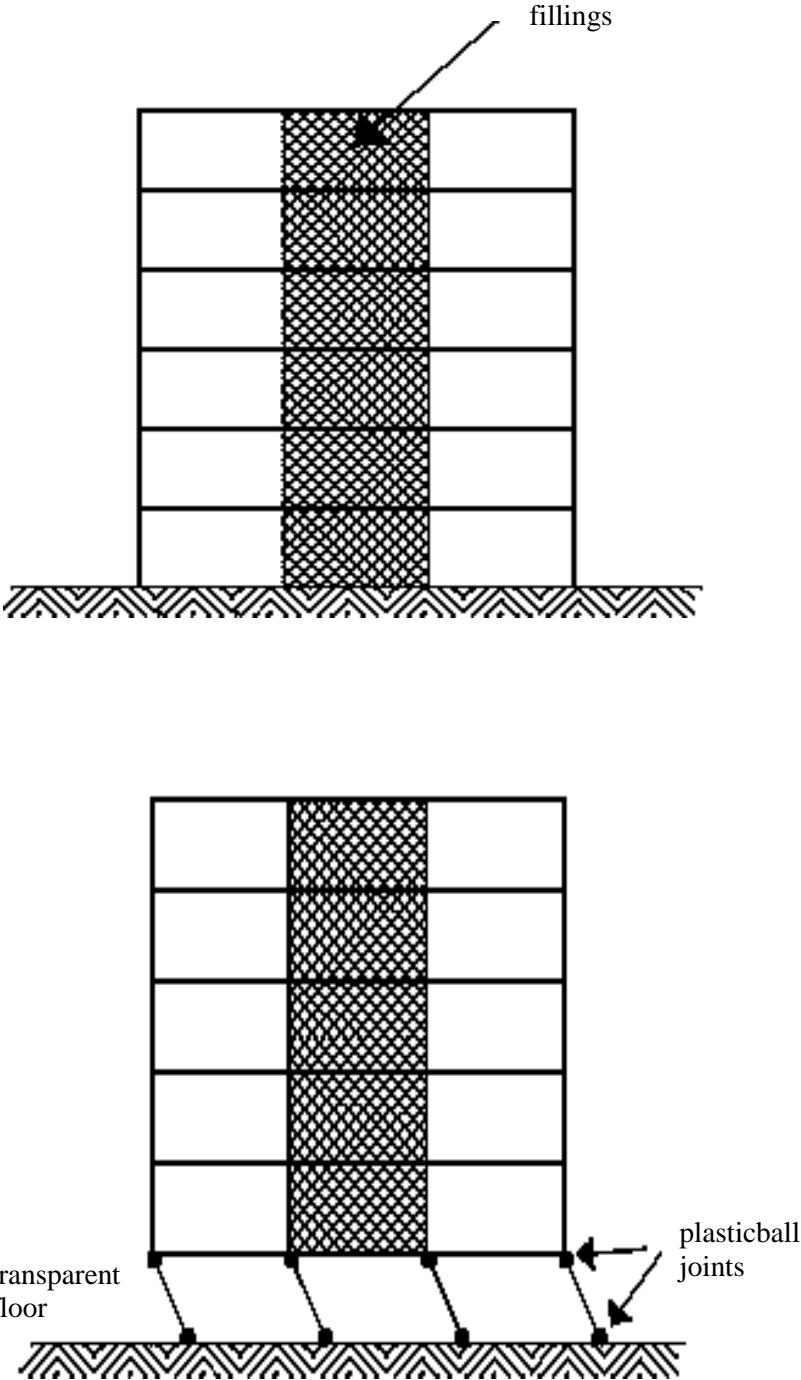


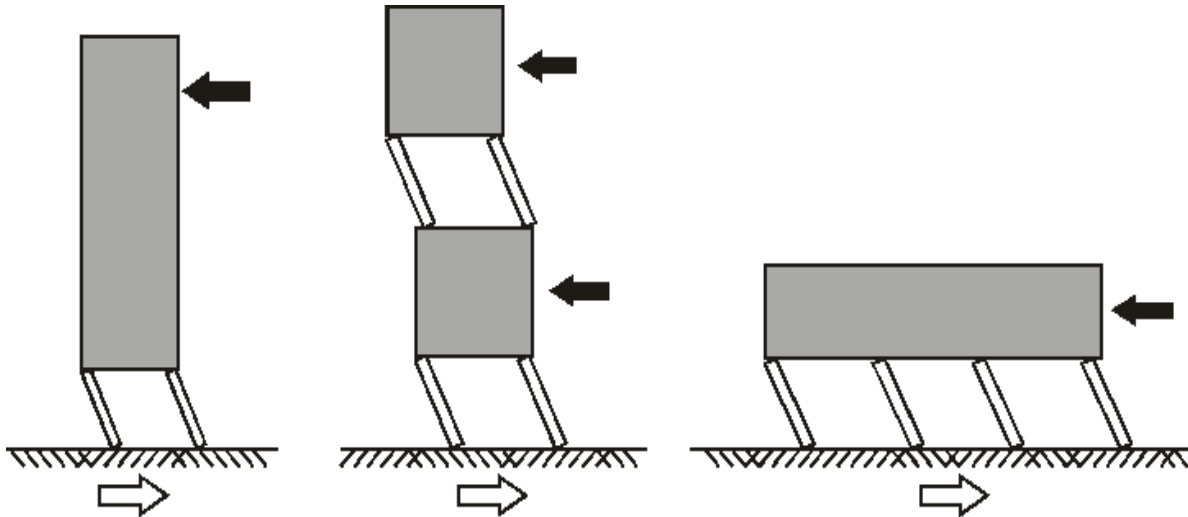
Figure V.6. Regularity in elevation

The principle of continuous and uniform distribution of the load-bearing elements of the primary structure necessitates ensuring continuity of columns and structural walls, lest the situation of a "soft story" be created, as depicted in **Figure V.7**.



**Figure V. 7.** Left: regularity in elevation. Right: flexible or “soft” ground level

Transparent levels are very common in buildings because the ground floor is left open due to its purpose: shops, offices, hotel lobbies, parking lots. However, transparent levels are strongly discouraged in seismic zones because they can act as flexible levels, concentrating all the deformations of the structure (see **Figure V.8**).



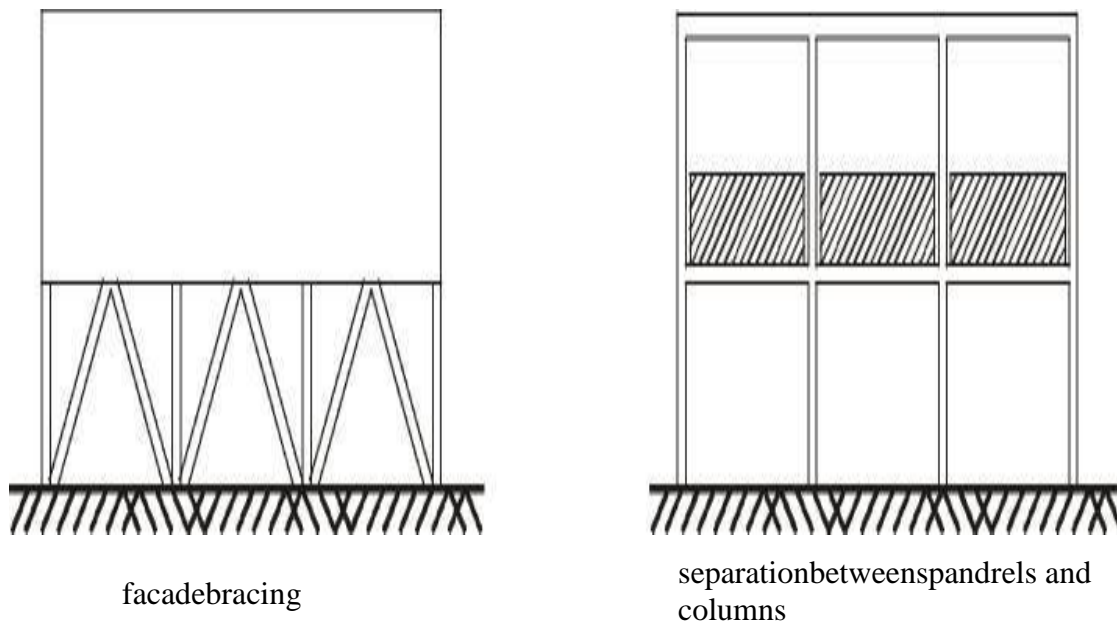
**Figure V. 8.** Buildings with transparent levels

When transparent levels are more flexible than other levels, the columns of these levels undergo significant deformations that can lead to the collapse of the building (soft story) (AFPS, 2002). The result of this arrangement often leads to the collapse of the "soft story," resulting in the total collapse of the building. This situation is particularly observed in reinforced concrete structures, where the columns:

- Under compression do not offer ductility against alternating shear and bending stresses.
- Under tension offer little resistance to bending.

The solution is to provide these open levels with a rigidity comparable to that of other levels, for example, by bracing the facade or by decoupling the spandrels (separating the columns) and allowing for equalizing the clear height of the columns of the main structure (see **Figure V.9**).

The U.S. UBC 1994 code limits the height of buildings with a flexible level to one story above ground level and 9 meters above ground level.



**Figure V. 9.** Solutions for buildings with transparent levels (AFPS, 2002)

Structures with frames in which infill walls are placed are particularly prone to "soft story" collapses because their analysis during the design phase is often conducted assuming that the structure is a frame structure and that the infill walls are non-structural, contributing only their mass.

The reality can be very different, and two detrimental situations are possible:

1. The infills are made of resistant masonry, in contact with the beams and columns, except for a specific floor left open or "transparent." In this case, the structure behaves like a discontinuous wall, and deformations concentrate in the columns of the transparent level, leading to the collapse of the "soft story," followed by the total collapse of the building.
2. The infills are made of resistant masonry in contact with the beams and columns, but no floor is left open or "transparent." In this scenario, the earthquake may initially create transparency by destroying the infill at the floor where the  $R_d/E_d$  ratio is the lowest. Once transparency is created, the subsequent events mirror those described in situation 1. The location of the level rendered transparent by the onset of seismic movement is random, as it is linked to the variable resistances of the infill masonry. Often, this level is still the ground floor, where shear is maximum.



**Figure V. 10.** Creation of transparency and ruin of floor (here the ground floor)

The countermeasures to these “soft floor” situations associated with fillings are as follows:

1. The study of the structure considers it as a masonry wall, and the evaluation of periods is done based on this model (resulting in smaller periods and greater shear force). The behavior coefficient  $q$  is the smaller one associated with masonry.
2. The study of the structure considers it as a frame. Precautions are taken not to build infills rigidly in contact with the frames, by inserting a flexible joint on the vertical and upper sides of the infills (see Figure V.9: separation between spandrels and columns).
3. The study of the structure considers it as a frame. The infills are made of masonry offering significantly less resistance and/or stiffness than the frame. Very weak masonry will be crushed almost instantly, while highly deformable masonry will follow the deformations of the frames without significantly changing their response. Comparing the "load-displacement" characteristics of a frame mesh and its infill in terms of stiffness and resistance is necessary to ensure the negligible influence of the infills. Without further information, a figure can be used to distinguish between "primary" and "secondary" framework to define the maximum relative contribution of the infills in terms of stiffness and/or resistance: 15% of the contribution of the frame structure.
4. Construction of buildings with frame structures as the primary bracing system, especially in reinforced concrete, is prohibited in seismic zones, and safer alternatives such as shear wall structures or steel frames are mandated.



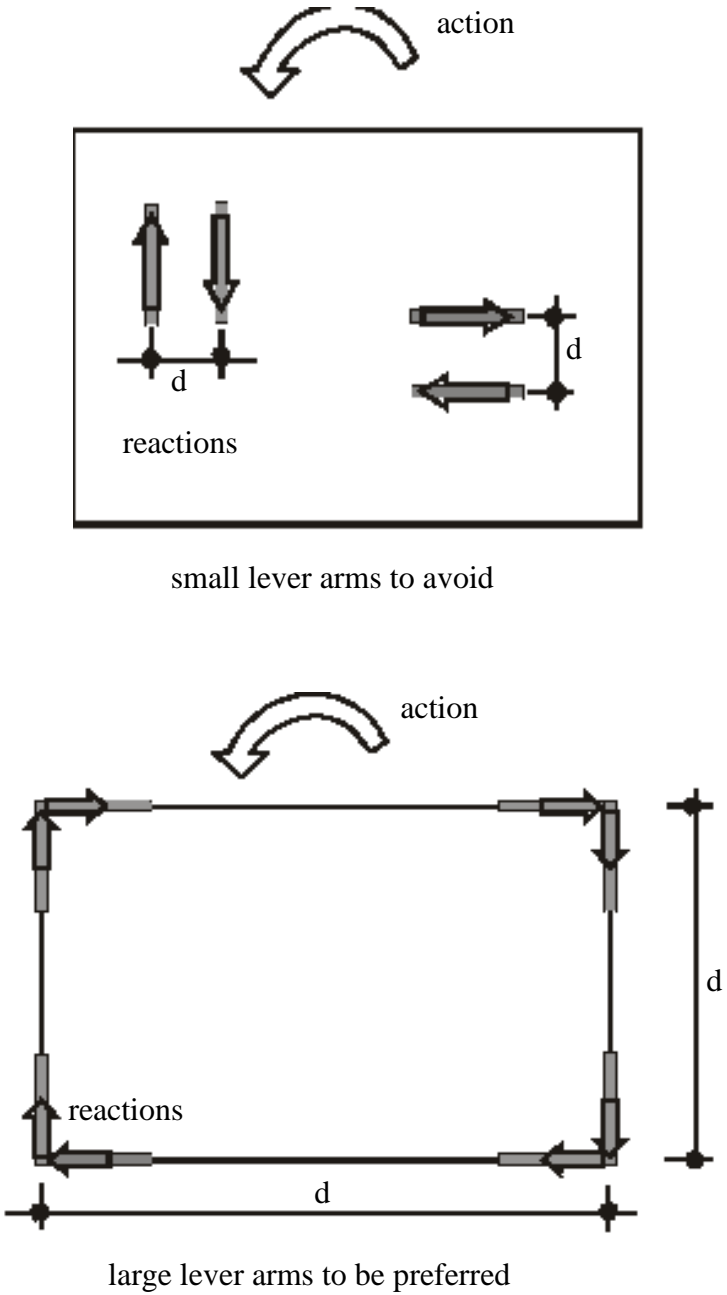
**Figure V. 11.** Good behavior of a building in nayou (primary structure) and peripheral structure (secondary structure). (Boumerdes, 2003)

Thus, the building depicted in **Figure V.10**, with its primary bracing structure consisting of a continuous reinforced concrete core and its secondary structure comprising peripheral concrete frames with infills, experienced some degradation of its infills. However, it not only avoided total collapse but also significant permanent deformations.

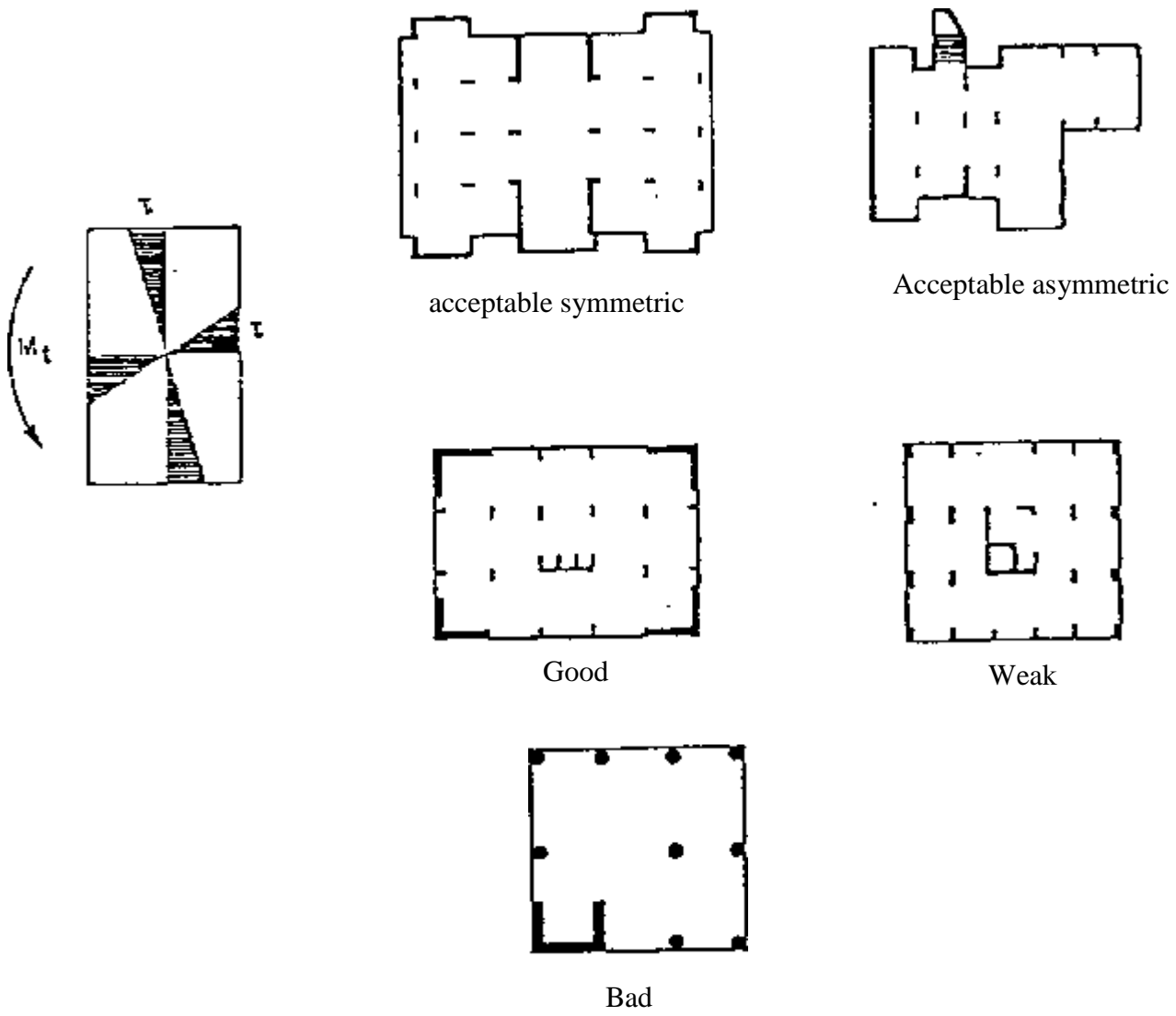
### **V.2.5. Torsional Stiffness and Resistance**

It has been explained in Section V.1 why an earthquake can subject a building to significant torsional stresses. The stress distribution in a solid subjected to torsion necessitates that elements capable of providing torsional stiffness/resistance to the structure be positioned as far towards the periphery of the building as possible to achieve their maximal effect. Indeed, for a given torsional moment  $M_t$ , the shear force  $V$  in each bracing will be derived from moment equilibrium, that is, from a relationship of the type  $V = M_t / d$ , and the greater the distance  $d$ , the smaller the shear force  $V$  will be (see **Figure V.12**).

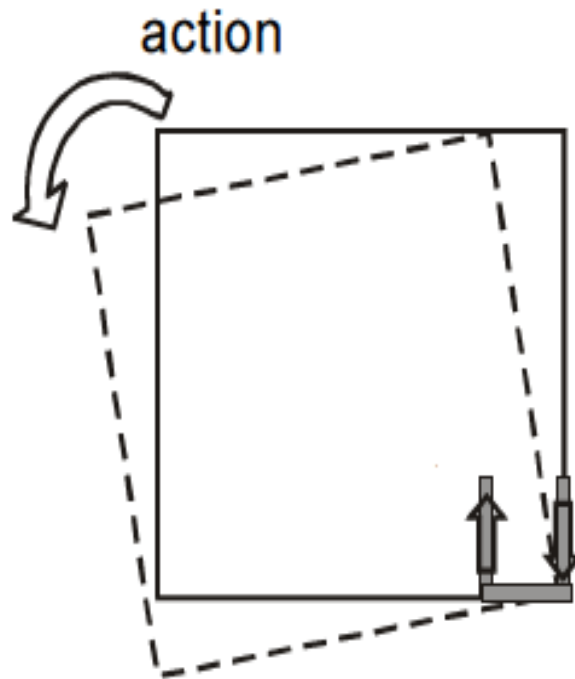
Appropriate resistance and stiffness to torsion are necessary to limit the movements of the building and the stresses on structural elements due to torsion. The conventional construction arrangement in non-seismic zones, where a single central core (staircase and elevator shaft) constitutes the sole bracing, offers little torsional stiffness and can lead to high stresses on peripheral frames.



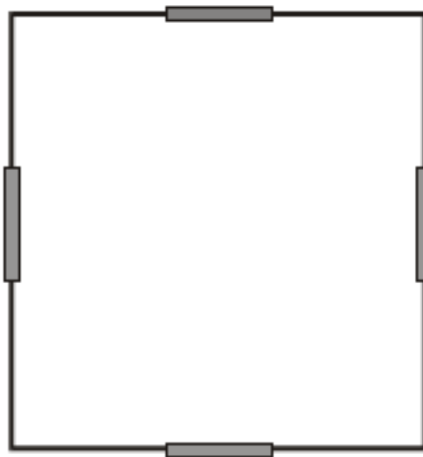
**Figure V. 12.** A large distance between the parallel elements promotes the resistance of the structure to torsion thanks to a significant lever arm in the horizontal plane.



**Figure V. 13.** Arrangements of bracing for the recovery of torsion



to avoid



to prefer

**Figure V.14.** An off-centered position of the bracing elements causes torsional stress on the building (in addition to a very weak lever arm) (AFPS, 2002)

### V.2.6. Effective Diaphragms

The diaphragms of a building are the horizontal structures that transfer the horizontal action resulting from the movement of the floor masses and their loads to the vertical bracing structures.

Diaphragms should be relatively inflexible within their plane to ensure an efficient distribution of horizontal action among the various vertical structures. Ideally, they ensure that there is no relative horizontal displacement between the vertical structures at each level where they are present.

In this scenario, the resulting horizontal action at a level is distributed among the vertical bracings in proportion to their relative stiffness. The most rigid vertical elements thus bear the heaviest loads.

When the stiffness of a vertical bracing decreases due to cracking or collapse, the loads it can no longer sustain are automatically redistributed by the horizontal diaphragm to the other vertical bracings. Therefore, it is desirable for the number of vertical bracings to exceed the minimum required for the stability of the structure.

The role of the diaphragm is played by the roof and floors, which can be constructed in various ways: reinforced concrete floor, composite floor, braced beam grid, spatial truss, horizontal frames

The stiffness of diaphragms depends on several factors:

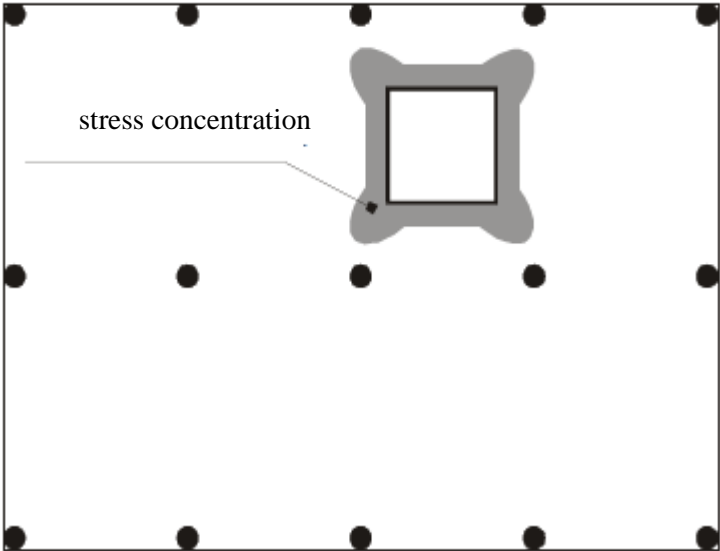
Their shape: Long and narrow diaphragms are flexible. Diaphragms with re-entrant angles may experience stress concentrations leading to damage.

- The respective stiffness of the diaphragm and the vertical bracing. If the stiffness of the vertical bracing is significant (masonry walls or concrete walls), moderate spans of the diaphragm are preferable to limit their flexibility.

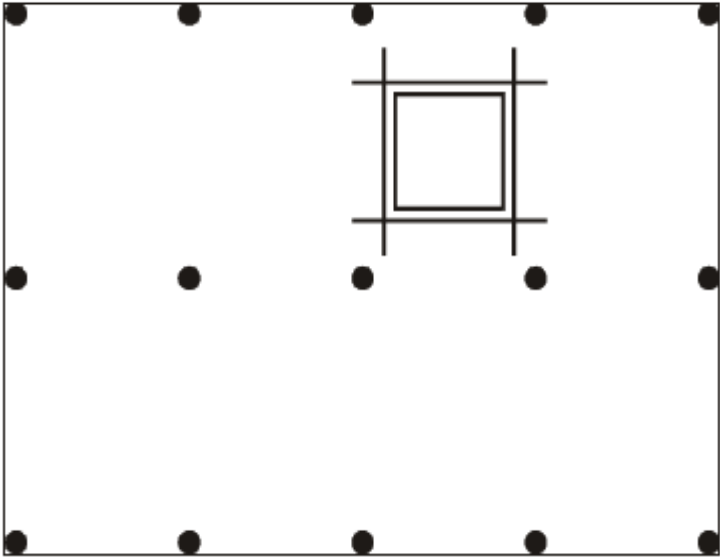
- Their material: Plywood floors on wooden joists behave as relatively rigid diaphragms in a timber structure but are flexible in a masonry structure.

- The effectiveness of solidifying their constituent elements (e.g., a truss diaphragm).

- The presence of openings (hatches) should be minimized. The presence of openings leads to stress concentrations, with the most significant ones occurring in re-entrant angles. Openings should be as small as possible, and their contours should be reinforced (see **Figure V.15**).



hopper

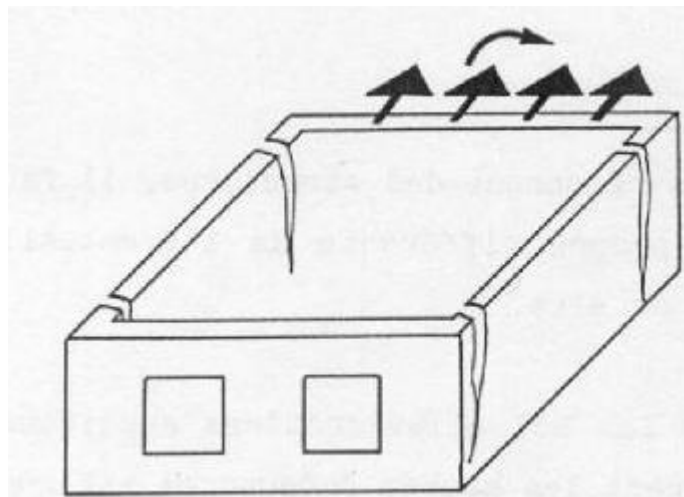


reinforcementreinforcementsaround the hopper

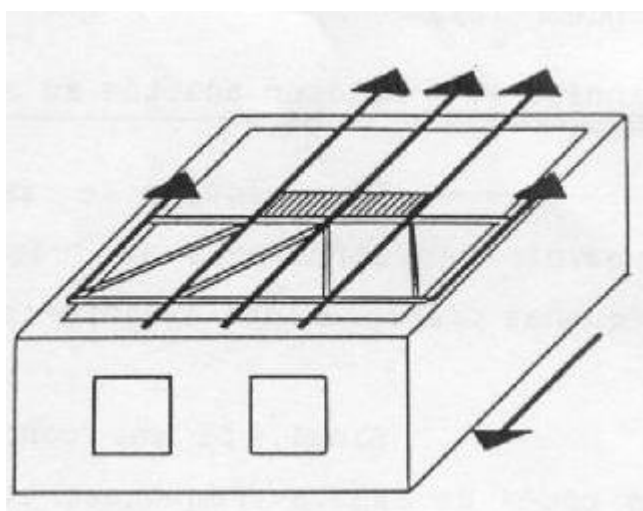
**Figure V.15.**Diaphragmwithhopper

The connections of a diaphragm to vertical bracing structures are calculated to allow the transfer of horizontal action from the considered level. Adequate connectors, such as studs or shear reinforcement, are used for this purpose.

The absence of an effective diaphragm in traditional masonry constructions explains the wall separations observed after earthquakes. In particular, wooden floors without proper anchorage do not prevent the relative spreading of walls. 80% of the 75 million Euros in damages caused by the Liège earthquake (1983, magnitude 4.7...) resulted from this lack of horizontal structural integrity. Concrete floors, being heavier, mobilize at their supports a resistance through friction and interlocking of materials, which can provide sufficient connection for mild earthquakes.



without diaphragm



with diaphragm

**Figure V.16** shows the effect of an earthquake on a masonry construction without (left) and with (right).



**Figure V.16.** Effect of an earthquake on a masonry construction without (left) and with (right)



**Figure V.17.** Liège, 1983. Effect of the weakness of the diaphragms (cracking at the corner of the walls) or the weakness of their connections to the walls (facade collapse)

### V.3. Eurocode 8 Criteria Corresponding to Design Principles

#### Preliminary Remark

We provide only an overview of the regularity criteria stipulated in Eurocode 8. For full details of the criteria, reference to the document is necessary.

#### V.3.1. Plan Regularity

The structure of a building classified as having plan regularity must be approximately symmetrical about two orthogonal directions concerning lateral stiffness and mass distribution. The plan configuration must be compact, defined for each floor by a curvilinear polygonal outline; any recesses from this outline (such as re-entrant corners or setbacks at edges) must not affect plan stiffness and must ensure that the area between the floor outline and the enveloping convex polygonal outline does not exceed 5% of the floor area. The plan stiffness of floors must be sufficiently significant compared to the lateral stiffness of vertical structural elements. The slenderness ratio  $\bar{\delta} = L_{\max}/L_{\min}$  of the building's plan section must not exceed 4 (where  $L_{\max}$  and  $L_{\min}$  are respectively the maximum and minimum plan dimensions of the building). The distances  $e_{ox}$  and  $e_{oy}$  between the center of rigidity and the center of gravity, measured respectively along the x and y directions perpendicular to the seismic x or y direction, must meet limitations:

$$e_{ox} \leq 0.30 \cdot r_x \text{ and } r_x \geq l_s \text{ (similarly in y direction)}$$

where  $r_x$  is the square root of the ratio of torsional stiffness to lateral stiffness in the y direction ("torsional radius"), and  $l_s$  is the mass-radius of gyration of the floor plan (square root of the ratio between the polar moment of inertia of the floor plan about the center of gravity of the floor and the mass of the floor). The significance of these parameters and their calculation.

#### V.3.2. Elevation Regularity

In a building with elevation regularity, bracing elements such as central cores, walls, or frames must be continuous from foundations to the top of the building. When there are setbacks at different levels, bracing elements must be continuous up to the top of the relevant part of the building.

<sup>2</sup>The lateral stiffness and mass of each level must remain constant or gradually decrease, without abrupt changes, from the base to<sup>2</sup> the top of the considered building.

In frame buildings, the ratio between the effective strength of each level and the strength required by the calculation must not vary disproportionately from one level to another.

## ***CHAPITRE VI***

### ***CALCULATION OF BRACING SYSTEMS MIXED FRAMES***

#### **VI.1. Introduction**

Bracing is a device designed to absorb wind forces in the structure and lower it to the ground. They are arranged on the roof, in the planes of the slopes "wind beams", and on the facade "stability supports", and must absorb the wind forces applied both to the gables and to the long sides.

#### **VI.2. Principle**

During an earthquake, a construction receives horizontal loads which, like vertical loads, must be transmitted to the foundation of the construction.

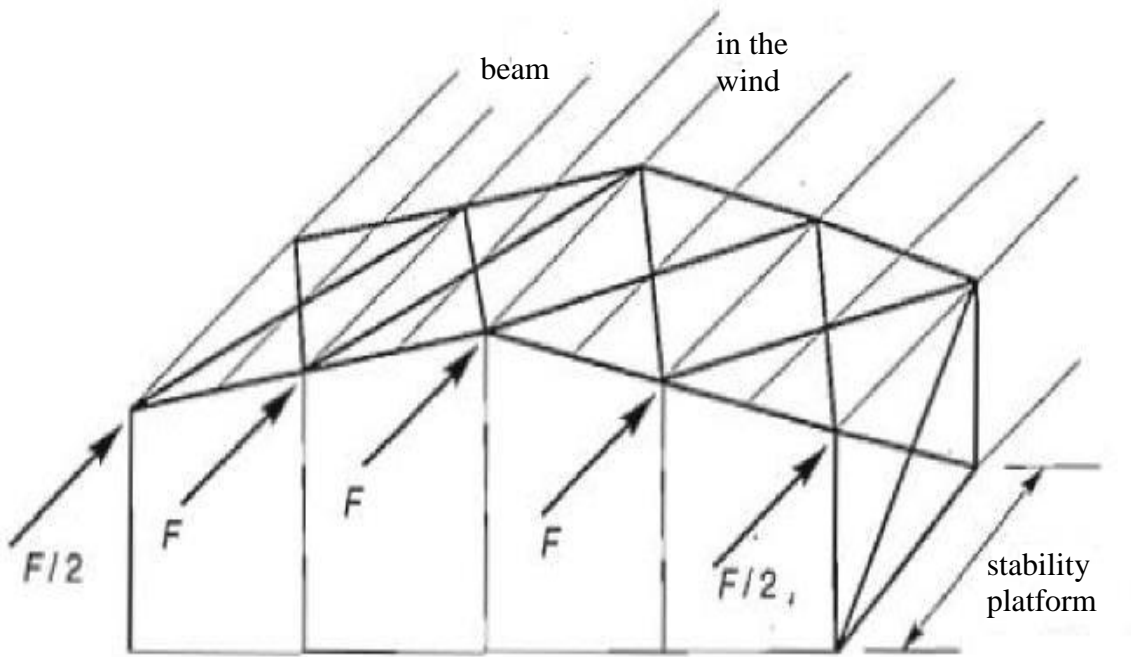
To do this, two approaches are possible:

- Self-stable structures: horizontal load descents pass through the same structural elements as vertical loads (walls, shells, three-dimensional trellises, crossed portals, etc.)
- Braced structures: the descent of horizontal loads passes through specific devices (articulated systems + bracing, etc.)

Braced structures are, for a large number of architectural parties, less expensive than self-supporting structures. The bracing of a structure must be horizontal and vertical. The quality of the connections between the structure and the bracing elements, and in general the quality of their implementation, determines their effectiveness.

#### **VI.3. Wind force on the gables**

The transmission of forces on the gables is similar to that on the long side and passes successively from the cladding to the rails, then to the posts, then to the transom of the edge portico. The latter not being rigid transversely, it is necessary to stabilize it by constructing a device, both on the roof plane (wind beam) and in the vertical plane (stability support).



**Figure VI.1.** Gable windbeam

## **VI.4. Stability block**

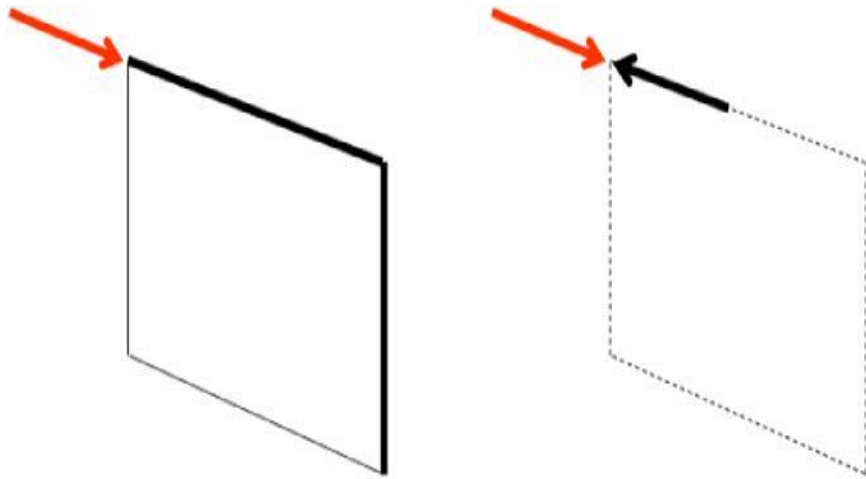
### **VI.4.1. Introduction**

A well-designed structure must be able to ensure its stability under the action of any external load and in particular under the action of horizontal loads (wind pressure on facades, seismic shock, vehicle impacts, etc.).

In other words, the general design of a structure, as well as each of its components, must ensure the descent of horizontal loads from their points of application to the foundations.

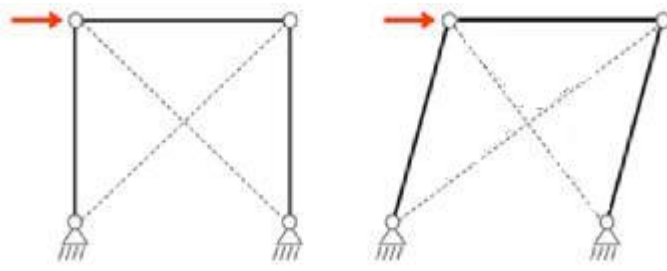
### **VI.4.2. Definition**

A stability support is a structural element inscribed in a vertical plane and capable of opposing a horizontal force parallel to its plane.

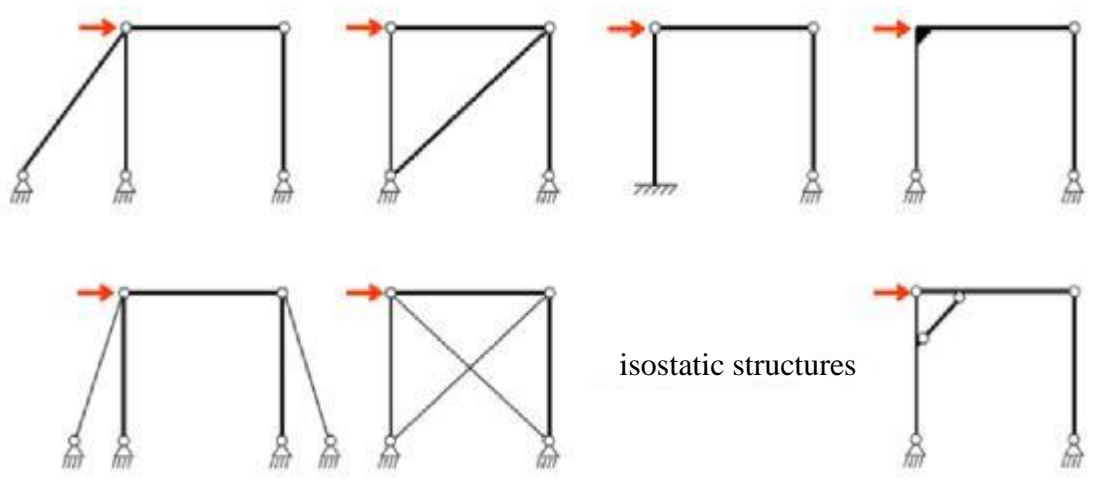


**Figure VI.2.** Principle of the stability block

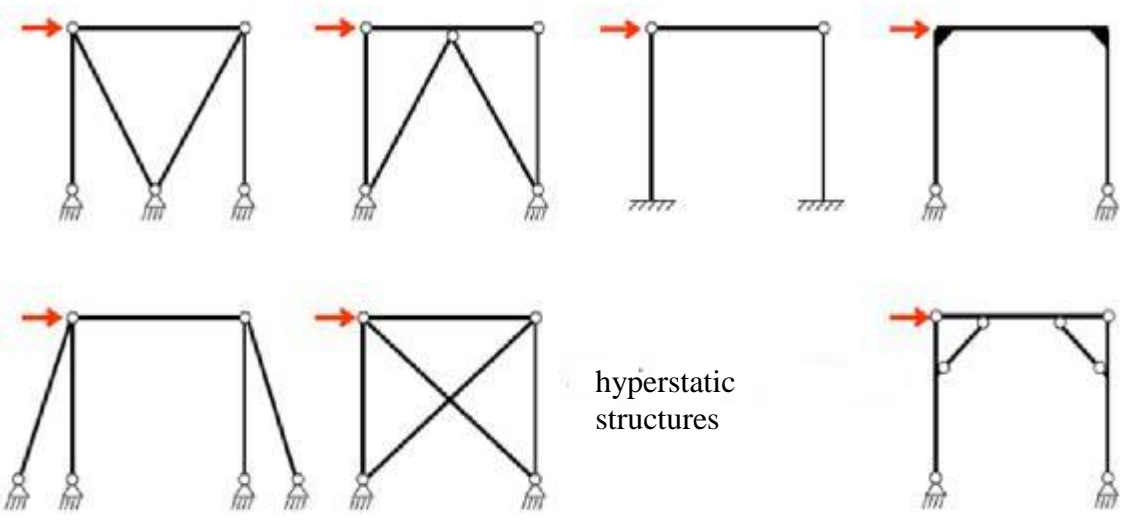
### **VI.4.3. Stability of 2D gantries**



unstable structure



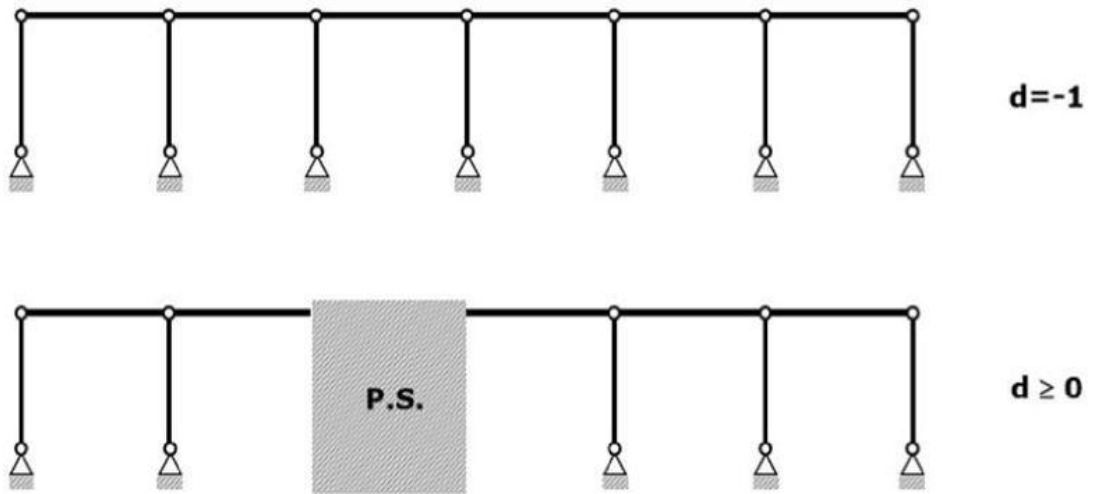
isostatic structures



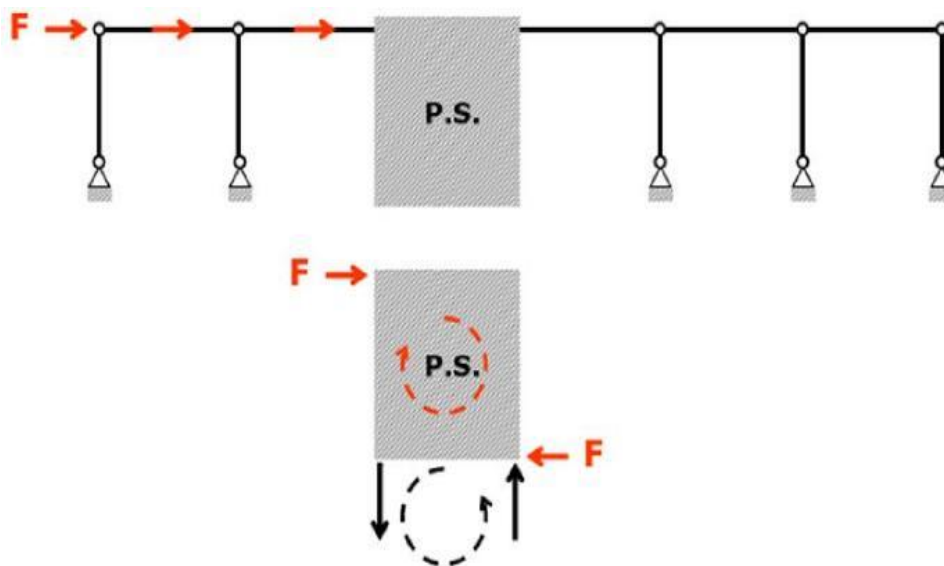
hyperstatic structures

Figure VI.3. Stability of 2D structures

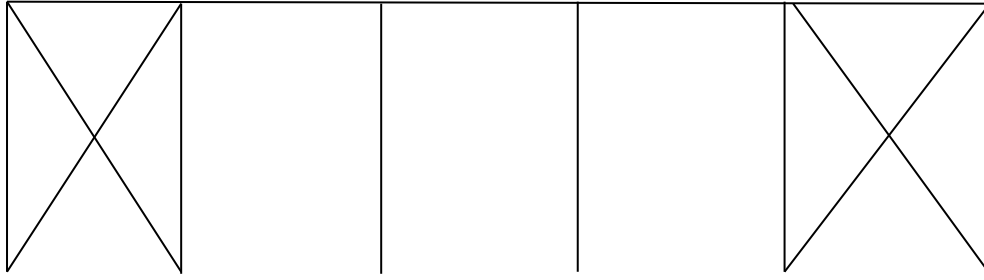
### VI. 4. 3.1. Stability of 2D structures



The balance of a stability platform:

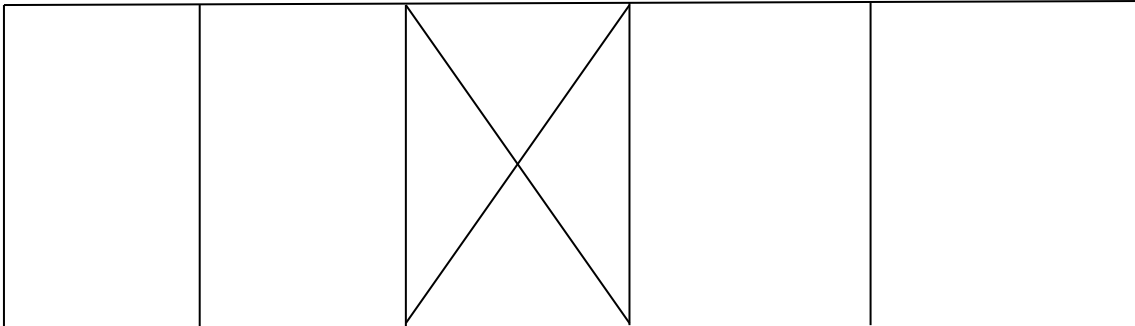


It is always in the interest of placing the stability support in the center of the building. If we place stability at each end of a building, it becomes blocked and expansion is not possible, which creates additional forces in the structure. In this case, we consider that each bracing takes up all of the forces applied to its gable.

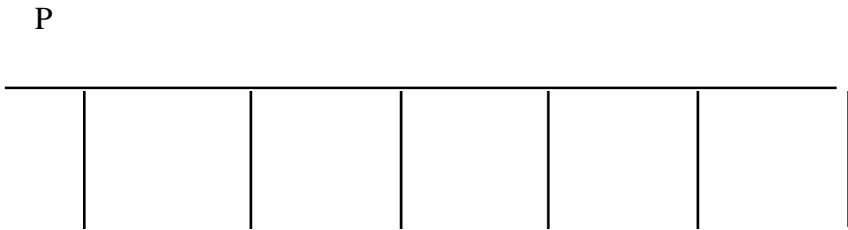


If we embed the plates on the posts we can certainly avoid stability, but the thrust at the head is distributed over the number of posts (to be avoided, in general).

If we place a single stability towards the middle of the building, the expansion can take place more freely, the thermal forces being divided into two parts on each side of the system.



Each post takes up a horizontal force  $P/n$

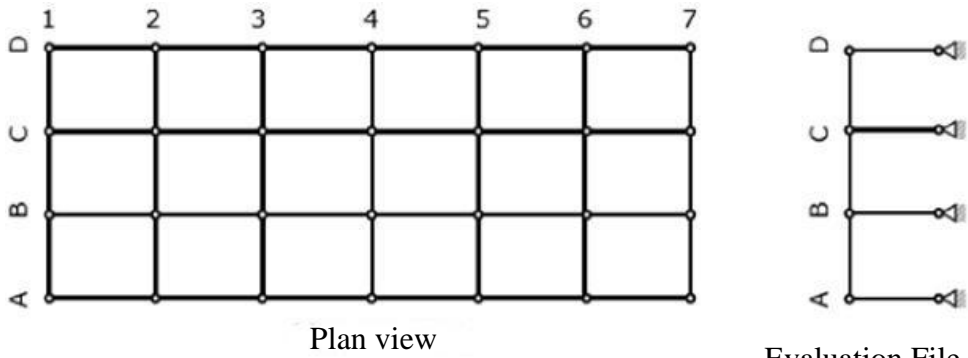


A single bracing placed at the start of the long section allows the assembly of the hall by advancement, continuously from the braced end.

For long halls, expansion joints must be provided. It should be noted that when for aesthetic reasons the supporting structure is visible; it is very exposed to temperature variations. (No thermal insulation).

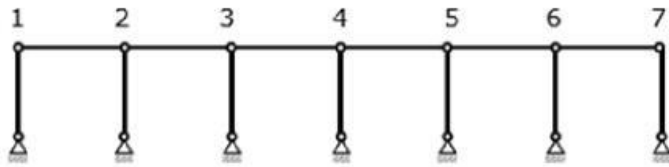
## **VI.5. Stability of frames in 3D**

### **VI.5.1. Unbraced frame**

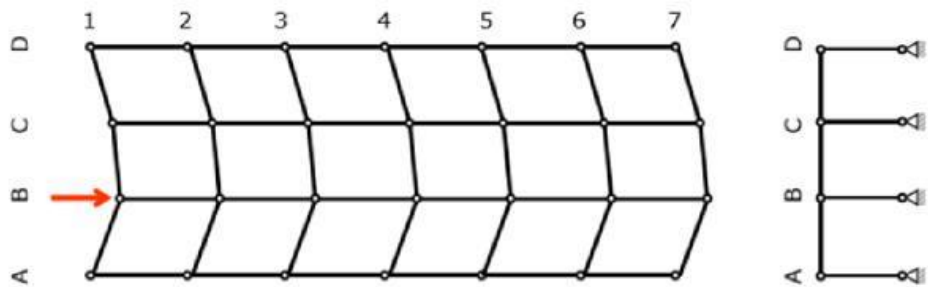


Plan view

Evaluation File Transversal 7

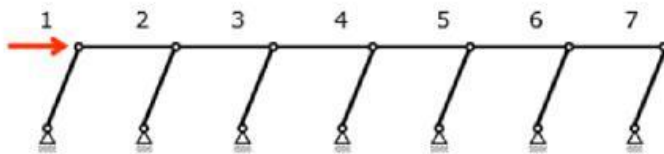


Evaluation Longitudinal file A



Plan view

Evaluation File Transversal 7



Evaluation Longitudinal file B

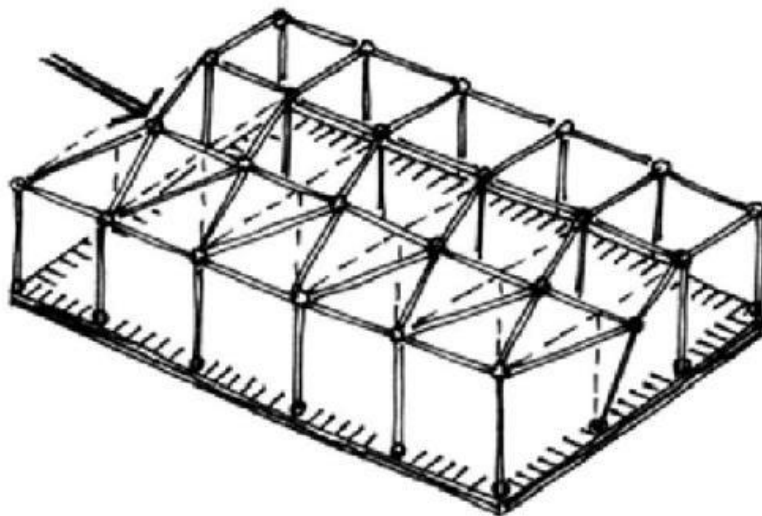
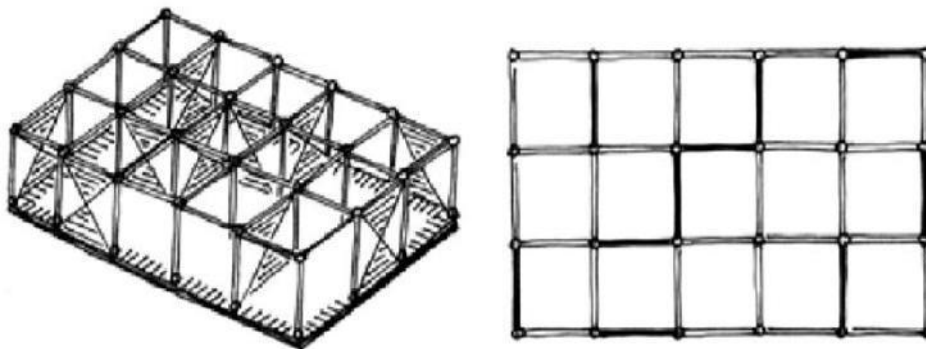
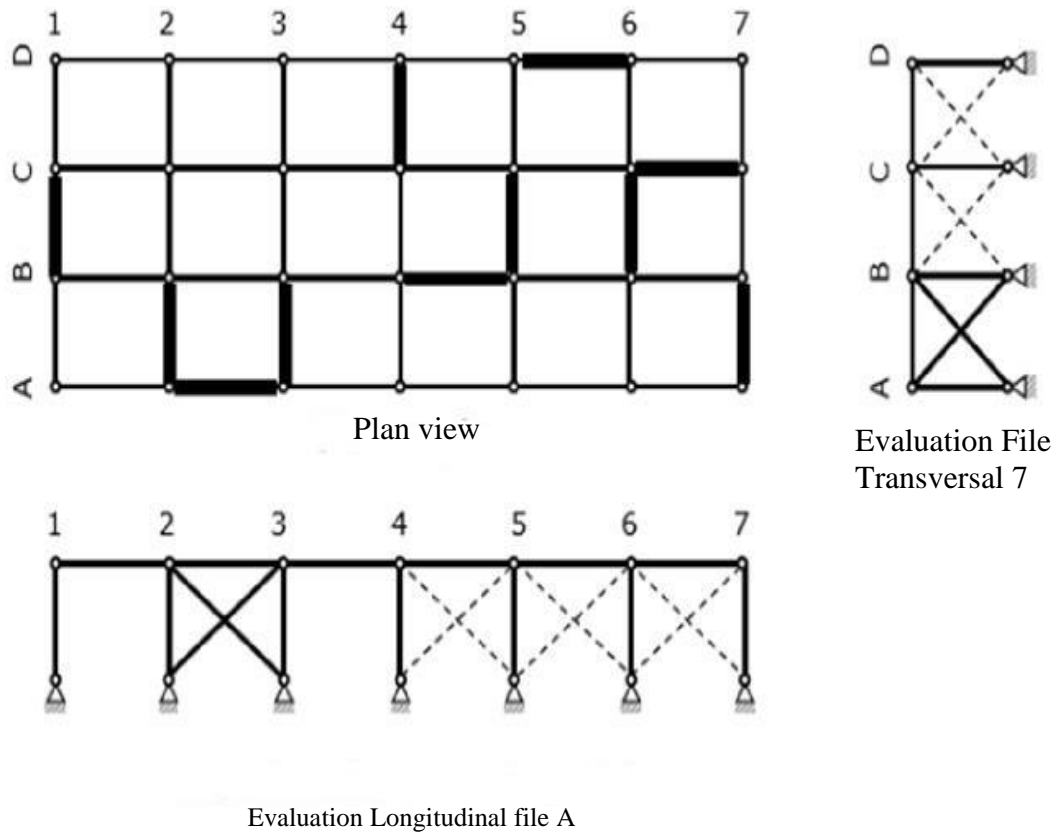


Figure VI.4. Unbraced 3D frame

## VI.5.2 Braced frame



**Figure VI.5.** Vertically braced 3D frame

## VI.5.3. The rigid diaphragm

A rigid diaphragm is any high floor (or roof) braced in such a way that it can behave like a beam. The supports of this beam will be the stability supports.

In the same way that a "classic" beam is stabilized by blocking 3 degrees of freedom (an embedding or an articulation + a sliding support or 3 sliding supports), it is necessary to block at least 3 degrees of freedom of the rigid diaphragm to ensure its stabil

#### VI.5.4. Rigid diaphragm principle

A rigid diaphragm can be compared to the lid of a cardboard box, sufficiently rigid in its plane to transmit the external horizontal forces to the 2 best oriented vertical walls.

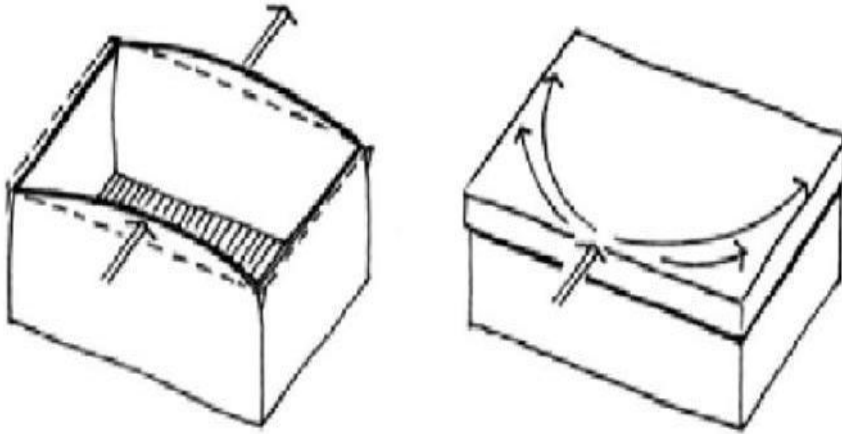


Figure VI. 6. Rigid diaphragm principle

#### VI.6. Bracing Rule « A »

En l'absence de contreventement horizontale, chacune des files longitudinales et transversales doit être équipée d'au moins une palée de stabilité.

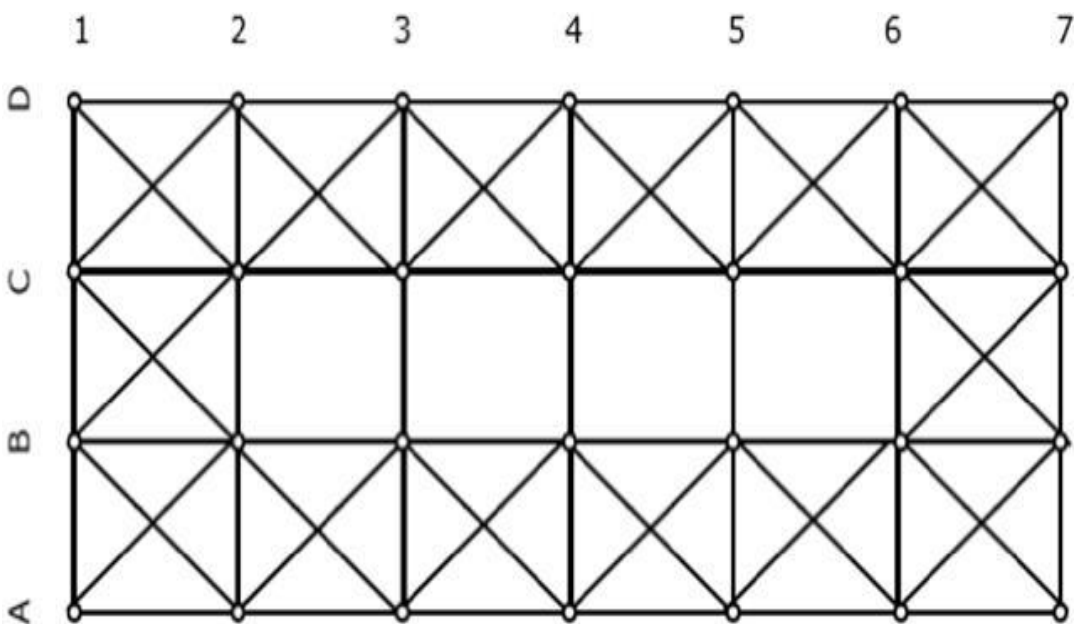
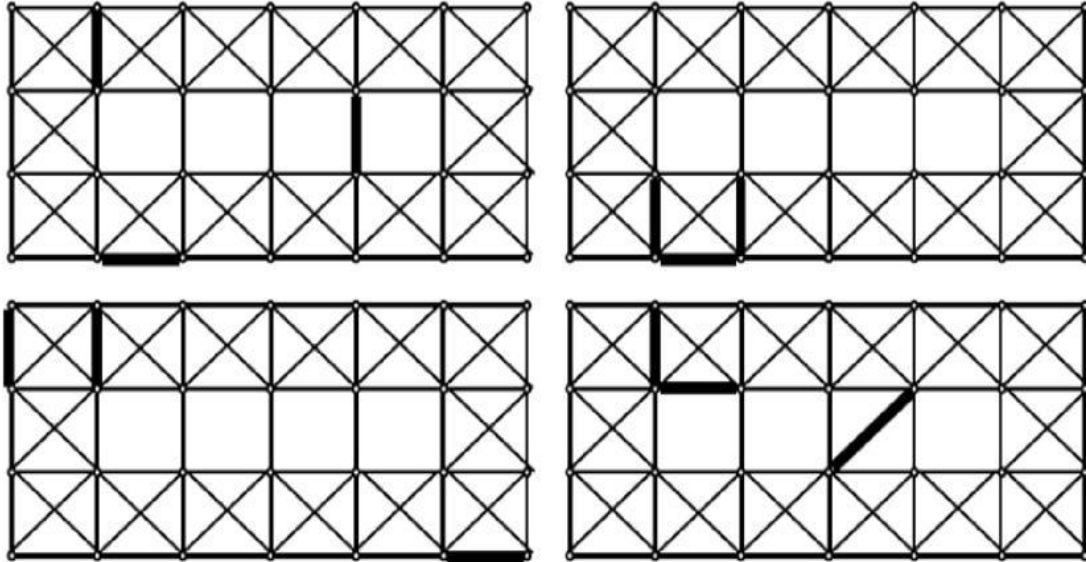


Figure V.7. Structure with horizontal bracing

## VI.7. Bracing Rule « B »

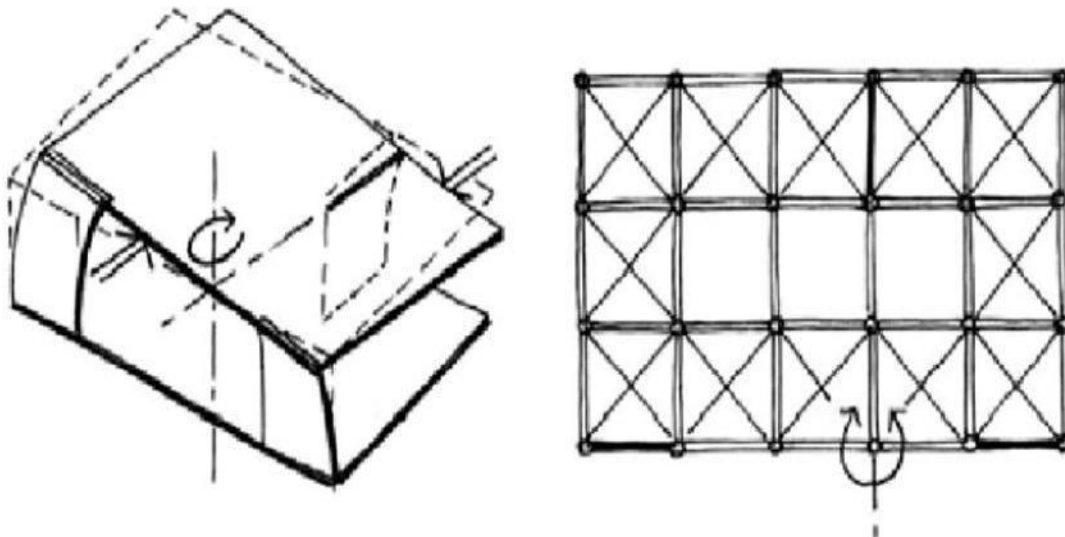
When the high floor (or roof) is capable of ensuring the “rigid diaphragm” function, the systematic bracing of each row can be avoided.



**Figure VI.8.** Correct arrangements of the 3 stability supports

Possible balance

Impossible balance



**Figure VI.9.** Incorrect arrangement: Concurrent bearings

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