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CLASSIFICATION OF
TALL BUILDING SYSTEMS

by

Daniel W. Falconer

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Professor in charge

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ABSTRACT

As the number of different high-rise structures in existence expands every year, so also is there an increase in the possibility of damage due to earthquake or other hazards. In the event of such damage it is important to be able to correlate damage intensity with the particular tall building system used. A classification scheme for these systems is required, and this thesis presents such a codification.

The systems selected for study include the structural systems, the structural materials, selected mechanical systems, the vertical transportation systems, and selected architectural systems. Greatest attention is given to the structural systems.

Of the various alternatives, a framing-oriented scheme is selected as a means of classifying structural systems. The fundamental systems within it are bearing wall, core, tube, and frame, together with the appropriate mixtures of these systems. A numerical designation system provides opportunity to catalog the specific details of the system in a computer data base. This in turn opens the way to the study of possible correlation of any observed damage with the system or subsystem.

1. INTRODUCTION

The object of this thesis is to develop a classification scheme for some of the more important tall building systems. The systems chosen for classification are the structural system, and selected mechanical and architectural systems. The major emphasis will be placed upon the structural system.

Tall buildings are highly sophisticated engineering projects. Due to the complexity of the structures, the most advanced engineering design techniques are needed in tall buildings. To develop these techniques, new and existing research and empirical studies need to be documented in a usable and accessible form.

By definition, a classification system imposes order on a large body of information. If there were only a few tall buildings in the world, a classification would not be needed. However, tall buildings exist all over the world, and their numbers are increasing every year.

In order to design better tall buildings, information must be collected on the performance of existing tall buildings. The classification helps create a structured order in which to store information collected about high-rise buildings.

Engineering research, both experimental and analytical, relies on a consistent method for recording data and information. The classification of tall building systems is a logical basis for such research.

In the past, it was not uncommon to totally separate the structural engineering from the mechanical and architectural aspects of tall building planning and design. Today, however, the tall building is more commonly designed from a "team" approach, with interaction between the key professionals. In keeping with this philosophy, the tall building classification systems are extended beyond the structural classification to encompass selected mechanical and architectural systems.

2. NEED OF CLASSIFICATION SCHEME

It is important to realize that a significant amount of construction will be required in the next 50 years -- enough to service twice the present world population according to some conservative estimates (Keyfitz) -- and a large percentage of that will be in the high-rise environment. Since in both present and future buildings the design load could, in fact, be attained, it is important to know how the various systems perform and which ones perform the best.

In the following chapters, fundamentally representative classification schemes for tall building systems will be presented. Why are they needed? Towards what use can these schemes be applied?

The answers to these questions go back to the need to determine the extent to which present analytical approaches adequately represent behavior in actual buildings under normal and extreme loads and under service situations and use. The basic question is this: is it possible to establish a correlation between the particular systems or subsystems used in tall buildings and the way in which these systems respond under extreme and service loads?

If the response can be predicted and confirmed in an appropriate sample of the large number of tall buildings throughout the world -- in other words if a correlation can be established between a particular system or subsystem and its behavior in specific applications -- then this information will be of fundamental importance in new designs. It will be of equal importance in assessing the probable performance of other existing buildings that have not yet encountered such loading and service conditions. Necessary steps for correction of any major shortcomings can then be recommended.

This type of research will require as complete an identification as possible of the tall buildings around the world and the details of the systems that are used therein which will be suitable for systems' studies. It will require documentation of the performance of these systems. To achieve this, an acurate survey must be taken of tall buildings and their systems worldwide.

Tall buildings are very complex entities, not easily separated into obvious distinctions by the casual observer. In order to create a consistent survey, the investigators will need to have a format for the survey's participants to follow. By definition, a classification lends order and structure to variable data. Therefore, a classification of major tall buildings' systems is considered essential before starting this survey.

Another major potential benefit of acquiring a large body of information about tall buildings, especially in earthquake-prone regions, is that a real-life laboratory is created. When an earthquake strikes, there would be a wide range of easily accessible information available to investigators and researchers. The various tall building systems (structural, mechanical, etc.) could be compared as to their ability to function during and after an earthquake. Interaction between different tall building systems could be studied to determine the combinations of systems that function well together and those that do not (Sun, 1979). Responsible authorities and private assessors could more quickly evaluate monetary and property losses by having prior knowledge of the damaged buildings. Projections could be made of future possible losses. It could assist damage evaluation teams as they prepare for site visits, and an inventory that includes the professionals involved will facilitate procurement of needed supplementary information.

It is expected that this thesis, in addition to establishing classification schemes for the essential tall building systems, will act as a basis for future tall building research.

3. TALL BUILDINGS AND THEIR SYSTEMS

The term, "high-rise", is defined in Webster's dictionary as a "building of many stories". This serves to illustrate the term's subjectivity. Do any clear and precise definitions exist, and on what basis are they founded?

Many local fire codes in the USA base their definition of a tall building on that which is not attainable with their fire fighting equipment. Some plumbing engineers would argue that only when a building has more than 25 stories do design concepts require modification for plumbing systems; therefore, only buildings taller than 25 stories are high-rise (Steele, 1975). Other professionals can argue from their perspective. Who is right?

The definition of a tall building was one of the first topics to come under discussion by the Council on Tall Buildings and Urban Habitat, an international group sponsored by engineering, archictectural, and planning professionals, that was established to study and report on all aspects of the planning, design, construction, and operation of tall buildings.

As described in its Monograph (Council, 1978-1981), no minimum height is specified. "The important criterion is whether or not the design is influenced by some aspect of tallness. A suggested definition, then, might be "a building in which tallness strongly influences planning, design and use"; or "a building whose height creates different conditions in the design, construction, and use than those that exist in common buildings of a certain region and period"." (For purposes of standardization, in connection with its survey of tall building characteristics, the Council collects information on buildings that are nine stories and more in height.)

For the purpose of research, it is desirable to categorize the different aspects of tall buildings. These different aspects are referred to as building systems. Beedle (1980) defines four distinct building systems: Loading Systems, Physical Systems, Functional Systems, and Building Implementation Systems. These are seen in Fig. 1. Under the "Physical Systems" heading are such items as foundation systems, structural framework, mechanical and service systems, and electrical systems. The building systems this thesis will classify are the structural systems, and selected mechanical and architectural systems.

In general, the structural system of a building is a three dimensional complex assemblage of interconnected structural elements (Council, Committee 3, 1980). The primary function of the structural system is to effectively and safely carry all the loads which act upon the building, and to resist sway by providing adequate stiffness. The structural system physically supports the entire building, and with it, all the other various building systems.

The mechanical systems studied in this thesis are the heating, ventilation and air conditioning (HVAC), plumbing and standpipe, and vertical transportation systems. Among other needs, the HVAC system in a tall building must be responsive to environmental requirements, energy consumption, and smoke and fire management . The plumbing and standpipe system must be able to meet the water demand of the high-rise under all service and emergency conditions. The vertical transportation system must respond to the user promptly, since its function is that of a time and labor saving device. By gaining a few seconds for each passenger on every trip, effective elevator service can save valuable man-hours over any specified time span (Adler, 1970).

The architectural systems examined in this thesis are the partition system and the cladding (curtain wall) system. The function of partitions in a building is the separation of large space into smaller areas for privacy or safety. The function of the cladding (curtain wall) system is to regulate the passage of light, moisture, temperature transfer, dirt, and, of course, people through the building's "skin". It must also serve to provide acoustical control from outside noise and to assist in fire control (Council, Committee 12A, 1980).

These particular mechanical and architectural systems were chosen because they generally meet the following criteria: during a natural disaster (earthquake, strong wind, fire) would the failure of these systems most likely lead to possible loss of life? The failure of either a part or of all of the structural system is an obvious threat to anyone in a tall building at the time of a disaster, and might also lead to the failure of the mechanical and architectural systems attached and supported at those points. These systems, in turn, might detract from the designed stiffness, flexibility or strength of the structural systems, thus leading to failure.

The loss of these mechanical systems in a tall building may constitute a threat to life. The failure of the vertical transportation system might trap people in possible need of medical attention. A tall building's ventilation system becomes vital during a fire, because of large amounts of smoke that must be expelled Similarly, the standpipe system is also of great importance in fighting fire in tall buildings since it delivers water to the sprinklers and fire hoses.

The failure of the cladding or partition systems might also constitute a hazard to life. The cladding system must be able to function during a strong wind to protect the occupants and contents of the building. In many tall buildings, the partition system is an integral part of the fire protection system by providing what is known as "compartmentalization" thus helping to prevent the spread of an existing fire (Council, Committee 2B, 1980).

4. STRUCTURAL SYSTEMS

This chapter presents the different types of tall building structural systems, and the various ways of classifying them. In Tables 1-11, shortened versions of work previously done, and available in literature is presented.

The structural system on a building must resist both gravity and lateral loads (i.e. wind, earthquake). As the height of the building increases, the lateral loads begin to dominate the structural concepts. Most structural systems have been shown to have optimum building heights, or rather, optimum height-to-width ratios. Figure 2 (Khan, 1974) schematically compares some frequently used steel and concrete systems on the basis of structural efficiency (as measured by weight per square foot of the system versus height of the building).

It is extremely difficult to create a classification system that succeeds in isolating consistant criteria for tall building structural systems. This is due to the large number of possible variables connected with high-rise structures, such as the number of stories, building material, framing system, load resistance properties, etc. Tall buildings themselves are diverse in nature of usage, location, geometric shape and architectural design. This indicates some in the difficulties in arriving at a accurate method for classifying high-rise structures.

4.1 Alternative Classification Schemes

After consideration of the various structural classification schemes developed and available in literature, three general approaches can be identified: loading-oriented classification (a listing of tall building structural members and subsystems by the load they resist, i.e., lateral and vertical), material-oriented classification (a listing of tall building structural systems by their main structural material), and framing-oriented classification (listing tall building structural systems by their framing method).

The different approaches and the appropriate classifications are grouped and discussed. General advantages and disadvantages to each approach are also presented.

A. Loading-Oriented Classification

The loading-oriented classification scheme organizes the structural components and subsystems according to the type of loading resisted -- whether gravity, lateral, or energy dissipation. Tables 1 and 2 are examples of this approach.

The components and members that make up the load resisting groups can be thought of as structural "building blocks", from which all tall building structures are constructed. Although the items within each group are usually not interchangeable in any specific structure, they are assumed to perform the same function (e.g. resist lateral loads).

One way to categorize a structural system is to define the combination of elementary structural building blocks that are employed in the structural system. In fact, this is how to classify a structure by the loading-oriented approach. These building blocks are, of course, not arranged haphazardly, but are integrated in such a way as to provide the most adequate support and stiffness while conforming to the architectural plan and maintaining overall economy.

The classification procedure for this type of approach is to group all of the structural components and subsystems presently in use in tall buildings together by load resistance characteristics; and to each building that is to be classified, assign various items from each group to define that particular structural system.

The classification that was developed by Committee 3 of the Council on Tall Buildings and Urban Habitat is such a loading-oriented classification. It groups "building blocks" based on a listing of vertical load resisting members, horizontal load resisting subsystems, and energy dissipation systems (see Table 1). The items grouped together to form the vertical resisting members include columns, bearing walls, hangers, and transfer girders. The items grouped together to form the lateral load resisting members include moment resisting frame, braced frame, shear walls, and combination systems. Items grouped under combination systems are tubes and core interactive structures, and are called "combination" because they usually are required to resist both lateral and vertical loads.

Lu (1974) has presented a classification using the same basic approach, namely, a listing of vertical load resisting members, horizontal load resisting subsystems, and energy dissipation systems. This arrangements is shown in Table 2. A more detailed listing of lateral load resisting subsystems is included, which clearly indicates the myriad of combinations of lateral load resisting subsystems employed in the design of tall buildings.

Generally, the main advantages of any loading-oriented classification are:

1. The assistance it lends to the structural designer. When designing a tall building structure, a loading-oriented classification can first tell which structural components and sybsystems are available and which load they generally resist (lateral, vertical, or energy dissapation).

2. It can be applied to virtually every tall building in the world, providing that the list of "building blocks" is complete. It would appear that no other type of classification can be as universally applied as the loading-oriented classification.

The main disadvantages of this type of classification are:

1. It cannot render a consistant physical description of the building. This is due to the many and varied ways these building blocks can be integrated to create a particular structural system.

2. It implies that certain structural members resist only one particular loading condition. In reality, the structural designer usually tries to have all members help resist loads from all sources and thus create a more efficient structural system.

B. Material-Oriented Classification

A second method of classifying structures is a material-oriented classification. This method separates structural systems on the basis of structural material (concrete, steel, masonry, wood, mixed). These distinctions are obvious and valid because many structural systems differ significantly depending on which structural material is used. The variables associated with concrete structures might be the ultimate strength of concrete, the slump of the mix, curing time, amount of pretension, placement of reinforcing bars, etc., most of which are not applicable to steel, masonry, or wood structures. The variables for a steel or masonry structure are also unique to that particular structural material. Tables 3 through 6 list classification schemes that use this approach.

Khan (1974) uses a material-oriented classification to discuss the different responses of various steel, concrete and mixed stuctural systems to lateral loads (see Table 3).

This approach is also used by the British Steel Corporation (1972) as seen in Table 4. As their name would indicate the British Steel Corporation limit their classification to tall steel structures. In their article, they discuss lateral load resistance of different structural systems, relative cost, and the speed of erection of the various systems.

A classification of tall building structural subsytems based on the lateral resistance of different construction material was developed by H.S. Iyengar (1980) and the subsystems are shown in Table 5. Iyengar, in his paper, discusses what the function of the subsystems are, and how to take advantage of the various material (steel, concrete, composite) properties in each subsystem, and develops a classification chart.

Committee 21A of the Council on Tall Buildings and Urban Habitat also has developed a material-oriented classification. Committee 21A limits the classification to tall concrete structures, and a list of these structures is shown in Table 6. A major advantage of this particular classification is that each concrete structural system is examined in chart form. By doing this, a logical comparison of the similarities and differences of each system can be achieved, which helps to give a "feel" for each type of system. The three main parameters examined in this chart are the difficulty of engineering, architecture, and construction of the various structural systems.

Generally, the main advantages of any material-oriented classification are:

1. It illustrates the differences that exist between structural systems created from different materials.
2. It identifies structural systems as a whole, not as parts of a whole. This makes it easier to classify a tall building by this approach than by the loading approach, at least preliminarily.

The main disadvantage is:

1. Many geometric structural schemes are not limited to one construction material. For example, a frame structure can be made of concrete, of steel, or a combination of both.

C. Framing-Oriented Classification

A third classification system is the framing-oriented or "descriptive" scheme. This approach attempts to classify tall building structural systems by a description of the structural framing system. Tables 7 through 11 give examples of the use of this approach.

The classification scheme shown in Table 7 was used in an extensive worldwide survey of tall buildings and their characteristics conducted by the Council (Beedle et. al., 1980). The system consists of a word or phrase which (traditionally) represents a certain type of structural system. These descriptions were then stored into a computer along with other data pertaining to a tall building (height, material, location, use).

In Schueller's (1977) classification, primary emphasis is given to visual and descriptive analysis of the structural systems (see Table 8). He lists 14 separate tall building structural systems in an attempt to adequately represent the spectrum of tall building structures.

The Applied Technology Council (1978) bases its classification on how well different structural systems resist an earthquake load (see Table 9). This classification was developed for application in a seismic design procedure for all building structures, and is not restricted to buildings that are tall.

Drosdov and Lishak (1978) developed a classification that categorizes the variety of existing structural systems into four primary loadbearing systems and six secondary (combination) loadbearing structures as seen in Table 10. The six secondary systems are, in fact, combinations of the four primary structures as shown in Fig. 3. This classification is part of a study of the dynamic response of different tall building structures.

Table 11 contains a structural classification scheme developed by the author at an early stage of the project which separated the structure into three categories: the structural framing system, the "augmentative" structural subsystem, and the floor framing system. The structural framing system is defined as the primary load resisting system of the structure. The augmentative structural subsystems are the subsystems which were added to the primary load resisting system to create a stronger and/or stiffer total structure. The floor framing system transmits the occupancy loads to the structural framing system, and may also serve to transmit lateral loads along its length between the vertical members.

The basis for classifying structures by this approach is as follows:

1. There is one and only one primary load resisting system in a tall building.
2. The number of augmentative structural subsystems in a structure vary from case to case.

3. There is one floor framing system that can be identified per building.

Generally, the main advantages of any framing-oriented structural classification scheme are as follows:

1. It groups together structures that respond similarly to a load (i.e., frame, tube, bearing wall, etc.). This is important when one wants to compare the performance of various systems and their responses to load.
2. It is the least redundant of any of the approaches, therefore, has the potential of being the most efficient. The loading-oriented approach is redundant if one member resists two loads (a very common situation); and the material-oriented approach is redundant if one system is constructed from different materials (also a common situation). The framing-oriented system does not encounter such redundancy.

The main disadvantage of this approach is seen when attempting to classify structures in great detail. As a framing-oriented approach begins with a generalized structure and works toward finer detail, the more information that is required to classify, the more complicated the organization of the data becomes.

To list all the various structural systems with their individual advantages and disadvantages is not within the scope of this thesis. The advantages and disadvantages of any system are always dependent on the individual constraints placed upon it (i.e. architectural scheme, construction time and money, height desired, loading characteristics, materials available).

4.2 Proposed Classification Scheme

After consideration of the various systems identified in the literature and a consideration of the advantages and disadvantages of each, the framing-oriented clasification scheme contained in Table 12 was selected and further developed to meet the following conditions:

1. The classification scheme must be simple in concept and application, yet detailed enough so that useful comparisons can be made.
2. The classification must be broad in scope in order to be usable in further studies.
3. The classification should be compatible with a computer-oriented system for storing information, retrieving it, and making comparison between the response of similar systems.

This framing-oriented classification scheme is one that separates the structure into three categories: the structural framing system, the bracing system, and the floor framing system.

The structural framing system consists of four major groups:

1. the bearing wall system
2. the core system
3. the frame system
4. the tube system.

As shown in Table 12, the structural systems have been listed in an organized way under each of the above four primary structural systems. They are futher discussed as follows:

1. A <u>bearing wall</u> structure is comprised of planar, vertical elements, which usually form the exterior and interior walls. They usually resist both the vertical and horizontal loads. Examples are shown in Fig. 4.

2. A <u>core</u> structure is comprised of load-bearing walls arranged in a closed form, usually with the mechanical systems (HVAC, elevators, plumbing) concentrated in this vertical shaft, allowing the building flexible space beyond the core. The core resists both vertical and horizontal load. Examples are shown in Fig. 5.

3. A <u>frame</u> structure is usually comprised of columns, girders, and/or beams arranged to resist both horizontal and vertical loads. The frame is perhaps the most adaptable structural form with regard to material and shape, due to the many ways of combining structural elements to adequately support the building. Examples are shown in Fig. 6.

4. A <u>tube</u> structure is usually comprised of closely spaced exterior structural elements, arranged to respond to a lateral load as a whole, rather than separate elements. However, the columns need not be spaced too closely. As long as the building responds similar to a cantilever, it is called a tube. This allows for more flexibility in interior space use, due to the lack of vertical interior structural elements. Examples are shown in Fig. 7.

The bracing subsystems shown as "Level B" in Table 12 define (1) what type of bracing is employed in a building (e.g. K-bracing, diagonal bracing, etc.), and (2) how it is relatively situated in the structure (e.g. frame bracing, core bracing, etc.). Many similar structures differ only in their bracing system. By making it a separate subsystem of the framing system, a more efficient classification scheme is achieved.

The floor framing subsystem is shown as "Level C" in Table 12. The floor system transmits occupancy loads to the framing system, and may also serve to transfer lateral forces, acting as a diaphram and as an intergral part of the framing system.

Figure 8 is the classification chart, with some example buildings classified. The numbers shown in Figure 8 corresponding to the structural system are retrieved from Table 12. The numbered designations are intended to provide a basis for grouping like systems and subsystems together along the lines shown in Table 12 and the example structures shown in Figures 4 through 7.

When using the classification tables, it must be remembered that framing and bracing in a building are obviously not physically separated. It is a technique used here to more efficiently classify the structure. Many structures require identification of both framing and bracing before the system becomes recognizable (such as a simple frame with a braced core and hat truss).

Under Level B, Bracing Subsystems, there are five categories. The first two categories (numbers 11-16 and 21-26) refer to in-frame bracing. The next category (numbers 31-36) refers to core bracing only. The next category (numbers 41-46) has two uses. If the structure has a braced core and hat/belt trusses, which are the same bracing type (e.g. they both are double diagonal bracing), this is the category to choose from. The other use is if a structure has a solid core with hat/belt trusses, this again is the category to choose from. The final category is if the structure has a braced core and hat/belt trusses, but employs two different bracing types (e.g. single diagonal core and double diagonal belt/hat truss).

The methodology for arriving at a classification number for any structure is as follows:

1. Identify which of the four major systems(wall, core, frame, or tube) describes the structure.

2. Scan Table 12, Level A (and the corresponding example figure) for the specific structural system used. (Example: simple frame and solid core)

3. The numbers that correspond to that system are the first two digits of the classification number.

4. Scan Level B in Table 12 (and the illustrations in Fig. 10) for the specific bracing subsystem used. (Example: frame bracing, one plane, double diagonal bracing)

5. The numbers that correspond to that bracing

subsystem are the next two digits of the classification number.

6. Scan Level C in Table 12 for the specific floor framing subsystem used. (Example: concrete beam and slab)
7. The numbers that correspond to that floor subsystem are the final two digits of the structural system classification number.

An example of how the generated number might look is as follows:

3. ss bb ff

where the "ss" represents the structural framing system, the "bb" represents the bracing subsystem, and the "ff" represents the floor framing subsystem. For the purposes of standardization, if a set of digits is unknown (e.g. the floor framing system if not known), the space should be filled by two question marks (??). If a subsystem is known not to exist (i.e. the building has no bracing), the space should be filled by two zeros (00).

The "3" in front identifies the tall building system; the structural system in this case. These "system" numbers correspond to the Council on Tall Buildings and Urban Habitat numbering of the committees dealing with the various systems.

5. STRUCTURAL MATERIAL SYSTEMS

This chapter will identify and categorize the main structural materials employed in high-rise construction. A preliminary classification scheme is presented in Table 13, and the characteristics of the materials are discussed.

Since the beginning of high-rise construction, structural material concepts have constantly been changing. In the nineteenth century, the two most commonly used structural materials were masonry and iron. It was soon discovered that the type of structural system that masonry is best suited for (the bearing wall system) is not very efficient when applied to tall buildings. The limit of this material became apparent with the 16-story Monadnock Building (1891) in Chicago, in which the lower walls were designed to be more than six feet thick (Khan, 1973).

Frame systems became more and more prevalent in tall structures around the turn of the century. This type of system was first made possible by using iron, and later, steel. The first example of a tall building totally supported by iron frame work was in 1883, with the construction of the 11-story Home Insurance Building. Reinforced concrete also had become a common structural material during this period. In 1903, the 16 story Ingalls Building was constructed of reinforced concrete (Schueller, 1975).

Today, the main high-rise structural materials are steel, reinforced concrete (prestressed or not), masonry (reinforced or not), and composite (steel and concrete). It is recognized that many structures containing structural cores use a different material for the core than in the framing. Therefore, when classifying the material of a structure, two digits are needed. The first represents the main framing system (wall, core, frame, or tube), and the second represents the structural core (if applicable, as in the case of a frame and core or a tube-in-tube).

The parameters that govern the choice of which structural material the engineer employs on any one building are many. This is due to the different characteristics associated with each material. Concrete, steel, and masonry have the following general characteristics:

1. Concrete and masonry have a minimal resistance to tension, while steel is equally strong in tension and compression. In prestressed concrete, an initial compression is provided to offset the effects of tensile stresses.

2. Concrete and masonry are subject to dimensional and property variability with time, while steel properties and dimensions are usually considered constant throughout the life. Creep, shrinkage, and rehydration all play a part in changing concrete and masonry structures' dimensions. Concrete also requires a certain elapsed time to gain designed strength.

3. In general, concrete structural members have larger cross-sectional areas than steel members. As a result, dead load tends to be more significant in concrete members. On the other hand, their stiffness also tends to be greater. As a result, sway, vibration and buckling tend to be more significant in steel members than concrete members.

4. Concrete offers almost unlimited flexibility with regard to architectural shape and expressions, while the vast majority of steel members are standard rolled shapes.

5. Concrete and masonry have inherent fire potection, whereas steel requires applied fore protection.

These are just some of the more obvious characteristics pertaining to steel, concrete, and masonry.

Over the past 100 years, the engineer's knowledge of these materials has increased dramatically. Yet, even today, research is still being carried out to further the knowledge of the different structural materials and their composite interaction (Kato et al, 1980).

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6. MECHANICAL SYSTEMS

This chapter will identify and categorize the major factors common to high-rise mechanical systems, the most important of which are plumbing, HVAC, and vertical transportation. A preliminary classification scheme is presented in Tables 14 through 16 for the three mechanical systems discussed.

The invention and improvement of tall building mechanical systems (plumbing, HVAC, and vertical transportation) have made it possible for the high-rise to become an attractive, livable environment. The development of the mechanical systems have also freed the architect and structural engineer from past restrictions and enabled them to use their creative ability in designing the modern, efficient tall building.

The development of the passenger elevator (1870-1900) meant that the height of the building was no longer limited by the occupants' willingness or ability to climb stairs. The elevator industry played a major role in setting the stage for the increased size and height of buildings in the early decades of the twentieth century. The increasing demand on elevator capacity and speed brought about further innovations such as multiple batch systems, local and express elevators, and double deck elevators (Adler, 1970).

In tall buildings erected before the general adoption of air conditioning, perimeter spaces were necessary for movable windows and natural ventilation. Dead air spaces in the interior were possible, and the general efficiency of total usable space was compromised. After forced air HVAC systems became accepted, the entire floor plan became the usable office space, and the efficiency of the floor space was improved (ASHRAE, 1976).

Plumbing systems in tall buildings went unchanged longer than any other mechanical system. The method used almost exclusively until the late 1950's and early 1960's to increase water pressure was that of single speed pumps carrying water to various gravity tanks. It is known as the gravity tank system (Council, Committee 2B, 1980). At that time, variable speed pumps and pump controls were developed to a point where booster pump systems started to replace gravity tank systems. Today, tall building plumbing engineers specify the booster pump system almost exclusively (Steele, 1975).

6.1 Heating, Ventilation, and Air Conditioning

The primary purpose of a heating, ventilation, and air conditioning system is to provide a specific set of pre-determined environmental conditions.

Table 14 lists many types of equipment and systems that are available. Most of the requirements of a particular building can be met by any one of several equipment/systems combinations. The choice of which system is most appropriate to any specific building lies in the evaluation of each systems application and of its quality.

The four general system categories (all-air, air-water, all-water, and multiple unit systems) are presented in Table 13 (number designations are given there as well). A brief discussion of each of them follow, together with the advantages and disadvantages of each system.

A. All-Air Systems

An all-air system is defined as a system providing complete cooling capacity by a cold air stream supplied by the system. Heating and ventilation are also usually accomplished by forced air (ASHRAE, 1976). All-air systems may be classified into two basic categories:

1. Single path systems -- those which contain the main heating and cooling coils in a series flow path, using common duct distribution to feed all terminals.
2. Dual path systems -- those which contain the main heating and cooling coils in a parallel flow path, using one duct for heating and one duct for cooling.

The usually cited advantages of an all-air system are:

1. Centralized location of major equipment
2. Wide choice of placement options

3. Ready adaptation of heat recovery systems
4. Adaptable to winter humidification
5. Design freedom for optimum air distribution.

The usually cited disadvantages of an all-air system are:

1. The additional duct clearance requirements
2. The long hours of fan operation in cold weather required by perimeter heating.

B. Air-Water Systems

In the all-air system, the building space is cooled solely by air. In contrast, the air-water system is one in which both air and water are distributed to perform the cooling and heating functions. Air-water systems are categorized as follows:

1. The two-pipe system -- systems which consist of one supply pipe and one return pipe, along with conditioned air from a central source.
2. The three-pipe system -- systems which consist of one hot supply pipe, one cold supply pipe, and a common return pipe.
3. The four-pipe system -- systems which consist of a separate hot loop and cold loop.

The air-and-water system has the following general advantages:

1. Because of the greater specific heat and much greater density of water compared to air, the cross sectional area required for the distribution pipes is much less for the same cooling task. (See Fig. 10.)

2. Individual room thermostat control possible.
3. Reduced size of central air conditioning apparatus.

The air-and-water system has the following general disadvantages:

1. Controls tend to be complex.
2. System is not applicable to spaces with high exhaust requirements, and/or high dehumidification requirements.

C. All-Water Systems

All-water systems accomplish cooling solely by the distribution of chilled water to terminal units located throughout the building. All-water systems are categorized as follows:

1. Two-pipe systems
2. Three-pipe systems
3. Four-pipe systems

The all-water system has the following general advantages:

1. No ventilation ductwork space is required.
2. Individual room thermostats are possible.

The all-water system has the following general disadvantages:

1. Total lack of humidity control.
2. Dependence on natural ventilation.

6.2 Plumbing Systems

The primary purpose of the plumbing system is to provide adequate water pressure at all times in all parts of the building. This entails delivering the water at the correct pressure at all locations and handling the discharge. The classification of plumbing systems can be separated into four categories; the gravity tank system, the hydropneumatic tank system, the booster pump sytem, or a combination of the above three (see Table 15).

A. Gravity Tank System

The gravity tank system consists of an elevated tank of adequate capacity with single speed pumps to raise the water to fill the tank. When the water level in the tank drops to a predetermined level, the pumps bring water up until the tank is full.

Compared to other pressure boosting systems, the gravity tank system has the following advantages:

1. No sophisticated controls are required
2. It is most reliable in case of power failures
3. There is minimum maintenance associated with this system
4. It provides additional reserve capacity for fire protection
5. Pump head is less than is required in other systems, and therefore uses less energy
6. There are minimum pressure variations in the

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distribution system.

The gravity tank system has the following disadvantages:

1. The tank must be elevated
2. The weight of the tank and water may increase structural costs
3. The tanks require interior maintenance
4. If there is a tank failure, large quantities of water will be released.

B. Hydropneumatic Tank System

The hydropneumatic tank system consists of a series of smaller tanks at various locations in the building with pumps to raise the water to the tanks. The hydropneumatic tanks are also known as pressure tanks, because the tanks use compressed air to achieve the desired pressure in the line.

Compared to the gravity system, the hydropneumatic tank system has the following advantages:

1. It does not have to be elevated
2. It can be located anywhere in the building

It has the following disadvantages:

1. There is the possibility of inside corrosion of the tank due to the addition of air in the tank
2. A pressure variation of 20 psi is normal
3. Pumps of a higher head are required.

C. Booster Pump System

The booster pump system varies the speed of continuously running pumps to hold a constant discharge pressure under varying flow conditions. The advantages of a booster system are:

1. No large tanks are required
2. Usually, there is a lower initial cost.

The disadvantages of a booster system are:

1. Sophisticated controls are necessary
2. The constantly running pumps can create a noise problem
3. There is no emergency water supply
4. Operating costs are high because the pumps do not operate at maximum efficiency.

6.3 Vertical Transportation

Vertical transportation is approached from the point of view of the user. Obvious subsystems, such as motor, counterweight, brake and elevator batch control are not treated.

Vertical transportation systems can be separated into three categores: elevators, escalators, and material movers (see Table 16). Elevators and escalators are commonly referred to as "people movers".

A. Elevators

Elevators are usually the primary people movers in tall buildings. An elevator system that is referred to as "single deck" is one that has one elevator per vertical shaft. A "double deck" has two elevator cars existing in the same elevator shaft, one atop the other. A "local" elevator can stop at any floor, while an "express" will skip a certain number of floors, then over a certain range behave as a local. The sky-lobby concept (Council, Committee 2A, 1980) is a shuttle elevator that goes from ground level to a lobby, where local elevators are available for access to other levels.

B. Escalators

Escalators are categorized by the relative arrangement, either crisscross of parallel. The first arrangement is more economical of space, the latter is more impressive in appearance(Adler, 1970). In either arrangement, escalators may be adjacent or separate.

C. Material Movers

Material movers are separated into two categories; pnuematic message tubes and tote box selective vertical conveyors. Delivery of more bulky materials are usually delegated to service elevators.

7. ARCHITECTURAL SYSTEMS

The two architectural systems briefly considered in this thesis are partition systems and cladding systems.

The development of the metal curtain wall has been looked upon as the introduction of pre-fabrication techniques to tall buildings. This partial pre-fabrication concept helped lead to the proliferation of tall buildings, due to a dramatic savings in both money and construction time. The building known as the "first skyscaper" was the Home Life Insurance Building, in Chicago. One of the major reasons for this title was that it was the first to employ nonloadbearing exterior wall (cladding). The cladding systems discussed in this thesis will be limited to the nonloadbearing type.

In tall buildings extra consideration is given to partitions, in particular to acoustics, fire protection and resistance, covering elevator shafts, and response to building lateral sway.

7.1 Cladding

The classification of cladding or curtain wall systems are separated into custom cladding (designed specifically for one job) or standard cladding (components and details are standardized by the manufacturer). In each, there are five categories which are based on assembly on-site (Council, Committee 12A, 1980). The five categories are: stick wall system, unit

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In the stick wall system the components are installed piece by piece, with vertical members (mullions), horizontal members, and windows as the pieces. The advantage of this system is its ease of shipping and the degree of dimensional adjustments to site conditions. The disadvantage of this system is the necessity of assembly in the field.

The unit system is a preassembled module, usually one floor in height. The unit and mullion system is installed mullions first, with the preassembled units placed between them. The advantage of these two systems is that good quality control can be maintained at the shop. The disadvantage of these systems is that units are usually bulky to transport.

The panel installation system is similar to the unit system, but with the jointing between panels at a minimum. The advantages and disadvantages are basically the same as with the unit system.

The cover-column-and-spandrel installation system consists of column and spandrel cover sections, and infilled windows or glazed units. The advantages of this system are relatively easy shipping and latitude of use with any column and spandrel spacing. The disadvantage of this system is the large amount of field work involved with its assemblage.

7.2 Partitions

The primary function of the partition system in high-rise building is the separation of large spaces into smaller ones for privacy and fire protection.

The classification of partition systems is separated into movable (demountable) partitions and solid partitions. All partitions referred to in this section are nonloadbearing. Some may assist the main structure, but, nevertheless, are nonloadbearing.

The solid partitions are categorized according to their construction material, either brick or concrete as shown in Table 18. The demountable partitions are categorized according to their support scheme, either post and infill, post and overlay, or postless. The postless partitions must reach from ceiling to floor for support, whereas the post supported partitions can be of any height.

This classification scheme is essentially the same as the one developed by Committee 12B of the Council on Tall Buildings and Urban Habitat. This scheme differs slightly from Timesaver Standards for Architectural Design Data, 1974. Timesaver groups partitions into the five following categories:

1. Steel framed walls
2. Solid laminated partitions

3. Laminated gypsum strip (stud partitions)
4. Wall furring systems
5. Column fire proofing

This scheme goes into more detail of "nuts and bolts" of individual types of partitions.

8. UTILIZATION OF CLASSIFICATION SCHEMES

Over the past 20 years, individual researchers and engineering damage evauluation teams have studied the effects of earthquakes, hurricanes and other natural disasters on particular buildings and regions of the world. More useful information could be extracted from these case studies if all the data could be logically compared. But there is presently no systematic method of correlating between general building systems and the performance of those systems.

The classifications presented in previous chapters can be a used to rationally identify tall building systems. With this acomplished, a system-by-system damage evaluation can be carried out for past and future disasters. The classification of tall building systems can also serve as a basis for an extensive tall building survey.

9. SUMMARY

A summary of this study is as follows:

1. The tall building systems are identified as the loading systems, the functional systems, the physical systems, and the building implementation systems (Fig. 1). The systems that are classified are the structural, material, mechanical, and architectural systems, all of which are subsystems to the physical systems.

2. From the literature, many structural categorizations and classifications were identified. Three alternative classification approaches were examined, a loading-oriented approach, a material-oriented approach, and a framing- oriented approach.

3. The framing-oriented approach was selected for use in the structural system classification scheme (See Table 12).

4. The major systems and subsystems in the classification scheme are the framing system, the bracing subsystem, and the floor framing subsystem.

5. A classification number is assigned to each system and subsystem as a basis for computerizing specific information about individual buildings. The numerical designators assist in grouping like systems together for the purpose of comparisons of the response

of the various systems to loading.

6. The material, mechanical, and architectural systems are catalogued similar manner -- albeit in a preliminary way -- and classification numbers are assigned.

Table 1
STRUCTURAL SYSTEMS
(Council, Committee 3, 1980)

Framing Systems to Resist Gravity Loads

1. Horizontal Framing Systems - Floor Structures

2. Vertical Framing Systems
   a. columns
   b. bearing walls
   c. hangers
   d. transfer girders
   e. suspended systems

Framing Systems to Resist Horizontal Loads

1. Moment Resistant Frames
2. Braced Frames
3. Shear Walls
4. Combination Systems
   a. Tube Structures
   b. Multiple Tube System
   c. Core Interaction Structures
5. New Structural Concepts
   a. megastructures
   b. cellular structures
   c. bridged structure

Energy Dissipation Systems

1. Natural Damping
2. Plasticity of Structural Materials
3. Highly Absorbant Structural Systems
4. Artificially Increased Damping
5. Advanced Foundation Design
6. Aerodynamic Provisions

Table 2
STRUCTURAL SYSTEMS (Lu, 1974)

Gravity Load Resistant Systems

1. Horizontal (floor) Framing
2. Vertical Framing
    a. bearing walls
    b. hangers
    c. load transfer girders

Lateral Load Resistant Systems

1. Moment Resistant Frame
2. Shear Wall or Truss
3. Combined Frame and Shear Wall or Truss
4. Moment Resistant Frame with Stiffening Features
5. Framed Tube
6. Core Structure
7. Combined Framed Tube and Core Structure
8. Framed Tube with Stiffening Features
9. Other Tube Structure

Energy Dissipation Systems

1. Ductile Frame and Wall
2. Damping Systems

Table 3
HIGH RISE STRUCTURAL SYSTEMS (Khan, 1974)

Steel Structural Systems

1. Rigid Frame
2. Shear Truss Frame
3. Shear Truss Frame with Belt Trusses
4. Framed Tube
5. Column Diagonal Truss Tube
6. Bundled Tube
7. Truss Tube without Interior Columns

Concrete Structural Systems

1. Frame
2. Shear Wall
3. Frame-Shear Wall
4. Framed Tube
5. Tube-in-Tube
6. Modular Tube

Table 4

FRAMING SYSTEMS FOR TALL BUILDINGS
(British Steel Corporation, 1972)

1. Rigid Frame
2. Core Type Structure
3. Shear Wall System
4. Braced Structure
5. Hull or Tube System
6. Suspended Structure

<u>Three Means of Resisting Lateral Loads in Structures</u>

1. Shear Wall
2. Rigid Connections
3. Diagonal (Truss) Bracing

Table 5

MIXED STEEL AND CONCRETE SUBSYSTEMS (Iyengar, 1980)

<u>Lateral Load Resisting Subsystem</u>

1. Floor Framing
2. Slab
3. Columns
4. Wall Panels
5. Cladding

Table 6

TALL CONCRETE STRUCTURES
(Council, Committee 21A, 1978)

Lateral Resistance Systems

1. Moment Frame
2. Tube
3. Framed Tube
4. Shear Wall
5. Shear Wall and Frame
6. Staggered Truss (Staggered Wall)
7. Gravity System
8. Diagonal (Braced Frame)
9. Braced from other structures
10. Bridged Systems

Table 7

DATA BASE STRUCTURAL SYSTEMS (Beedle,et.al., 1980)

1. Rigid Frame
2. Braced Frame
3. Staggered Frame
4. Frame With Load Bearing Walls
5. Frame With Central Core
6. Frame With Shear Walls
7. Core With Cantilevered Floors
8. Core With Suspended Floors
9. Framed Tube
10. Braced Tube
11. Tube-in-Tube

Table 8

COMMON HIGH RISE STRUCTURES (Schueller, 1975)

1. Bearing Walls
2. Cores and Bearing Walls
3. Self Supporting Boxes
4. Cantilevered Slab
5. Flat Slab
6. Interspatial
7. Suspended
8. Staggered Truss
9. Rigid Frame
10. Core and Rigid Frame
11. Trussed Frame
12. Belt-Trussed Frame and Framed Core
13. Tube-in-Tube
14. Bundled Tube

Table 9

STRUCTURAL SYSTEMS (Applied Technology Council, 1978)

Type of Structural System	Vertical Seismic Resisting System
1. Bearing Wall System	Light framed walls with shear panels
2. Building Frame System	Shear Walls
3. Moment Resisting Frame System	Special Moment Frames
	Ordinary Moment Frames
4. Dual System	Braced Frames
5. Inverted Pendulum Structures	

Table 10

STRUCTURAL SCHEMES (Drosdov, Lishak, 1978)

Primary Structural Systems

1. Framed systems (Frame)
2. System with Flat Walls (Wall)
3. Core-Trunk System (Core)
4. Envelop-Type System (Tube)

Secondary (Combination) Structural Systems

1. Frame-Braced System (Frame & Wall)
2. Frame System (Frame & Core)
3. Frame-Envelop System (Tube & Frame)
4. Trunk-Wall System (Core & Wall)
5. Cellular System (Tube & Wall)
6. Trunk-Envelop System (Tube & Core)

Table 11

TALL BUILDING STRUCTURAL CATEGORIZATION

Primary Strucural Framing System

1. Bearing Wall
2. Core
3. Frame
4. Tube

Augmentative Structural Subsystems

1. Structural Wall
2. Structural Core
3. Truss System
4. Repeated Girder
5. Moment Resisting Frame

Floor Framing Subsystem

1. Steel
2. Concrete
3. Composite

Table 12
FRAMING-ORIENTED STRUCTURAL CLASSIFICATION

Level A: FRAMING SYSTEMS (PRIME & HYBRID)

1. Bearing Wall

10 Bearing wall
11 Bearing wall & core
12 Bearing wall & frame

2. Core

20 Perimeter core
21 Perimeter core & frame
22 Perimeter & central core
23 Suspended
24 Suspended & Frame
25 Suspended & Shear Walls
26 Cantilevered Floors
27 Cantilever & Frame

3. Frame

30 Simple Frame
31 Semi-Rigid Frame
32 Rigid Frame
33 Simple Frame & Shear Walls
34 Simple Frame & Solid Core
35 Semi-Rigid Frame & Shear Walls
36 Semi-Rigid Frame & Solid Core
37 Rigid Frame & Shear Walls
38 Rigid Frame & Solid Core
39 Exterior Truss Frame

4. Tube

40 Framed Tube
41 Trussed Tube
42 Bundled (Modular) Tube
43 Perforated Shell Tube
44 Deep Spandrel Tube
45 Framed Tube-in-Tube
46 Trussed Tube-in-Tube
47 Shell Tube-in-Tube
48 Spandrel Tube-in-Tube
49 Framed w/int. cols.
50 Trussed w/int. cols.
51 Shell w/int. cols.
52 Spandrel w/int. cols.

Table 12, Continued

Level B: Bracing Subsystem

Frame Bracing One Plane

11 Single Diagonal Bracing
12 Double Diagonal Bracing
13 Horizontal K Bracing
14 Vertical K Bracing
15 Knee Bracing
16 Lattice Bracing

Frame Bracing Two Planes

21 Single Diagonal Bracing
22 Double Diagonal Bracing
23 Horizontal K Bracing
24 Vertical K Bracing
25 Knee Bracing
26 Lattice Bracing

Core Braced (Two Directions)

31 Single Diagonal Bracing
32 Double Diagonal Bracing
33 Horizontal K Bracing
34 Vertical K Bracing
35 Knee Bracing
36 Lattice Bracing

Core With Hat\Belt Truss

41 Single Diagonal Bracing
42 Double Diagonal Bracing
43 Horizontal K Bracing
44 Vertical K Bracing
45 Knee Bracing
46 Lattice Bracing

Core Braced and Hat/Belt Truss

51 Single Diagonal Core/Double Diagonal Belt/Hat
52 Double Diagonal Core/Single Diagonal Belt/Hat
53 K Braced Core/Single Diagonal Belt/Hat
54 K Braced Core/Double Diagonal Belt/Hat
55 Knee Braced Core/Single Diagonal Belt/Hat
56 Knee Braced Core/Double Diagonal Belt/Hat
57 Lattice Braced Core/Signel Diagonal Belt/Hat
58 Lattice Braced Core/Double Diagonal Belt/Hat

Table 12, Continued

Level C: Floor Framing Subsystem

Steel	Concrete	Composite
11 Pre-fabricated	21 Flat Slab	31 Steel Beam and Slab
12 Steel Beam and Deck	22 Beam and Slab	32 Steel Beam and Slab on Metal Deck
13 Steel Joist and Deck	23 Precast Slab Beam and Slab	33 Concrete Encased Beam
	24 Joist	34 Steel Joist and Slab

Typical Designator: 35.41.31

Level A: Framing System
Level B: Bracing Subsystem
Level C: Floor Subsystem

Table 13

Structural Material System

1. Unreinforced Masonry
2. Reinforced Masonry
3. Reinforced Concrete
4. Prestressed Concrete
5. Structural Steel
6. Composite Concrete and Steel
7. Vertically Mixed
8. Mixed Throughout
9. Wood

Table 14

H. V. A. C. CLASSIFICATION (ASHRAE, 1976)

1. All-Air	2. Air-Water	3. All-Water	4. Multiple Unit
1 Single Path	1 Two Pipe	1 Two Pipe	1 Window A\C
2 Dual Path	2 Three Pipe	2 Three Pipe	2 Thru-Wall
	3 Four Pipe	3 Four Pipe	3 Rooftop A\C
			4 Unitary A\C
			5 Direct Expansion, Water-Loop Heat Pumps

Table 15

PLUMBING SYSTEM CLASSIFICATION
(Council, Committee 2B, 1980)

1. Gravity Tank
2. Hydropnuematic Tank
3. Booster Pump
4. Mixed

Table 16

VERTICAL TRANSPORTATION SYSTEMS
(Council, Committee 2A, 1980)

1. Escalators	2. Elevators	3. Material Movers
1 None	1 Single Deck, Local	1 None
2 Criss Cross	2 Single Deck, Local and Express	2 Pneumatic Tubes
3 Parallel	3 Single Deck, Sky Lobby Concept	3 Vertical Box Conveyors
	4 Double Deck, Local	
	5 Double Deck, Local and Express	
	6 Double Deck, Sky Lobby Concept	

Table 17

CLADDING SYSTEM CLASSIFICATION
(Council, Committee 12A, 1980)

Cladding Type	Instaltion Method
1. Custom Walls	1. Stick Instalation
2. Standard Walls	2. Unit Instalation
	3. Unit and Mullion Instalation
	4. Panel instalation
	5. Column-Cover-and-Spandrel Instalation

Table 18

PARTITION SYSTEM CLASSIFICATION
(Council, Committee 12B, 1980)

Permanent	Demountable
1. Masonry Brick	3. Post and Infill Panels
2. Concrete Block	4. Post and Overlay Panels
	5. Postless

Loading Systems

Gravity
Temperature
Earthquake
Wind
Fire
Accidental Loading
Water and Snow

Functional Systems

Utilization
Ecological
Site
Esthetics
Space Cognition
Access and Evacuation
Infiltration Protection
Environmental
Transportation
Energy Efficiency

Parking
Ownership, Financing
Operation
Maintenance
Management
Building Services
Communication
Security
Fire Protection
Urban Services

Physical Systems

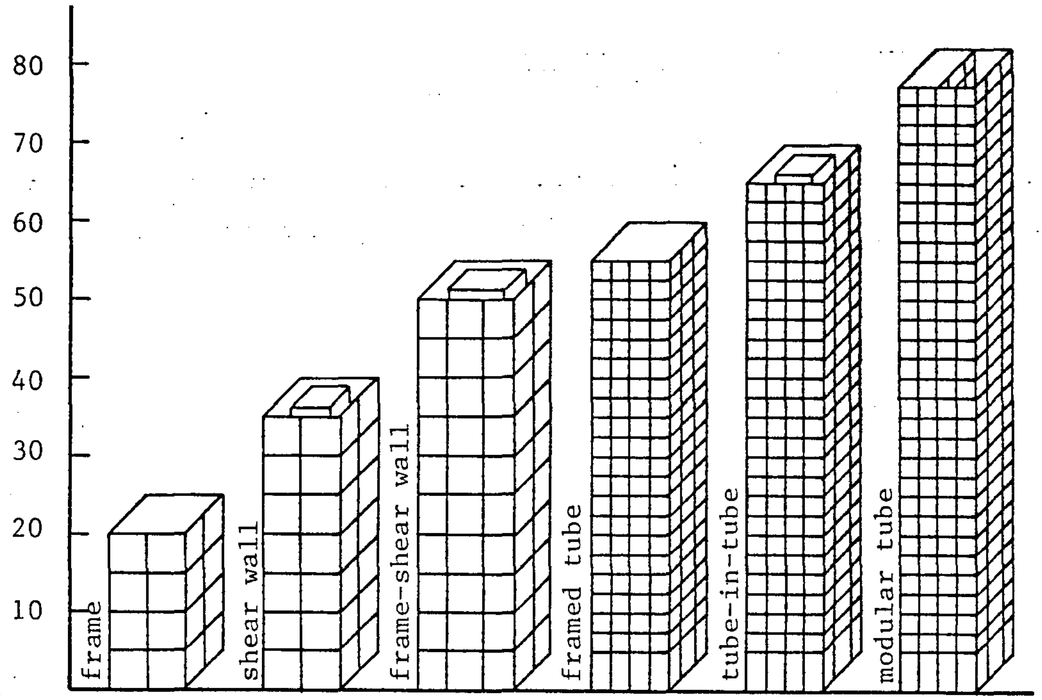
Foundation
Structural Framework
Mechanical Systems
Electrical

Architectural
Fitting and Furnishings
Contents
Utilities

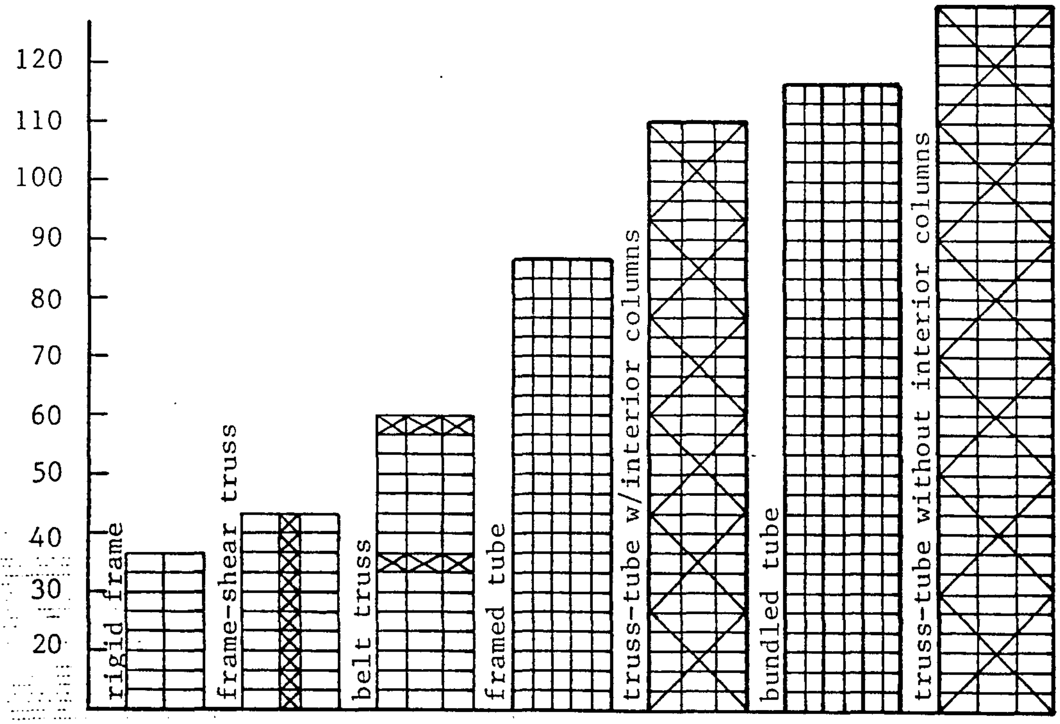
Building Implementation Systems

Need
Planning
Design
Construction
Operation
Demolition

Fig. 1: Tall Building Systems (Beedle, 1980)

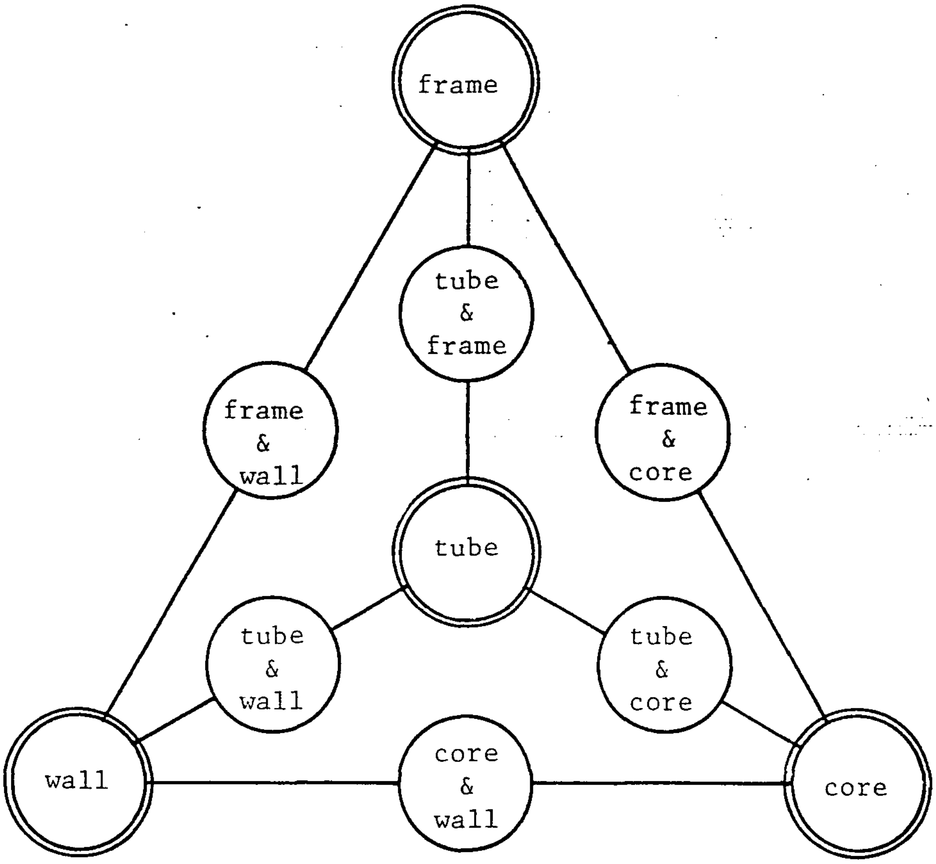


Concrete Structural Systems



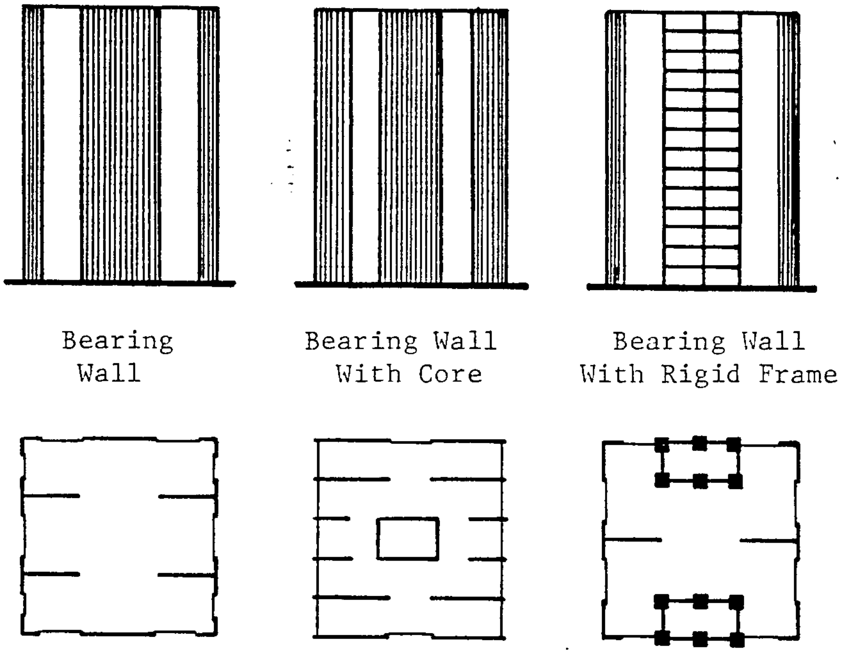
Steel Structural Systems

Fig.2 (Khan, 1974)



Classification of Structural Systems of Multi-Story Buildings

Fig. 3 (Drosdov, Lishak, 1978)

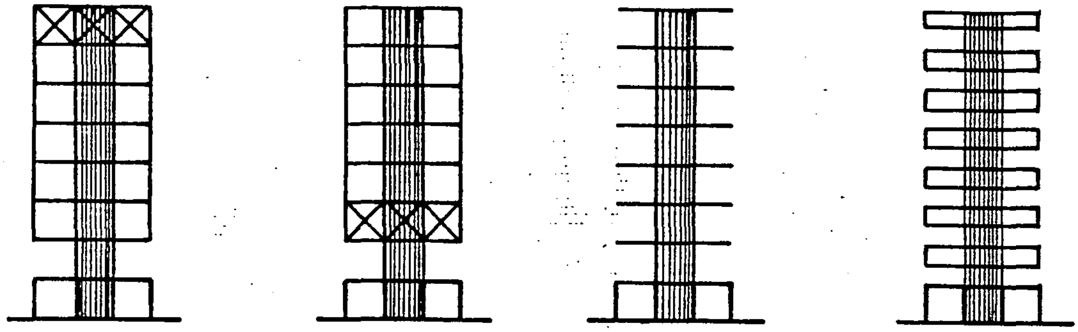


Bearing Wall

Bearing Wall With Core

Bearing Wall With Rigid Frame

Fig. 4: Bearing Wall Systems

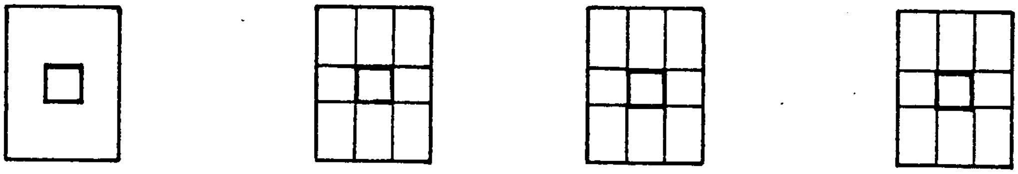


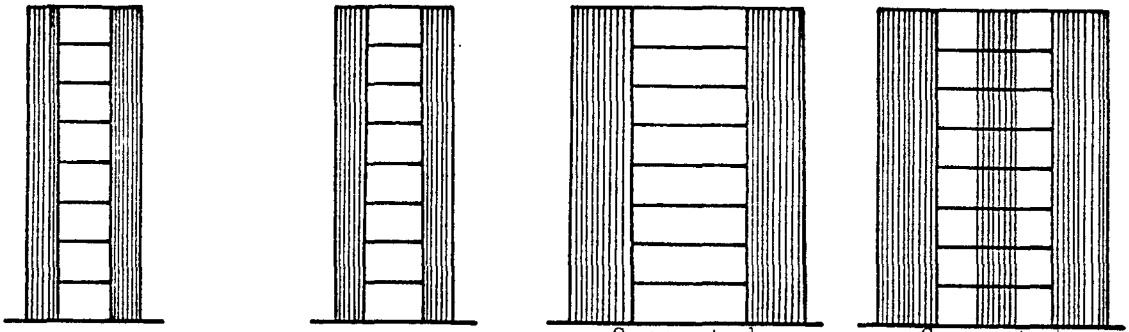
Suspended Top Truss

Suspended Bottom Truss

Cantilever Floors

Cantilever Connected Floors





Corner Core

Corner & Interior Core

Separated Perimeter Core

Separated Perimeter & Interior Core

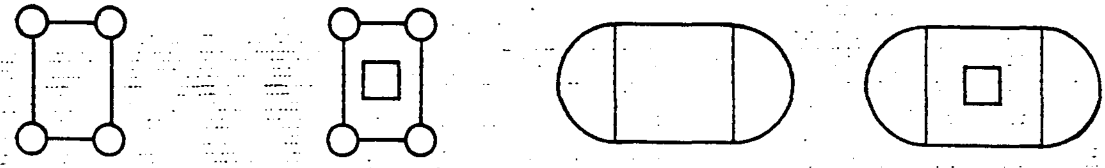
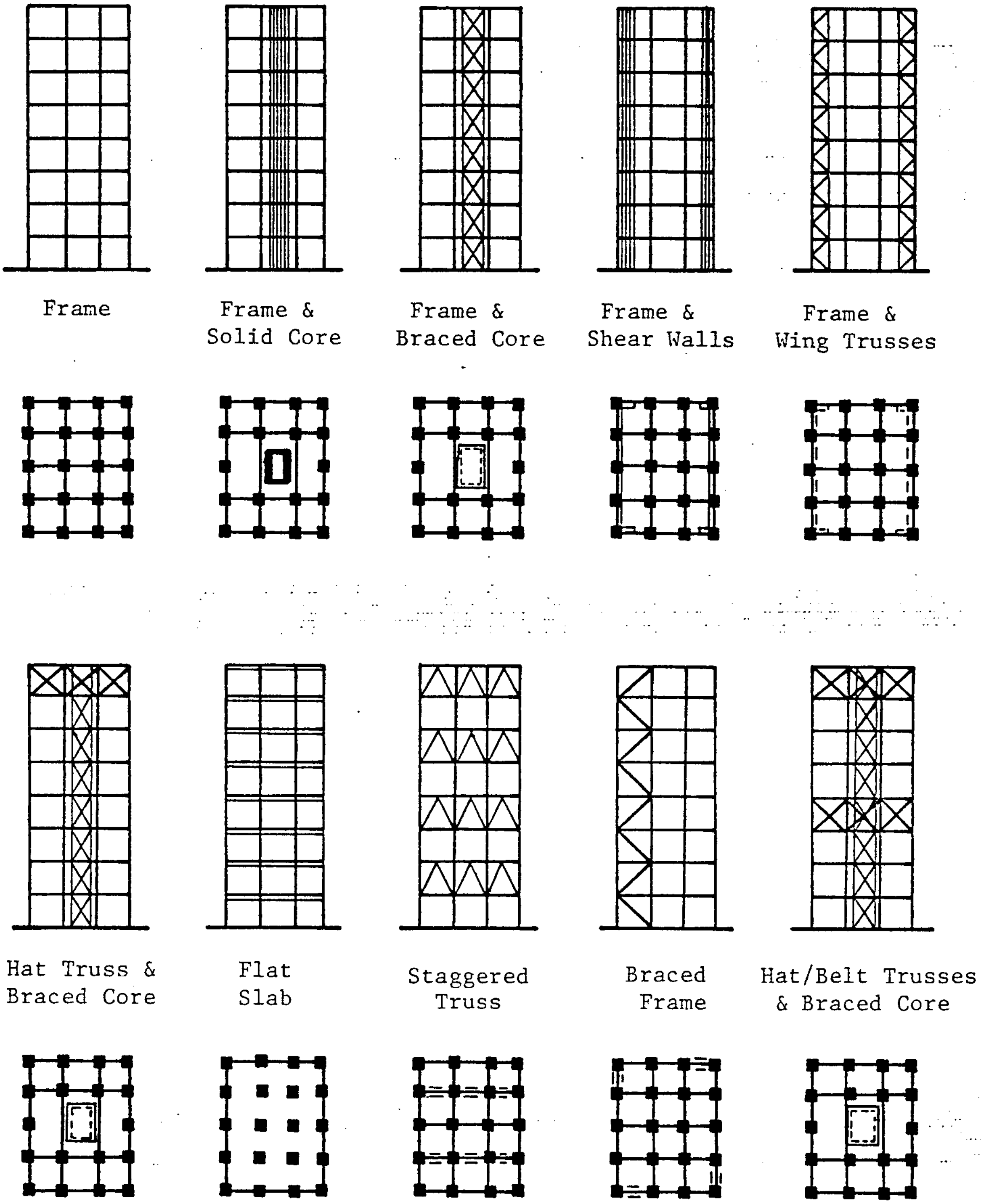


Fig. 5: Core Systems



Frame

Frame & Solid Core

Frame & Braced Core

Frame & Shear Walls

Frame & Wing Trusses

Hat Truss & Braced Core

Flat Slab

Staggered Truss

Braced Frame

Hat/Belt Trusses & Braced Core

Fig. 6: Frame Systems

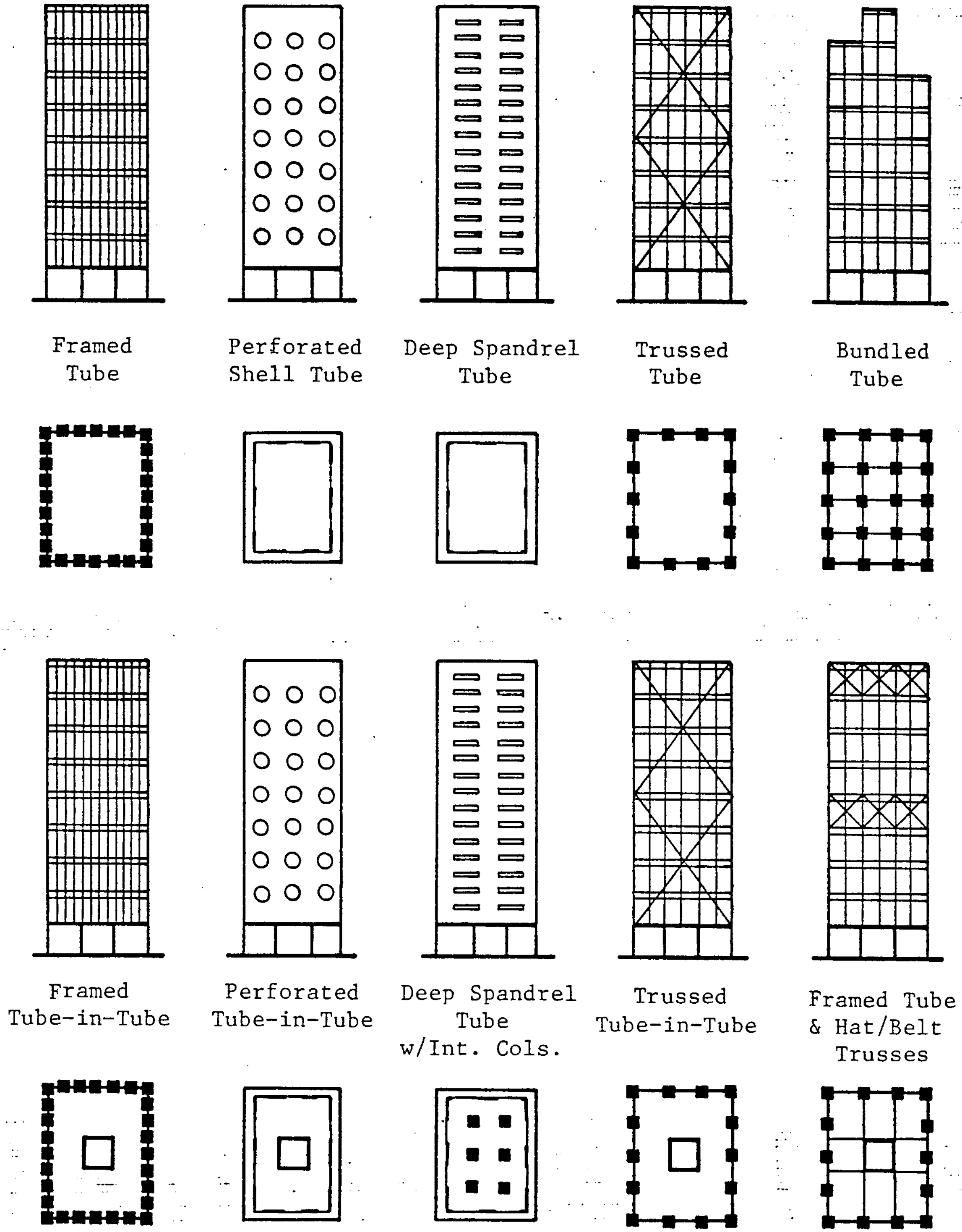


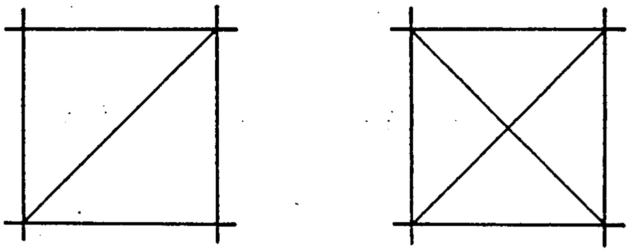
Fig. 7: Tube Systems

Building Name	Structural[a] 3			Material[b] 9
	Framing	Bracing	Floor	
Penzoil Place	Frame 38	42	31	Steel 53
MLC Centre	Tube 47	00	31	Concrete 33
Park Towers	Wall 11	00	21	Concrete 30
Collins Place	Tube 45	00	31	Steel 53
BHP House	Tube 53	42	32	Steel 55
USS Building	Frame 36	4?	??	Steel 55
Chase Manhattan	Frame 33	??	??	Steel 50

[a] See Table 12

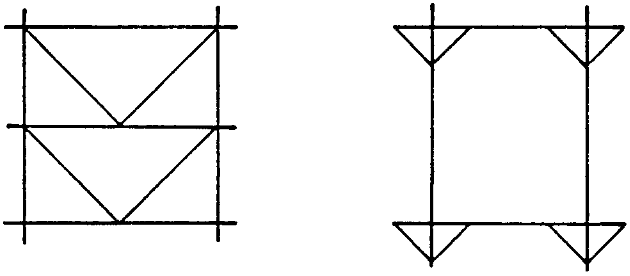
[b] See Table 13

Fig. 8: Sample Classification Chart



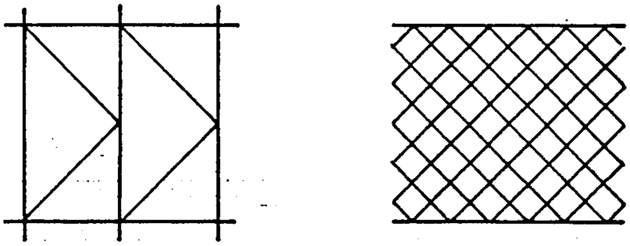
Single Diagonal Bracing

Double Diagonal Bracing



Vertical K-Bracing

Knee Bracing



Horizontal K-Bracing

Lattice Bracing

Fig. 9: Bracing Types (Council, Committee 3, 1980)

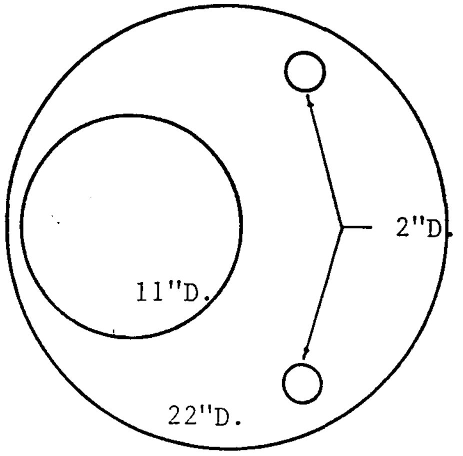


Fig. 10: Space Comparison: All-Air vs. Air-Water

(ASHRAE, 1976)

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