Chapter 2
Introduction to Structural Design

2.1 The Features of Modern Structures

The purpose of modern structural design is to provide the structure with up-to-standard operational functions. Physical integrity serves as a prerequisite for a functional structure to withstand external interference. The physical integrity is provided by load-bearing components, which comprised of numerous specific materials. Thus, modern structural design will need to follow the principle of "take it as s a whole while start from the subsystem." It means when we design for the subsystem we still have to take into account the mechanics, aesthetics, and the need of sustainable development of the entire structure. The modern structural design should focus on three main parts: mechanical concepts, aesthetic concepts, and sustainable development, which are independent while interrelated at the same time.

One feature of modern structure is to meet growing functional demands. These demands are not confined to the increment of height (the record of the highest building has been constantly rewritten), the prolongation of bridge span (the record of the longest span has also been constantly rewritten), and the addition of new structural systems (new structural systems and new materials have sprung up and been applied to actual construction). Newer demands are embodied more in the aspect of "green" sustainable development.

The development of modern structural engineering has to coordinate the social, humane, and natural development. Modern high-rise structures, bridges, spatial structures are not in blind pursuit of being impressively high, wide, or giant but have put the emphasis upon "functional requirement," "energy conservation," and "being environmentally friendly." Therefore, engineers need to contemplate upon aesthetics and sustainable development on the basis of the overall conception; meanwhile, they are supposed to employ mechanics and structural systems to compose and decompose structure, turning a complex structure into simplified three-dimensional framework, two-dimensional plane substructure, or even one-dimensional linear or nonlinear components and composing these components

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back to a modern structure which could meet diversified functional requirements of being ultra-high, long-span, spatial, etc.

1. Being ultra-high: Due to the limitation of urban land, ultra-high or high-rise structures have become one of the trends nowadays. Following Shanghai Jin Mao Tower (88 stories, 420 m high) and Shanghai World Financial Center (101 stories, 492 m high), an even higher skyscraper known as Shanghai Center is under construction and will be completed in 2014. For ultra-high structures, proper design needs to focus on seismic performance, as well as wind load, wind induced lateral deformation, and overturning moment at the foundation.
2. Long span: Long-span bridges have naturally built over wandering rivers. Typical types include cable-stayed bridge, suspension bridge, and varied arch bridge. Take the recently completed Jiangyin Yangtze River Bridge for instance, its main span stretches over 1385 m. Both Shanghai Lupu Bridge and Chongqing Chaotianmen Yangtze River Bridge are steel arch bridges with spans of 540 m and 552 m, respectively, and are currently on top of the world's largest span arch bridge list. Along with the increase of the span, issues such as wind vibration, earthquakes, structural dynamics, and stability will become prominently significant. Those concerns will pose great difficulty and challenge upon the structural design and calamity prevention.
3. Novelty: With growing constructions in twenty-first century, more and more novel structures and new technologies have been emerging. The features of novel structures lie in the peculiarity of the presence and the complexity of its stress state, which for the moment is devoid of available code to abide by, in terms of effective approaches of analysis and design. As a result, performance of such structures might not be predictable and controllable as it is supposed be.

Last century had witnessed an enormous amount of ultra-high-rise structures, ultra-long-span bridges, and a collection of novel structures with distinctness. To analyze their performance under severe conditions is extremely complicated and challenging. However, as long as the fundamental mechanical principles are followed, and reasonable models are applied, it is possible to effectively evaluate different preliminary designs then find the optimum one.

When it comes to ultra-high-rise structures, they could be simplified as cantilever beams in the preliminary design. In that case, stress state could be analyzed; structural systems and configurations compared; approximate dimensions of major components determined; and construction costs of different structural systems estimated. Then questions can be raised in selecting different design schemes, such as reinforced concrete or steel, reinforced concrete core wall system or steel frame, a simple rectangle layout or a complex H layout, and a simple cuboid with identical section or a trapezoid with variable sections. All these questions could be answered through the application of conceptual design and analytical methods illustrated in this book. Figure 2.1 shows the Shanghai Jin Mao Tower and its simplified model of a cantilever beam.

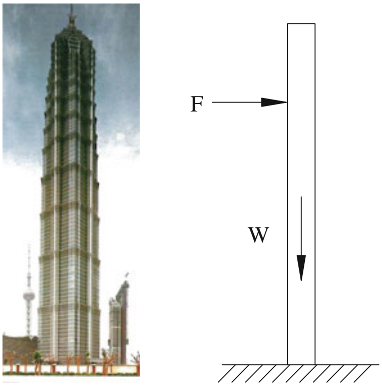


Fig. 2.1 Shanghai Jin Mao Tower and its simplified model of cantilever beam

As for long-span structures, especially bridges, they are simplified as simply supported or continuous beam in the preliminary design. In that way, stress states could be analyzed; approximate dimensions of major components determined; and construction costs of different structural systems estimated. For instance, the adoption of simply supported beam or continuous beam, and the selection of reinforced concrete structure or steel structure should result in significant difference regarding costs and configuration. Figure 2.2 shows the Donghai Bridge of Shanghai and the simplified model of its cable-stayed bridge (over the main channel).

When approaching novel spatial structures, they could be simplified as arch structure or suspension structure or a combination of several structural systems in the preliminary design. Similarly, stress states could be analyzed; approximate dimensions of major components determined; and construction cost estimated. Figure 2.3 illustrates the steel structure of "Bird's Nest" stadium in Beijing and the simplified model of its portal-rigid frame. From Fig. 2.3b, we know that the "Bird's Nest" actually is achieved through laying 48 portal-rigid frames around the oval opening in the roof; Fig. 2.3c shows the simplified model of one portal-rigid frame.

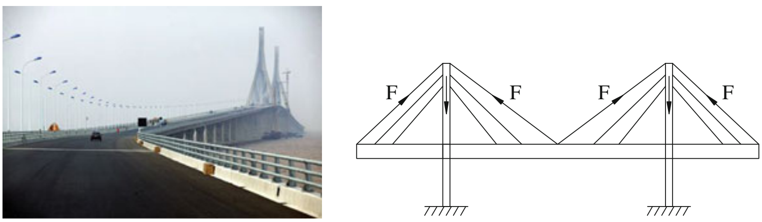


Fig. 2.2 Shanghai Donghai Bridge and its simplified model of cable-stayed bridge

Fig. 2.3 Beijing “Nest” stadium and its simplified model of portal frame. **a** Beijing “Nest” stadium, **b** the structures, **c** portal frame

2.2 The Processes of Structural Design

As Wilson adapted from an unknown author in his book [5]:

> Structural engineering is the art of using materials that have properties which can only be estimated, to build real structures that can only be approximately analyzed, to withstand forces that are not accurately known, so that our responsibility with respect to public safety is satisfied.

Therefore, structural engineering is the combination of technology (mechanics) and art (aesthetics). It requires our structural engineers and architects to ensure the reliability of designed structure through technical means. Meanwhile, it also requires realizing aesthetics and operational functions through artistic means. In other words, with the guarantee of structure integrity, art is also given a creative role in design. And the need of sustainable development should be also taken into account.

All the above tells us that there is no such thing as the only correct solution in structural design but satisfactory design. Besides, structural design requires estimation of properties of material, approximate analysis of structural model, and estimation of potential external loads, in order to ensure the safety and satisfactory operational functions of the structure. Moreover, architectural design is in essence a “conceptual design” from schematic to preliminary and finally to detailed design. Conceptual design does not only play an important role in schematic design but also provide guidance for preliminary and detailed design. Therefore, for structural engineers and architects, learning about the concepts and systems of modern structural design is of considerable significance.

Traditional civil engineering education puts too much emphasis on detailed design of structure and precise analysis of mechanics while ignoring the application of a global perspective of mechanics and systems. Modern structural design expects designers to propose satisfactory structural system and concepts in the early stage of design. Outstanding conception and schematic plan could not only guarantee the feasibility of the overall design but also optimize the plan and economize the costs of construction, in which way physical integrity and aesthetic concern are delivered and requirement of sustainable development is met.

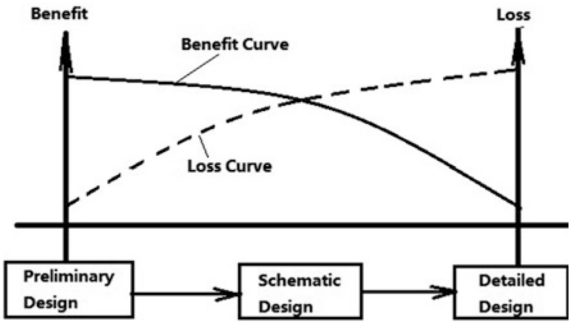


Fig. 2.4 Conceptual design in all stages of structural design

Architectural design consists of three consecutive stages: schematic design, preliminary design, and final detailed design. And conceptual design could be applied through the entire process of structural design. Figure 2.4 illustrates the significance of conceptual design in all stages. If a better design is selected in the earlier state of design based on conceptual design, it would maximum the benefits in terms of structural rationality, artistic configuration, and economized costs, all of which would results in a favorable winning bid. If the conceptual design is well applied in the stage of preliminary or final detailed design, especially on key issues, certain benefits are still expected. However, compared to the early stage, the benefits gained in the latter stage would be relatively smaller. Similarly, tiny errors in the earlier design stage might results in significant loss at the later stage. Numerous lessons have been learned.

This book aims to provide the readers with concepts and deeper knowledge of mechanics as well as its application in all structural systems so that readers would be able to analyze the key issues of structure from a global perspective and well apply the concepts and systems of the structure in schematic design as well as in preliminary design. In this way, benefits are maximized and loss in later design and construction is avoided.

2.3 The Process of Architectural Design

2.3.1 The Elements of Architectural Design

Before the introduction of architectural design, some nomenclatures concerning architectural and structural design have to be clarified [6].

1. Civil engineering: the summation of all permanent artificial structures that are made of physical materials in order to improve the living conditions of human beings.

2. Structural engineering: the summation of all structural systems that are solid-made, capable of force bearing, and manifest in diversified configurations and in the purpose of improving the living condition of human beings.
3. Architecture: a course about interior and exterior arrangements of structure so as to achieve operational functions. The arrangement does not only have to meet the requirements of spatial combination but also have to provide an artistic configuration as well as a sense of harmony with the surrounding environment.
4. Structural engineer: Structural engineer is responsible for plan, design, construction (quality, cost and control of construction period included), maintenance, and rehabilitation of the structure.
5. Architect: Architect is responsible for schematization (skyline of the group of structures included), spatial composition of the structure, aesthetic design and management of the internal and external configuration, and decoration and coordination with surrounding environment.

To design a new structure or to evaluate an existing one, three essentials need to be given proper concerns:

1. Functions. Structures should possess certain operational functions to meet the need of human activities;
2. Structural integrity. Structures should be constructive, structurally reliable, and economically feasible.
3. Aesthetic experience. Structures should provide a symbol of social and aesthetic values for the users, and harmony with the surrounding environments.

From the above three essentials of architectural design, we could see that architects are more concerned with the functional and aesthetic performance. Structural engineers are more concerned with the structural integrity. A successful architectural design has to be a comprehensive work created together by architects and structural engineers, which all the essentials are fulfilled in a collectively optimum manner.

2.3.2 The Relation Between Structure and Architecture

Unlike other industrial or agricultural product, architecture is a unique product displaying spatial arrangement as well as the surrounding environment. Each one of them is unique in a way of its district nature and how it interacts with its surroundings. There are no two identical leaves in the world, and so it is true for architectural products. Structures are supposed to be a creative product completed by architects and structural engineers together. The capability of architectural design of architects and that of structural design of structural engineers should be tightly integrated and harmoniously complemented.

Figure 2.5 shows the "Arabian Tower" project [8] which was awarded by international structural engineer association in 2000. The intention is to display a yacht sailing on Arab sea, providing a special natural feeling for direct senses and

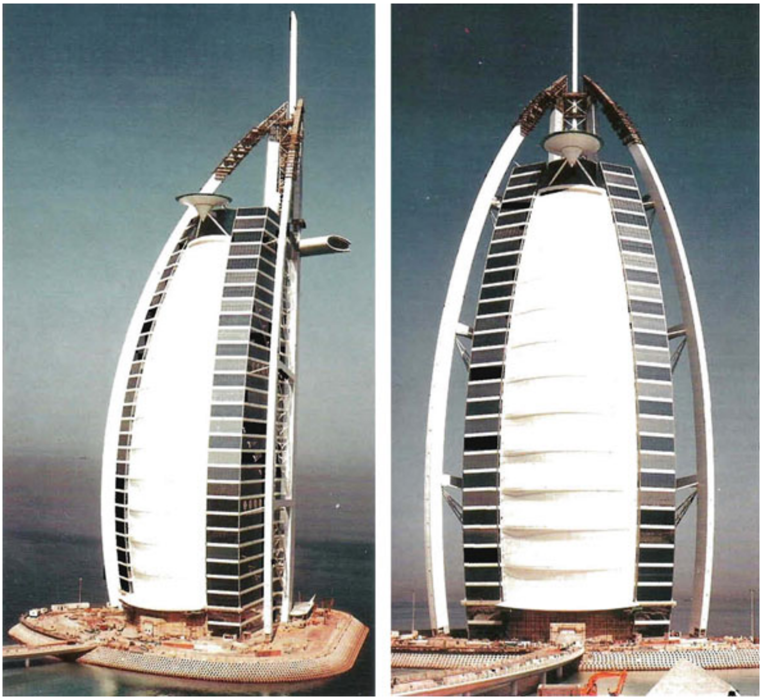


Fig. 2.5 Tower of Arabs [7]

indirect imagination. The entire configuration of the structure is like a canvas, connected to the giant curved pillar frames on the front and back. The mutual support provides a significant horizontal stiffness to the main structure. The extension of giant curved pillar frames takes the form of the mast of a canvas sail; the building is built upon the artificial island at the bay, on the basis of which the podium looks like the hull of. The whole work embodies a perfect combination of architectural and structure design and synthetically reflects the achievement in all aspects of aesthetics, society, humanity, architecture, and construction technology. Among these factors, architectural design plays a leading role in meeting requirements of aesthetic expression and operational functions while structural design guarantees the feasibility of construction and reliability of the structure.

For infrastructure design, most projects are structural engineering-oriented. Figure 2.6 shows the two-story tunnel of Shanghai Fuxing Eastern Road, which is a two-way, “double-barreled” tunnel of eight lanes. When projects of such nature are concerned, so as to meet functional requirements of the project, the emphasis of construction will be inevitably put on matters of civil engineering including the selection and layout of the route, structural design of underwater and underground structures, excavation techniques, and ventilation. Architect has a relatively limited role in infrastructure construction projects.

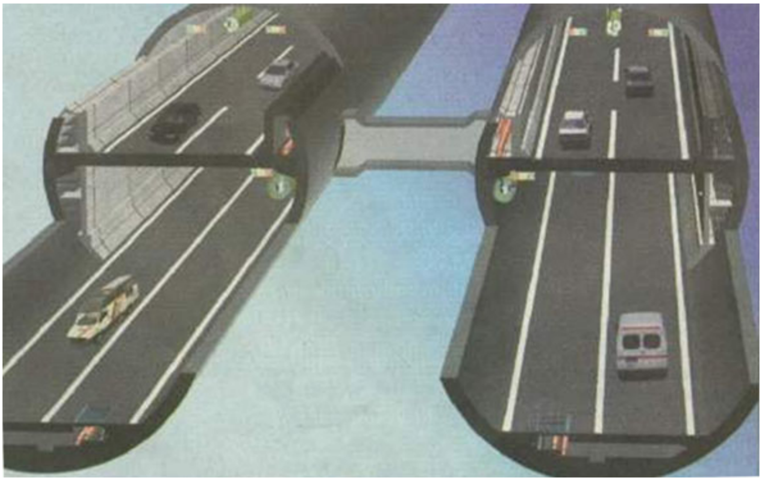


Fig. 2.6 Double-layer tunnel in East Shanghai Fuxi road [8]

Therefore, architects and structural engineers relay on each other in a complementary way. As for different projects, primary role shifts between them. However, due to the different backgrounds, architects and structural engineers are sometimes found to have difficulty in cooperation. This is due to that the architecture is a complex of tangibility and intangibility and that of abstract and concrete notions. Architects put more emphasis on general and global aspects, such as spatial forms and atmosphere created. On the other hand, structural engineers focus more on tangible and concrete structures and detail aspects. Different ways of thinking sometimes result in difficulty in communication.

Architects deal with issues in a global and top-to-bottom way. On the basis of experience, they take primal conditions, restraints, and available resources into consideration so as to conceive a spatial arrangement with the emphasis upon the entire structural system. This will provide not only the operational functions but also an expression of aesthetics. Howbeit, traditional education instructs that structural engineers take a local and bottom-to-top approach and start from learning the treatment of details regarding specific beams and columns with certain neglect of an overall performance of structures and requirements of sustainable development. In this way, a chasm is formed between architects and structural engineers. As a result, communication and creative cooperation, which are of great significance in schematic design and preliminary design, are restrained.

In the stage of schematic design, issues regarding the entire structure rather than details of local components are the major concerns to be dealt with for both architects and structural engineers. Only a profound understanding of relations between the different spatial forms of the architecture could better enhance the comprehension of the demand for local components. Thus, the architecture is first regarded as an integral spatial form, in which case structural analysis of the entire structure comes as the priority and derives substructural systems and key components; then concepts and knowledge of fundamental mechanics could be applied to attain a perfect structure possessing all three essentials of architectural design.

2.3.3 The Process of Architectural Design

The process of architectural design takes three steps as follows:

1. **Schematic design**

The first stage of architectural design is schematic design. In this crucial stage of design, an architectural design of the entire structure would be visualized in accordance with requirements from the owner. And the interaction between major substructures, the construction feasibility, and costs are to be considered. After owner is satisfied, approval from local bureau of planning and administration is also needed. A schematic design is generally required to provide a three-dimensional model, overall schematic plan, simple plane and elevation layout, estimation of total costs, and construction plan. Schematic design sets the tone of overall quality of the architectural design, and thus probability to win the bid.

2. **Preliminary design**

The second stage is preliminary design. In this stage, improvement shall be made to the plan of choice. Preliminary design is expected to determine the dimension of substructural systems, that of major components and the relation between major components together with their geometric and spatial dimensions. At the completion of preliminary design, a detailed version of the overall plan, plane and elevation layout, dimensions of major components, the estimation of total cost, and plan of construction shall be expected. Preliminary design, after being submitted, could be employed as a reference in construction bid.

3. **Detailed design**

The third stage goes to detailed design. In this stage, preliminary design selected by owner and design-related professionals would update the plan to final detailed plan for construction. Priority of this stage is given to detailed design of substructures and all structural components, including the selection of specific materials and determination of construction technology, and detailed design for construction. Detailed design offers guidance for construction, in which case any modification shall need the approval from designers and owner.

What we emphasize is that architectural design is an iteration process with levels and steps, in which architects and structural engineers provide and depend upon feedbacks from each other. From the very first stage of schematic design, repeated modification shall be anticipated. An optimized edition of design would be eventually accomplished through interactions of feedbacks and modifications.

T.Y. Lin once said "We must learn to distinguish principal contradiction from numerous contradictions." To design from a perspective of overall performance is of utmost importance for both architects and engineers. It does not mean that detail design is not important, and inappropriate construction of details actually led to many structural failures. Generally, architects and structural engineers shall first establish a comprehensive understanding of the overall spatial form and relevant operational functions. And then they focus on the detailed design of specific overall system, substructures, and components to achieve an optimized design.

2.3.4 The Application of Structural Concepts in Architectural Design

Concepts of mechanics shall be brought into architectural design as early as possible in the design process. A reasonable consideration of structural concepts could lay the necessary foundation for the following preliminary and detailed design. In other words, architects are supposed to cooperate with structural engineers in the early stage of architectural design.

It is possible and necessary to introduce concepts of mechanics in the early stage of design. Structures are required to provide all sorts of services which entail vertical transportation, horizontal transportation, and systems indispensable in daily life such as water, electricity, gas, heating, ventilation, air conditioning, acoustics, lighting and waste disposal. Space for vertical and horizontal transportation is embodied in structures as elevator shafts and corridor of all sorts. Since all these facilities mentioned above have to be allocated within the specified geometry from the perspective of operational functions, coordinated arrangement is required. From the perspective of mechanics, vertical transportation such as elevator shaft often constitutes vertical components with fortified integrity which undertakes self-weight and horizontal forces. This is particularly notable in high-rise structures, for that vertical transportation of elevator shafts often constitutes the core tube commonly seen in high-rise structures and comprises "tube-in-tube" structure with outer frame-tube (Fig. 2.7).

Figure 2.7 shows a typical "tube-in-tube" high-rise structure; the outer tube is an external wall framework being comprised of close columns and horizontal beams; as for the inner tube, it is the concrete shear wall elevator shaft. The inner tube is connected to the outer tube through the slab on each floor, in which case an integral "tube-in-tube" structure is realized with high strength and stiffness to resist horizontal loads.

As for other indispensable systems for daily life such as heating, ventilation, air conditioning, water supply, power supply, and gas supply, they could be integrated in horizontal and vertical pipes of variable sections and installed. And their spatial arrangement has to be integrated with mechanical system of the structure. For

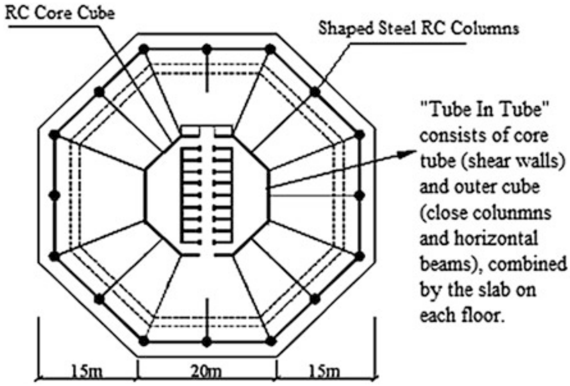


Fig. 2.7 "Tube-in-Tube" structural system [9]

instance, horizontal pipes for equipment could be arranged within the space between secondary beams or on the transfer floor.

Moreover, despite that the influence of acoustics and lighting is categorized as architectural physics, it still has everything to do with structural configuration. For instance, acoustics has a decisive call upon the spatial configuration of roof. Specifically, an arched roof could produce converging effects, which is quite fit for concert halls and opera houses; as for dish-shaped roof, it has diverging acoustics, which is adoptable for exhibition halls and libraries.

In sum, in early schematic stage of architectural design, architects and structural engineers are supposed to work collaboratively and bring in concepts and systems of mechanics as early as possible. A successful architectural design shall be the fruit of wholehearted cooperation between architects and engineers as well as a quotable case of successful application of mechanics and structural systems.

2.4 The Structural Behavior and Design Principles

2.4.1 The Structural Behavior and Energy Principle

1. **The energy principle**

To ensure that the structure provide operational functions as expected, a physical integrity has to be kept under external interference, which specifically indicates that structure would not fail under the combination of all external loads.

The law of motion of all matters is correlated with certain change of energy in its nature. Take downward-flowing water as an example. It is the function of gravity potential energy. The service state of structures reflects the mode of motion of material systems; it relates to certain change of energy within the structure; the actual state of structure more often than not indicates the extreme state of certain energy [9]. In other words, investigation of the energy changes of the structure could lead to the determination of stress state of the structure. And this would be of great help when it comes to dealing with complex issues such as strength, dynamics, and stability of the structure.

2. **Static equilibrium and the principle of minimum total potential energy**

Under the action of external load, the interior of structure would produce stress and strain response to exterior displacement. Strain energy is generated inside the structure and external work is done by external work upon displacement. In light with principle of least action in mechanics, nature produces nothing that is not necessity. As for structures, the least action is the total strain potential energy within the structure and this strain potential energy generated within is the minimum potential energy produced by the work done by the internal stress upon the internal strain. If supports of the structure are not displaced, reaction force of structure does not do work; in accordance with the principle of energy conservation, total potential energy of the structure is the algebraic summation of internal strain energy and the work done by external loads. Assuming that the structural displacement concerning total potential energy is virtual displacement and the internal strain of structure is virtual strain, the extreme value of total potential energy could be calculated (which is to conduct variation) and the equilibrium equation of the structure could be attained. Thereby, the essence of force method applied to static indeterminate structure in mechanics is consistent with that of the principle of virtual work expressed by virtual displacement and the principle of minimum total potential energy. Similarly, the essence of displacement method applied to static indeterminate structure in mechanics is consistent with that of the principle of virtual work expressed by virtual force and the principle of minimum total complementary energy.

3. **Dynamic equilibrium of structure and the principle of minimum total potential energy**

According to the principle proposed by D'Alembert, dynamic equilibrium could be regarded as equivalent static equilibrium posterior to the introduction of inertial force. As a matter of fact, the load bore by the structure and the internal force constantly change with time. The result of this simplification turns dynamic issues into static issues of keeping dynamic equilibrium at any moment. In the sense of an instant, the principle of minimum total potential energy holds true to dynamic equilibrium of an instant when the structure as a whole is concerned.

Therefore, in the sense of an instant, Rayleigh approach, equivalent to the principle of minimum total complementary energy, could also be applied to dynamic equilibrium of structure in an instant. Rayleigh approach establishes the equation between maximum strain energy and the maximum kinetic energy. When the structure is in its natural vibration state, Rayleigh equation could provide the natural vibration frequency of the structure.

Natural vibration frequency is an intrinsic nature of structure, which varies with the distribution of stiffness and mass but not to the magnitude and type of external loads. Natural vibration frequency serves as the foundation of research upon dynamic response of structure in the early stage. However, in that stage of structural design, components are not decided yet the deadweight and distribution of stiffness. As a result, natural vibration frequency could only be estimated through simplified calculation.

An accurate calculation of natural vibration frequency together with dynamic analysis might be excessively detailed, involving theories of structural analysis of depth, and would not be elaborated in this book. Readers with an interest in those approaches could refer in Refs. [5, 9].

4. **Stability and the principle of minimum total potential energy**

Some structures remain in equilibrium of stability under relatively small load. As the load gradually increases to certain extent, although the ultimate strength or even the elastic limit of material has not been reached, deformation has largely increased to the extent that structure fails to bear any more loads. In this case, overall instability or local buckling takes place.

Overall instability in nature originates from fundamental change in equilibrium state, being transited from stable equilibrium to unstable equilibrium. Unstable equilibrium temporarily meets the requirements of equilibrium, or from the energy point of view temporarily suits the principle of minimum total potential energy. Nonetheless, a small "tip" from the outside would break the equilibrium and results in overall instability.

During the transition from stable equilibrium to unstable equilibrium, a critical state exists and that is the so-called neutral equilibrium state. Load applied in such a state is designated as critical load of instability. When it comes to structural design, load designed for the structure to bear shall be smaller than critical load of instability so that instability is prevented. Since issues regarding instability could be summed as that of transition between equilibrium states, extreme value of total potential energy within a structure at its critical state could be calculated so as to determine an equation of critical equilibrium and critical load of instability.

Local buckling is the instability of components and is similar in nature to overall instability.

2.4.2 Overall Stability of Structure and Stability in Its Geometric Composition

When schematic design is in process, overall stability and that in geometric composition have to be checked; otherwise, conception and analysis of strength and stiffness would deem meaningless.

1. **Overall stability of structure**

All permanent structures are supported by the foundation. The structure as a whole needs to have effective support from the foundation.

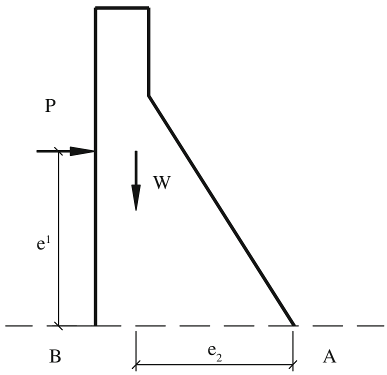


Fig. 2.8 Overall stability of the dam

As for the dam shown in Fig. 2.8, two fundamental requirements for overall stability are given as follows:

(i) Stability regarding horizontal load: $P < W \cdot f$
P is the lateral water pressure upon the dam; W is the deadweight of the dam; f is the friction coefficient between the dam and the foundation.
(ii) Stability regarding overturning moment (relative to point A at the bottom): $P \cdot e_1 < W \cdot e_2$
e_1 and e_2 represent the length of arm of force, as shown in Fig. 2.8.

2. **Stability in geometric composition of the structure**

Structure is comprised of many components and only when these components compose in a rule-abiding geometric way could the structure stay stable. Otherwise, when the structure itself is geometrically unstable, tiny little interference from external load could lead to considerable (infinite in theory) displacement. Hence, geometrically unstable structure is not qualified to take load and has to be excluded before schematic design starts. This is especially significant when the design is for spatial truss and latticed truss comprised of numerous bars.

Fundamental principle of geometric composition for a stable truss structure could be described as: Truss structure is formed by many a "triangle discoid" which is a geometrically stable unit composed by three hinged components. Truss structure itself could be regarded as geometrical constant and is supported by the foundation through three or more non-convergent connecting bars.

Figure 2.9 shows a stable truss structure; it consists of eight "triangle discoid," number 1, 2, and 3 of which connects with the foundation. As for the truss in Fig. 2.9b, although it has the same number of bars as the structure in Fig. 2.9a, it is a geometrically variable structure due to the difference in geometric composition.

Figure 2.10 shows a geometrically unstable truss structure getting support from the foundation through three bars converging at point O. Since these three bars could not prevent the structure from rotating around point O, this truss is considered as geometrically unstable.

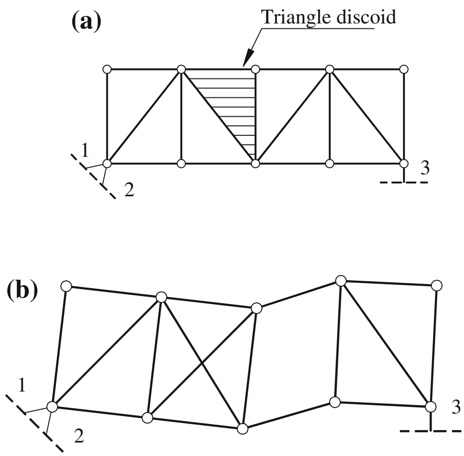


Fig. 2.9 Comparison of stable truss and geometrically variable structure, **a** the stable truss, **b** the geometrically variable structure

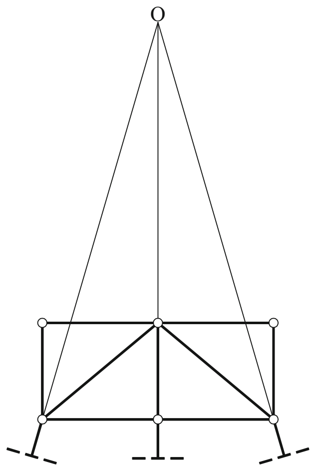


Fig. 2.10 Geometrically unstable truss

From the perspective of mechanics, geometrically unstable structures have no resistance in at least one direction which enables the structure to move without restraint in that specific direction. If looking at the matrix of overall stiffness matrix of a geometrically unstable structure, at least one zero elements would exist among all diagonal elements.

2.4.3 The Upper- and Lower-Bound Theorem in Limit Analysis of Structure

An important step of structural design is to conduct limit analysis, which is to find the ultimate bearing capacity and the failure mode. Since materials are capable of producing plastic deformation to some extent, the ultimate state of structure generally is its plastic limit state. Limit analysis is to study the ultimate bearing capacity of structure in its plastic limit state. When the load working on the structure augments to a certain limit, the material of structure transforms into a plastic state, in which case deformation infinitely multiplies and the structure fails to bear loads. And this state is called plastic limit state of structure. The goals of plastic limit analysis of structure are: (1) to determine the ultimate bearing capacity of structure; (2) to determine the stress distribution that meets the requirements of boundary conditions in the limit state of structure; and (3) to find out the most probable failure mode.

To determine the ultimate bearing capacity of structure, one has to know external forces, geometric boundary constraints, and the material properties. As mentioned before, the properties of material, external loads, and geometric boundary constraints are not accurately known, therefore reasonable estimations are needed. Conditions needed in the meantime are: (1) yield strength and constitutive model of materials; (2) equilibrium condition; and (3) compatibility condition. Yield strength and constitutive model of materials are based on experiments, while equilibrium and compatibility have to be satisfied in limit state.

Solution that meets all three conditions mentioned above is considered as a complete solution, which in other words is the complete solution to the ideal bearing capacity of structure which simultaneously meets sufficient and necessary condition for structure failure. Due to the complexity of load bearing and the uncertainty concerning properties of material, external loads and geometric boundary constraints, complete solution is not easy to attain which makes simultaneous meeting of three conditions impossible for limit analysis. Nevertheless, two theorems are developed from the theory of limit analysis: the lower- and upper-bound theorem. The upper-bound theorem proposes sufficient condition for failure which indicates that the structure will surely fail once such load is imposed upon the structure. Since the bearing capacity proposed by upper-bound theorem is generally larger in magnitude than the potential load that structure might have to bear, it is unsafe to design with reference to assumed failure of the structure derived from upper-bound theorem. Lower-bound theorem proposes necessary condition for the prevention of structure failure, meeting the condition of which means the structure is safe under the action of such load. Therefore, it is conservative applying the lower-bound theorem in design.

Current code indicates that limit design for normal section of reinforced concrete beam employs assumed stress distribution on the normal section and a flexure failure mode. It assumes that tensile reinforcements begin to yield and compressed concrete is up to its compressive strength. The equilibrium between the internal and the external force on the normal section could be employed to determine ultimate flexural bearing capacity of the beam. This is a typical solution derived from the lower-bound theorem, which meets only the equilibrium condition and material capacity with the exception of deformation compatibility.

In sum, when designers conduct ultimate bearing capacity (strength) design for structures, it should be noted that limit analysis does not get the complete solution which meets all three necessary and sufficient conditions of failure; instead, it usually gets a lower-bound or upper-bound solution which meets two out of three conditions. On one hand, a good limit analysis of structure shall have a most likely mode of failure anticipated and in the meantime have a relatively lower (under given mode of failure) upper-bound load designed. On the other hand, a good limit analysis of structure shall also find out the most probable mode of equilibrium between the internal and the external force and as a result of having a relatively higher (under given mode of failure) lower-bound load designed, which enables a more accurate estimation of the bearing capacity of the structure.

2.4.4 Instability and Structural Dynamics

Modern structural design features structural dynamics and structural stability as factors that have to be considered. Estimation of dynamic features such as fundamental frequencies is usually needed in early schematic design.

Frequent earthquakes and other dynamic loads directly threat the safe operation of structures. For instance, resistance to strong seismic movement holds the key to a safe design for ultra-high-rise structures; in the meantime, vertical seismic effect is threatening the safe operation of ultra-long-span bridge. Dynamic response of spatial structure under the action of complex and variable dynamic loads also poses difficulty to structural design.

Under complex combination of loads, light-weight and thin-walled structures (especially spatial structures) are especially prone to local buckling and overall instability issues, such as local buckling and overall stability of thin-walled component in compressed areas. As for long-span structures, overall buckling is more likely to happen. Since the slender components are prone to buckling failure, sometimes reinforcement is needed to provide sufficient stiffness, which keeps the slenderness ration within a reasonable range and avoid local buckling.

To illustrate consideration of buckling stability in structural design, Fig. 2.11 shows an example of a reinforcement design process for U-shaped steel beam. Figure 2.11a shows a U-shaped steel beam under the point load *P*; the bending

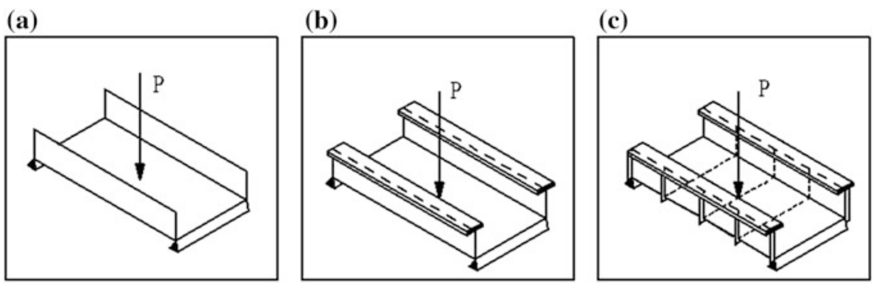


Fig. 2.11 Process of reinforcement design for a U-shaped steel beam [9]. **a** Reinforced at end of beam, **b** reinforced at beam flange, **c** reinforced at the web

moment produces longitudinal tensile stress on the bottom surface and compressive stress on the upper surface, the latter of which might induce local buckling on the wing. Figure 2.11b illustrates the approach to locally reinforce the transverse stiffness of the wing so that local compressive buckling of the wing is prevented, and thus the overall bearing capacity of the beam is enhanced. As load increases, buckling failure could happen to the web or bottom plate due to lack of restrains. Figure 2.11c shows that horizontal reinforcement is installed to prevent local buckling at the web or bottom plate, and the overall bearing capacity of beam is further enhanced.

Although structural dynamics and structural stability are not of same nature, they are apparently interactive with each other. A typical example is the famous Tacoma Narrows Bridge, which collapsed due to overall instability under strong wind in 1940, several months after opened to traffic.

The deck of Tacoma suspension bridge consists of a variety of light-weight and thin-walled structures. Figure 2.12a shows the bridge prior to collapse [6]. Under a

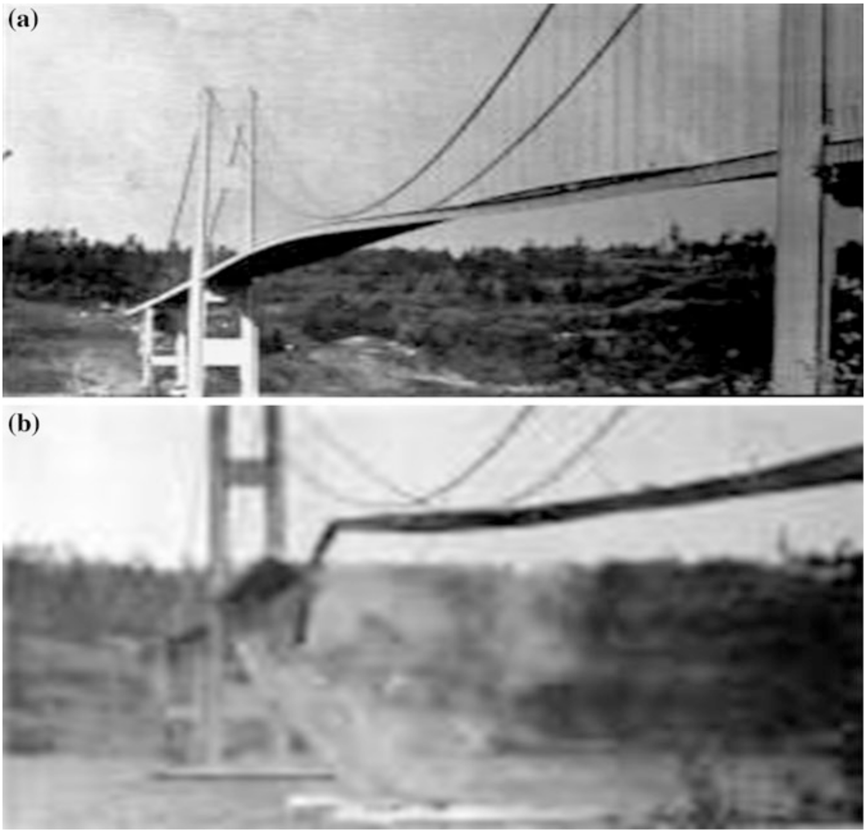


Fig. 2.12 Overall instability failure of Tacoma suspension bridge [6]. **a** Before failure, **b** after failure

series of complex aeroelastic flutter, the slender deck system is prone to lateral buckling. However, the suspension cables could not effectively prevent lateral deflection (actually designed to allow the bridge to sway in wind), which eventually caused the collapse. Since this accident, wind tunnel testing became a necessary experiment to examine the aerodynamic performance for new long-span bridges. Figure 2.12b shows the moment that the bridge was collapsed.

Modern structural design takes into consideration the factors of dynamics and those of stability without exception [10]. Unfortunately, structural engineers still have to rely on complicated mathematical formulae and modeling methods (or other numerical discretization methods), in the help of computers. Due to the scale of complexity and time consumption, this approach is difficult to be implemented in the earlier stage of design. Therefore, it is necessary to find some simplified models and approaches to estimate and evaluate overall structural stability and dynamic performance.

2.4.5 Fundamental Principles of Structural Design

Structural engineering is based on practical experience as well as theoretical mechanics. Three fundamental principles shall be paid attention to in regard of conceptual design and systematic composition of structure:

The first fundamental principle is that the ductility of structures (capacity to withstand plastic deformation) should provide considerable tolerance for excessive loads, which forms the first "perimeter" to prevent any possible errors from inevitable simplification, or even mistakes from engineers as human beings. The second fundamental principle is that details like joints should be carefully designed so that premature failure is avoided. The third fundamental principle is that building more redundancy through static indetermination is also effective to prevent premature structural failure.

1. **The utilization of ductility of structures**

Ductility describes the ability to withstand plastic deformation under extreme loads. It induces ductile failure and functions as a storage capacity to resist extreme external loads.

One of the three fundamental principles for structural engineering is that "structural ductility could provide considerable tolerance for minor errors of engineers." That is to say, small errors from simplified calculation or in design will be mitigated by redistribution of stress within materials. Then the structure would continue to bear load without catastrophic failure even when it is overloaded to certain extent. Granted that it is possible and effective to use simplifications in structural design, however, when dealing with brittle materials, engineers should carefully take the brittleness into consideration to avoid sudden brittle failure.

Many designers favor the "lower-bound theorem" to control structural safety. It refers to a stress path (also known as force flow) design. If force flow is in balance with external loads and the stress of material along the path does not exceed the material strength, the structure is deemed safe. In this way, the service load is always lower than strength so the safety is achieved.

Recently, endeavors have been made to include equilibrium conditions and material constitutive conditions into structural design. American Concrete Institute (ACI) has already applied the lower-bound theorem in its design for joints, torsion, and shear design in its design code. However, special attention should be given to steel components, especially steel connections between column and beam. Despite its ductile nature, steel might turn to a brittle material under triaxial loading conditions. In this case, in order to achieve desired safety level, a proper design would come from the lower-bound theorem viewing steel as a brittle material.

For main load-bearing components, the force flow should be designed to be as clear as possible. The force flow substructures should also be clear so that the corresponding contribution could be easily determined. The "force flow" within the structure should take the shortest path to the support. Moreover, the main "force flow" of structure shall be as smooth as possible and take the form of a natural streamlined curve. A disturbed line of force flow inevitably leads to local stress concentration which would not only produce additional deformation but also raise the cost due to higher material volume to achieve desired safety level.

In addition, the ductility could enable much more energy absorption so that more deformation before failure is tolerated and the failure process is prolonged. This is of special significance in terms of seismic performance. And steel structure is quite outstanding in this respect.

When it comes to structural design, there is no so-called the only correct solution. Designers, facing a lot uncertainty, should be able to identify the relatively satisfactory solution or ideally the optimal solution.

2. **Connection and joint design**

The second fundamental principle of structural engineering is that "The second fundamental principle is that details like joints should be carefully designed so that premature failure is avoided." The significance of joints should be emphasized because they are at the "key positions" and crucial to the overall structure. Numerous structural failures were caused by joints failure. Apart from steel structures, a great many reinforced concrete structures have been improving joint ductility to improve seismic performance. More often than not, the joints of reinforced concrete structures would be densely reinforced in order to achieve better seismic performance due to improve joint ductility. Much more energy will be absorbed during a seismic event which enables the structure to be: (1) intact under minor earthquakes; (2) functional and repairable (non-yielding) under moderate earthquakes; and (3) non-collapsing under major earthquakes.

To ensure normal functions of the structure, joints are supposed to be reliable; however, large amounts of joints failure are induced by small defects in material itself, welding sequence and quality, weather conditions, and supporting conditions. It should be given careful consideration to joint design so that the joint would live up to expectation.

As a matter of fact, the cost of joints accounts for considerable percentage of the overall cost, especially when novel spatial structures are concerned, in which case costly cast steel joints are needed. And joint design has to meet comprehensive requirements of strength, stiffness, ductility, and budget, so that joints are stronger than connecting components. When the structure is overloaded, plastic hinges are forced to develop in components so better structure stability is achieved and premature collapse is prevented.

3. **The utilization of static indetermination**

The third fundamental principle of structural design is that building more redundancy through static indetermination is also effective to prevent premature structural failure. A robust system is required to take into consideration that some components might fail due to reasons which are not designed for (such as terrorist attacks). It is also important to correctly evaluate the impact of accidental failure upon the overall bearing capacity of the system. Therefore, redundancy is provided through static indetermination to deal with contingencies such as the damage of local components inflicted by fire, earthquake, wind vibration, and terrorist attacks.

Static indetermination (redundancy) is an effective way to improve the robustness of the structure, which means the risk of premature overall structural failure due to accidental failure of certain components is mitigated. Redundancy allows more room for stress redistribution and serves as another "perimeter" for the safety of structures. From this perspective, "vulnerability" of structure could be diminished.

As for a frame structure, an increment of static indeterminations usually will not impact the cost and construction techniques significantly. Although static indeterminate structures generate additional stress under temperature gradient and uneven subsidence, frame structures more often than not are still designed and constructed with a great many static indeterminations so that the integrity and reliability of the structure are enhanced.

Attention should also be paid to the distribution of static indeterminations within the structure. Excessive concentration of static indeterminations as well as insufficient redundancy should both be avoided in design. Figure 2.9b shows an example: The second-to-the-left joint of the truss is one of static indeterminate and the third-to-the-left joint is geometrically unstable due to the lack of one diagonal bar member. The example also explains that local insufficient static indeterminations might result in inadequate safety and local premature failure.

2.5 The Loadings Analyses

The accuracy of load estimation has a direct impact upon the safety and economic efficiency of structural design. Underestimation puts the structure in danger while overestimation leads to an economically inefficient and oversized cost of construction. We will discuss how to reasonably select a probable load of design in this section.

All structures undertake corresponding loads in their service condition, and therefore, the selection and determination of load become the very first factor to be considered in structural design. Since an actual load could hardly be precisely known, load estimation becomes a significant issue in the early stage of design. Therefore, a reasonably estimated design load is needed so that major errors in early age calculation could be avoided.

All external interference that induces stress and deformation could be collectively designated as "load." Loads upon the structure could be divided into two types: direct and indirect loads. And the former is then divided into dead loads and live loads. Dead load refers to the load that does not change over time, such as structure self-weight and permanent facilities. As for the live load, it refers to the load that varies with time, such as service live load, wind load, seismic load, snow, vibrations due to mechanical facilities and other high-frequency vibrations, and impact load. Uneven foundation settlement and temperature gradient, classified as indirect loads, might generate stress and deformation as well. This type of loads is difficult to estimate and usually ignored in the early stage of design; nonetheless, some construction measures would take place to compensate the effect, such as the installation of settlement joints or expansion joints.

In the early stage of design, major loads that call for consideration include vertical loads (deadweight and vertical live loads), wind load, and seismic load. Content followed will introduce simplified estimation of loads; as for precise load selection, please refer to the "Load code for the design of building structures (GB50009-2012)" [11].

2.5.1 Vertical Load

1. **Vertical dead load**

Vertical loads are mostly comprised of vertical dead load and live load. Dead load mainly refers to the self-weight of the structure. In the early stage of design, a convenient way to estimate the self-weight is by distributing the overall deadweight of structure to the unit of floor area and calculating the equivalent uniform load. Dead load of the structure usually consists of self-weight of floor, roof, ceiling, wall, partition, column, and affiliated facilities such as corridor, transfer floor, escalator, and elevator shaft. The estimation of dead load could be conducted according to known density of the material and potential dimensions of components; as for concentrated weight of walls and columns, they could be turned into equivalent uniform load. For instance, wall area of residential buildings is estimated as 2–3 times the internal floor area, while that of commercial buildings is estimated as 1–2 times the internal floor area. In this way, as long as density of the material and potential dimensions of components are known, deadweight could be quickly estimated. For instance, the density of steel is 7850 kg/m^3, that of concrete about 2400–3000 kg/m^3 and that of brick masonry about 1000–2000 kg/m^3.

In the early stage of design, in light of gained experience and material of choice, equivalent uniform load of deadweight of structure could be approximately taken as:

Next, dead load shall be adjusted in accordance with dimensions of components from preliminary design. When it comes to final detailed design, dead load shall be further adjusted with reference to detailed dimensions of components. In this way, rough estimation of deadweight in beginning could finally be turned into reasonable determination of dead load.

Since structural stability usually favors structural deadweight, overall estimation of dead load could help designers to better assess the integrated impact generated by wind and seismic load, and thereby a better estimation of effectiveness in resisting lateral load could be achieved.

2. **Vertical live load**

Vertical live loads refer to service live loads of all kinds. Since some live loads are distributed on a small surface and others in a large area and might vary with time, it is difficult to precisely calculate. In the early stage of design, live loads could be approximately taken as equivalent uniform static load; as for the magnitude, reference could be made to corresponding entries in “Load code for the design of building structures (GB50009-2012)” [11]. Table 2.1 lists the standard value of some common live loads.

3. **Vertical snow load**

Snow load is a vertical load acts upon roofs. In cold regions, snow load sometimes becomes the control load in structural design. When that is the case, careful calculation has to be conducted with reference to relevant design code [11].

Table 2.1 Standard value of some common service live loads [11]

Application	Classification	Standard value (kN/m^2)
Floor	Residences, hotels, office buildings, classrooms, etc.	2
	Auditoriums, theaters, cinemas, etc.	3
	Malls, exhibition halls, station halls, etc.	3.5
	Bookstores, archives, storerooms, etc.	5
Roof	Non-accessible roof	0.5
	Accessible roof	2
	Roof garden	3

In the early stage of structural design, uniform snow load is usually calculated with reference to the standard value of local snow load and to different types of roof; the result refers to the uniform snow load on horizontal projection plane. For instance, the standard snow load of Shanghai urban area is 0.2 kN/m^2; when the angle of roof is less than 25°, the snow load of that roof on horizontal projection plane is 0.2 kN/m^2.

When it comes to the calculation of vertical live loads on the roof, the larger of snow load and service live load shall be selected; there is no need to do summation, because the probability of simultaneous occurrence of these two types of loads is quite small.

4. **Example of vertical load estimation**

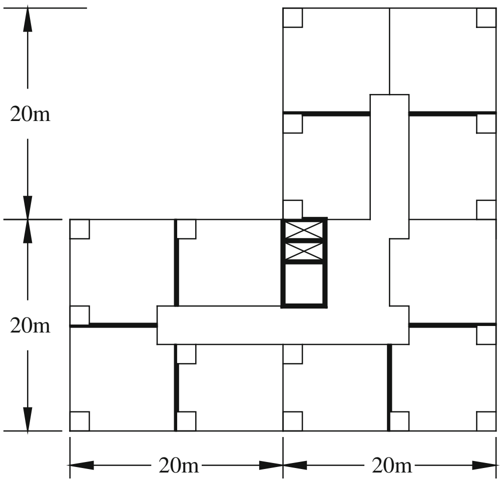
A 10-story commercial office building takes the form of a frame-shear wall-reinforced concrete structure. The plane layout of its standard floor is as shown in Fig. 2.13. Live load on the roof is assumed to be identical with floor live loads. Estimate the vertical uniform load for design.

Solution

1. **The deadweight of floor of a standard floor**

The area of this floor is 20 × 40 + 20 × 20 = 1200 m^2. Thickness of slab is estimated as 10 cm and that of the ceiling plastering and floor pavement is about 3 cm. If the density of concrete is taken as 3000 kg/m^3, then the deadweight of estimate slab of this floor would be estimated as (0.1 + 0.03) × 30 = 3.9 kN/m^2, and total deadweight of this floor would be 1200 × 3.9 = 4680 kN.

Fig. 2.13 Layout of a commercial building



2. **Deadweight of the wall of a standard floor**

The height of this floor is 3 m; the length is about 400 m; and that of the shear wall is 100 m. Assuming that the shear walls have identical density with common walls, then the surface area of wall on this floor is about $3 \times 400 = 1200\ \text{m}^2$ (in this commercial building, the ratio between surface area of the wall and that of the floor is (1); the deadweight per unit surface area (columns included) is estimated as $2.0\ \text{kN/m}^2$; and total deadweight of wall on this floor is $2.0 \times 1200 = 2400$ kN.

3. **Total deadweight of the building**

Total deadweight of the building is the summation of the deadweight of slabs and walls of ten standard floors.

$$10 \times (4680 + 2400) = 70{,}800\ \text{kN}$$

4. Average deadweight of each floor is attained by dividing total deadweight of the building by total surface area.

$$(4680 + 2400)/1200 = 5.9\ \text{kN/m}^2 = 590\ \text{kg/m}^2$$

This estimation is within the range of aforementioned common deadweight of reinforced concrete structure, being between 5 and 9 kN/m^2.

5. The value of vertical load of design is attained by multiplying average deadweight of floor by a dead load factor of 1.2 and then be added with standard live load on that floor multiplied by a live load factor of 1.4. Since it is an office building, standard live load 2 kN/m^2 could be acquired in Table 2.1. Assuming that the live load on the roof is the same with that on the floor, so in global design and calculation of structure the structural design calculation vertical use shall be

$$1.2 \times 5.9 + 1.4 \times 2 = 9.88\ \text{kN/m}^2 \approx 10\ \text{kN/m}^2$$

2.5.2 Wind Load

In non-seismic regions, wind load is the main lateral load. Windward side of the building directly bears the wind pressure while other sides might have wind pressure or wind suction to bear.

1. **Determination of wind load**

The magnitude of wind load that structure has to bear correlates with windward area, speed of wind, air density (varies with height and temperature), configuration, and surface roughness of structure, as well as factors concerning surrounding environment of the structure. In the early stage of design, wind load bore by the structure could be simplified as the sum of standard value of wind load upon windward side and that upon leeward side. Standard value of wind load is related to local basic wind pressure.

Basic wind pressure p_0 and basic wind speed v_0 are directly converted by expression $p_0 = v_0^2/1600$. Basic wind speed v_0 is measured by meteorological administration through specifically stipulated field sampling, in which case data of average annual maximum wind speed are collected from the height of 10 m with duration of 10 min and then deducted with a once-in-fifty-year probability.

Under normal circumstances, basic wind pressure p_0 could be found in the diagram of national basic wind pressure listed under "Load code for the design of building structures" [11]. For instance, in Shanghai area, p_0 is 0.55 kN/m^2; Guangzhou is 0.50 kN/m^2; Beijing is 0.45 kN/m^2, and so on. When it comes to design for high-rise structures, wind load is selected with reference to once-in-a-hundred-year probability. In this case, simplified calculation of wind load shall raise basic wind pressure (once-in-a-hundred-year) by multiplying a factor of 1.10.

In the early stage of design, standard value of wind load could be estimated with basic wind pressure. In the next stage of preliminary design, wind load is calculated according to the load code with careful consideration of specific parameters such as the factors of shape, height variation factor of wind pressure, wind vibration factor, terrain roughness factor. As for structures of significance, wind tunnel testing is needed to simulate actual wind environment so as to accurately determine parameters such as distribution of wind pressure and shape factor. An example is given to demonstrate the estimation of wind load.

2. **Example of wind load estimation**

A 10-story commercial office building located in downtown Shanghai is 30 m high with plane layout displayed in Fig. 2.14. Basic wind pressure of this region is $P_0 = 0.55$ kN/m^2. Estimate the overturning moment M_w and shear force Q_w induced by wind load upon the foundation.

Solution

Assuming that maximum intensity of wind pressure of this region goes from right to left, as shown in Fig. 2.14. The shape coefficients of wind load are given as:

that of the windward side $\mu_1 = 0.8$

that of the leeward side $\mu_2 = -0.5$ (minus sign means suction)

Assuming that the building bears uniform wind pressure p_0

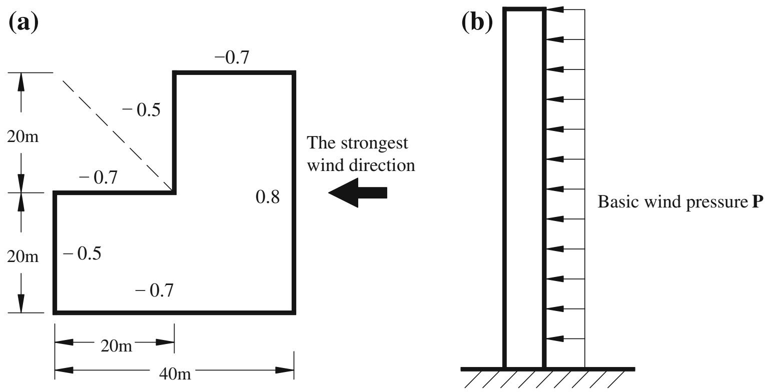


Fig. 2.14 Shape coefficients of wind load and distribution of basic wind pressure, **a** shape coefficients and main direction of wind, **b** distribution of basic wind pressure

Lateral distributed load of wind along the height of structure is

$$p_{\text{wl}} = \mu_s \times p_0 \times 40 = 1.3 \times 0.55 \times 40 = 28.6 \text{ kN/m}$$

Resultant force of wind pressure acts upon vertical centroid of the structure

$$F_w = 30 \times 28.6 = 858 \text{ kN}$$

Shear force on the foundation $Q_w = F_w = 858$ kN
Overturning moment induced by wind load upon the foundation

$$M_w = 858 \times 15 = 12{,}870 \text{ kNm}$$

If the building is higher than 30 m, the influence of height of structure and wind vibration factor upon wind load has to be considered. Vertical distribution of wind load is no more simple uniform no more, but rather like an inverted trapezoid with big end up. As for specific values, please refer to relevant code [11].

3. **Wind tunnel testing**

There has not been a universal calculation equation for shape factor that could be applied to all types of structures and "Load code for the design of building structures" provides only some typical configurations for reference. Therefore, when it comes to particular structures, shape factor of wind load is often determined by wind tunnel testing. Take the Shanghai Pudong International Airport Terminal as an example (Fig. 2.15), the configuration of which embodies a seagull, flying over the sea. Surrounded by giant tilted glass walls, the building sends forth a strong sense of rhythm and stands as a fine example of modern architecture. When it comes to

Fig. 2.15 Shanghai Pudong International Airport

the wing of the structure, it is composed of an arched roof and corresponding truss components. At the turn of each summer, under the action of typhoon from southeastern coastal area, the arched roof generates an enormous amount of airlift force which is possible to lift off the entire roof system. To avoid it, bar system is needed to secure arched roof system. But how would the design of these bars go? And the calculation of wind load? Evidently, available theories could not serve as a solid foundation for the establishment of relevant calculation model for airlift wind load with such complexity. Therefore, specific experiments are needed to determine the state of stress of both the entire structure and the bar system. Specifically, a model of scaled-down seagull-shaped terminal was made and it was tested in a wind tunnel to determine the state of stress of the roof induced by wind load form all directions. Then the test results were used in the design of the entire structure and the bar system.

2.5.3 Seismic Load

1. **General estimation of seismic load**

Seismic load is a dynamic load in nature. Its magnitude correlates with intensity of the seismic event, distance to seismic epicenter, site conditions, quality and natural vibration period of structure, and many other factors; therefore, it is extremely complicated and difficult to precisely anticipate and calculate seismic force, especially when it concerns some potential issues that might arise even more difficulties in the seismic force estimation. Unsynchronized ground motion is one particular concern for large lateral structures such as bridges, which might cause differentiate seismic responses from one end to another. Another issue is epicenter area earthquakes which will induce significant impact loads on structures. All abovementioned issues are still popular research topics.

In the early stage of structural design, since dimensions of components are not decided yet, seismic response could not be accurately calculated and analyzed.

Therefore, simplified calculation is usually applied. In later stages of structural design, when dimensions of components are decided, an accurate computer-program based further analysis of seismic response could be conducted.

Since seismic force inflicted upon structures is proportional to the mass of structures, percentage of seismic force to total mass of the structure G_e is employed in simplified calculation. For instance, in regions with six-degree seismic fortification intensity, seismic force only accounts for 2–5 % of total mass of structure while in regions with seven-degree or higher seismic fortification intensity, seismic force could be up to 10–20 % of total mass of structure. Keep in mind that the seismic load acts upon structures as a lateral load, although a lot less in magnitude than general vertical load, it is still the major reason that causes damage and even failure to structures. In the early stage of schematic design and its relevant calculation, simplified method as followed could be used to estimate seismic force F_{eq}:

In regions with seven-degree seismic fortification intensity

$$F_{\mathrm{eq}} = 0.1G_e \tag{2.1}$$

In regions with eight-degree or higher seismic fortification intensity

$$F_{\mathrm{eq}} = 0.2G_e \tag{2.2}$$

As for the total deadweight of structure G_e, when the structure is simplified as one mass point, it should be taken as 100 % of total deadweight; when the structure is simplified as a series of mass points, G_e should be taken as 85 % of the total deadweight.

As we discussed, structures usually has a lower resistance to later load compare to vertical loads resistance. Therefore, more structure failure is due to seismic loads. In the stage of schematic design for high-rise buildings, vertical movement of the ground could usually be ignored and horizontal seismic force induced by horizontal movement of the ground is the only factor to consider. As for ordinary structures, seismic force is assumed to be vertically distributed as an inverted triangle; mass of each floor is assembled to its centroid and thereby point of application of overall seismic load F_{eq} is determined.

As for long-span or spatial structures, since their vertical stiffness is relatively smaller, vertical vibration often occurs under the action of seismic forces. In this case, vertical resistance to seismic forces needs to be calculated; the method is similar to that of estimation of horizontal seismic forces: 10–20 % of representative value of total gravity load of the structure is taken [as indicated in Eqs. (2.1) and (2.2)] and the only difference is the vertical direction.

2. **Estimation of natural period of vibration**

In the early stage of structural design, to prevent resonance vibration in structures and foundations, dynamic response of structure, in other words fundamental natural period of vibration T_1, needs to be estimated. The approach listed below is simple and convenient to apply but could only be applied to frames or shear walls with rectangular plane layouts, such as reinforced concrete frame-/shear wall structures.

$$T_1 = 0.33 + 0.00069\left(H^2/B^{1/3}\right) \quad (2.3)$$

$$或\ \text{or} \quad T_1 = (0.04 \sim 0.09)N \quad (2.4)$$

In the equation, H refers to the total height of structure, B the total width, and N the number of floors.

3. **Seismic load distribution along height**

In the estimation of lateral seismic effects upon high-rise structures, the mass of each floor could simply be assembled to the elevation of each floor; so it is with seismic force. Equivalent assembled mass consists of total vertical constant load of deadweight of the structure and equipment on each floor along with 50 % of vertical live load.

Seismic load originates from inertial force generated by ground acceleration of mass of structures. The magnitude of acceleration is proportional to the vibration amplitude of the structure. As for structures no higher than 40 m, the distribution of seismic force could be approximately taken as a vertical inverted triangle as shown in Fig. 2.16a. Figure 2.16b shows a diagram explaining the seismic force on each floor. When the structure is higher than 40 m, vertical distribution of amplitude

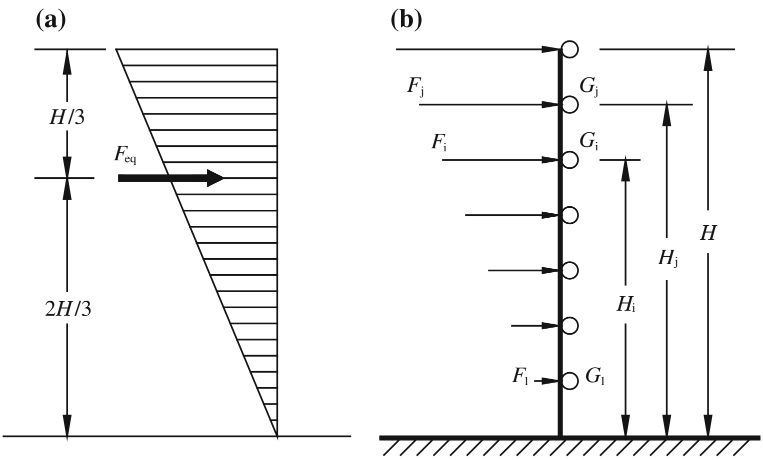


Fig. 2.16 Diagram of distribution of seismic force. **a** Distribution of seismic load, **b** simplified model of calculation

starts to show clear nonlinearity. Nonetheless, in case that height and stiffness between each floor of structure is relatively evenly distributed, distribution of seismic force could also be simplified as a vertical inverted triangle in the early stage of design.

Standard value of seismic force on *i*th floor F_i:

$$F_i = \frac{Gi \cdot Hi}{\sum_{j=1}^{n} Gj \cdot Hj} \quad F_{\mathrm{eq}}(i,j = 1, 2, \ldots, n) \tag{2.5}$$

F_{eq} in Eq. (2.5) refers to total lateral seismic force upon the structure, which could be calculated by Eqs. (2.1) and (2.2) with reference to seismic intensity fortification criteria. In Eq. (2.5), n refers to the total number of floors, G_i is the sum value of constant load and 50 % of live load on *i*th floor; H_i is the height of *i*th floor.

4. **Structural configuration and load effect**

To sum up, configuration of structure is related to lateral load induced by earthquake or wind. Table 2.2 is the comparison between effects of wind and seismic load in accordance with typical configuration of structures [6]. It shows that the overturning moment (2*Ph*/3) induced by wind load of inverted pyramid configuration is as much as two times as it (*Ph*/3) of pyramid configuration. As for overturning moment induced by seismic load, there is 6 times difference between two configurations amounts to six. This is a good example of the significance in configuration selection.

5. **Example of estimation of seismic load**

A 10-story office building, located in Shanghai downtown, is 30 m high and its plane layout is as shown in Fig. 2.13. Seismic fortification intensity in this region is 7°. Please estimate the shear force Q_{eq} and the overturning moment M_{eq} induced by seismic load upon the foundation.

Solution

Height of the building is 30 m; that of each floor is an identical 3 m; and the plane layout is a 40 m × 20 m L-shape. Total estimated weight of the structure is 70,800 kN, in which case 15 % of total weight could be deducted for the structure is a multi-story building. Total horizontal seismic force is calculated by Eq. (2.1):

$$F_{\mathrm{eq}} = 0.1\ G_{\mathrm{eq}} = 0.1 \times 0.85 \times G_e = 0.1 \times 0.85 \times 70{,}800 = 6018\ \mathrm{kN}$$

In accordance with the plane layout of structure, diaphragm is of large stiffness within the plane and therefore could be assumed to be rigid and free of deformation. Thus, mass of the same floor is assembled to a vertical virtual axis that stems from centroid of the structure and the mass of the whole structure is formed along the axis in the form of a string of mass, which is the so-called multi-node model.

Table 2.2 Comparison between effects of wind and seismic load in accordance with typical configuration of structure [6]

		inverted pyramid	inverted prismoid	cuboid	prismoid	pyramid
Effect of wind load	windward surface	inverted triangle	inverted triangle/rectangle	rectangle	rectangle /triangle	triangle
	Distribution of load	concentrated force P arm of force 2h/3	concentrated force P、P arm of force $2h/3$、$h/2$	concentrated force P arm of force $h/2$	concentrated force P、P arm of force $h/2$、$h/3$	concentrated force P arm of force $h/3$
	Bending moment	$M_w=2Ph/3$	$M_w=2Ph/3$、$Ph/2$	$M_w=Ph/2$	$M_w=Ph/2$、$Ph/3$	$M_w=Ph/3$
Effect of seismic load	Distribution of mass	inverted parabolic triangle	inverted triangle	rectangle	triangle	parabolic triangle
	Distribution of load	concentrated force $3P/2$ arm of force $4h/5$	concentrated force $4P/3$ arm of force $3h/4$	concentrated force P arm of force $2h/3$	concentrated force $2P/3$ arm of force $h/2$	concentrated force $P/2$ arm of force $2h/5$
	Bending moment	$M_s=6Ph/5$	$M_s=Ph$	$M_s=2Ph/3$	$M_s=Ph/3$	$M_s=Ph/5$

Evidently, an L-shaped layout inevitably generates eccentricity and corresponding eccentric moment Me between the center of mass and the centroid on the same floor. However, these eccentric seismic force and moment are relatively smaller compare to lateral seismic force and overturning moment and therefore serve as subsidiary factors. In the early stage of design, influence of eccentricity and eccentric moment could be temporarily ignored.

Vertical load on ith floor G_i is calculated as follows:

$$G_i = (5.9 + 0.5 \times 2) \times 1200 = 8280\ \text{kN}$$

Horizontal seismic force F_i, distributed to each floor, could be attained by Eq. (2.5) and is now listed in Table 2.3.

Seismic shear force on the foundation $Q_{\text{eq}} = \sum_{i=1}^{10} F_i = F_{\text{eq}} = 6018\ \text{kN}$

Table 2.3 Horizontal seismic force on each floor

No. of floor i	1	2	3	4	5	6	7	8	9	10
Height of ith floor H_i (m)	3	6	9	12	15	18	21	24	27	30
Seismic force F_i (kN)	109	218	327	436	545	654	763	872	981	1090

Seismic overturning moment on the foundation $M_{\text{eq}} = \sum_{i=1}^{10} F_i H_i = 125{,}895$ kNm

Seismic force is assumed to be distributed as an inverted triangle as shown in Fig. 2.16; in that case, the overturning moment upon the foundation is given as:

$$M_{\text{eq}} = F_{\text{ek}}(2H/3) = 6018 \times 2 \times 30/3 = 120{,}360 \text{ kNm}$$

Compare the overturning moment M_{eq} derived from two approaches, the error rate is:

$$(125{,}895 - 120{,}360)/125{,}895 = 4.4\ \%$$

Since the difference derived from these two methods is within 5 %, both of these two methods can be used in simplified calculation of seismic force in the early stage of design.

2.5.4 Other Loads and Effects

All factors that would generate indirect load effect and result in internal stress and deformation are designated as indirect loads in engineering. Major indirect loads that structures would encounter include temperature effect, differential subsidence, long-term deformation (creep), and stress loss (stress relaxation).

1. **Temperature effect**

As a fundamental physic law, temperature change could induce expansion and contraction upon materials. If such deformation is not restrained, no stress would generate inside the material. However, actual structural deformation is more often than not restrained or confined; therefore, internal stress consequently generates within the structure. For instance, external change of temperature leads to changes of dimension of structure from the outside, while the internal temperature of structure roughly remains the same; as a result, temperature-induced strain and stress would arise within the structure. Furthermore, when it comes to the casting of mass concrete, the interior of concrete would generate huge amounts of heat through the process of hydration; since the swelling of its volume is constrained by cooler external concrete, massive temperature-induced stress or even cracking of concrete would develop as a result. Thermal expansion and contraction of material is an objective existence, which is quite difficult to calculate to an accurate extent. For the moment, to solve this problem, engineers usually rely on special construction design. For instance, the outer frame is designed to be slightly deformable relatively weak columns are installed in the corners while high-stiffness walls and columns are placed in the center. Through connecting a ductile exterior frame with high-stiffness interior frame, temperature-induced internal stress is reduced. Moreover, expansion joints and construction seams are usually needed over a section along the length of structure.

2. **Differential settlement**

Due to the inhomogeneity of foundation soil and the unevenness of vertical loads, when the foundation takes up a relatively large surface area, differential settlement usually occurs; as a result, additional stress would build up in structures. Differential settlement more often than not leads to unfavorable consequences such as failure of components, cracking especially on walls, and more seriously damage to structures. To prevent such occurrences, detailed investigation shall be carried on the soil condition of construction site and sufficient measures such as improved soil consolidation or pile-intensified foundation shall be added to the foundation design.

Another conventional method is to engineer planar partition in accordance with different heights and sections of structure and to install settlement joints so as to disconnect the foundation and enable free settlement between different parts of the structure.

3. **Change of internal stress and strain induced by long-term loads**

Under continuous action of long-term loads, creep develops over time, which is a phenomenal of increased deformation under constant load in materials. Such an occurrence might result in excessive or unexpected deformation. For instance, excessive defection develops in bending members under long-term loads, which might cause trouble for steel crane girder to remain “flat” during service life. As for prestressed structures, both methods of pretensioning and post-tensioning suffer creep-induced loss of prestress, which is a major concern in prestressed structures design.

Solution usually is to estimate potential deformation or creep. In the early stage of construction, to reserve room for deformation or to apply additional prestress could be used to solve prestress loss or excessive deflection problems.

2.6 The Acting Loads and the Structural Deformation Response

When the structure is at normal working condition, loads will results in deformation. Displacement of certain key point of the structure is usually taken as the measure of structural response to loads. Thus, P–δ curve as shown in Fig. 2.17 is also known as load–displacement curve [6], which in essence reflects the state of structure under different loads. Generally speaking, the principle of structural design is to make sure that structures keep working in an elastic state under combination of loads (dead load, live load, wind load, and seismic load). The wind load in this combination refers to potential maximum wind load determined by the load code for the region of construction while the seismic load is determined by regional seismic fortification criterion stipulated in the load code. As shown in Fig. 2.17, the structure, under the action of designed load, shall still have a comparatively large reserve of bearing capacity.

Under the action of vertical dead load, vertical displacement could happen to all locations of the structure. For instance, vertical deflection could happen to floor slabs, primary and secondary beams while vertical displacement could happen to walls and columns. In those cases, vertical displacement is often very small, and the lateral displacement is even smaller. After vertical live load is applied to the structure, due to the same applied direction with vertical constant loads, vertical displacement response of structure shall increase somehow but still maintain within an elastic range.

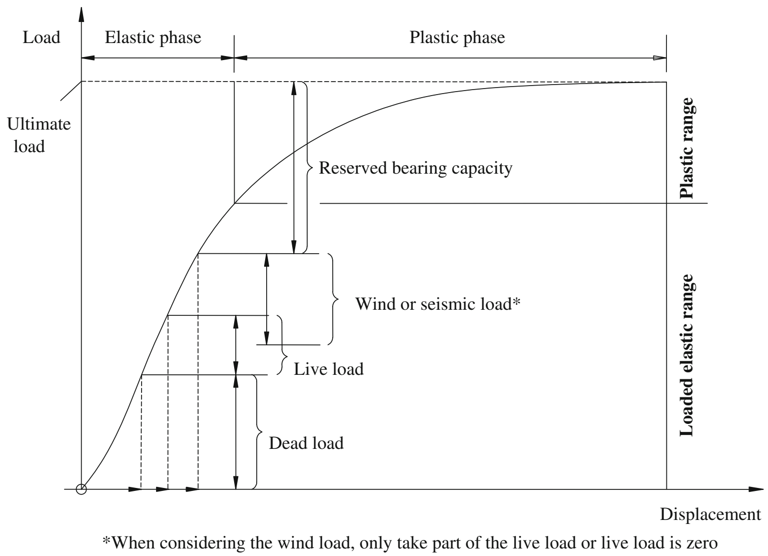


Fig. 2.17 Load–displacement curve of structures [6]

In practice, design value of wind load and that of seismic load shall not be combined, for that the probability of simultaneous occurrence is quite small. Similarly, wind load or seismic load shall not be combined with 100 % vertical live load but with 50 % vertical live load in general. Lateral displacement induced by wind or seismic load is much greater than that generated by dead load and live load. Under the action of wind or seismic load, relatively large lateral displacement could develop and generate significant stresses within the structure, which serves as the major cause of structure failure. Nonetheless, wind or the seismic load is not ever-lasting but short-term dynamic load. Therefore, under the action of load of such kind, allowable stress of material could be raised. For instance, allowable stress of material could be multiplied by a dynamic load coefficient of 1.33 [6].

Structures are required to remain in an elastic state (the upward segment of inclined straight line as shown in Fig. 2.17) under the action of unfavorable load combinations of all kind. Prior to failure, structures still need to go through an elastic–plastic state (the upward segment of the curve as shown in Fig. 2.17). As for most ductile structures, they still need to go through a sheer plastic state, in which case the bearing capacity of structure remains unchanged while displacement displays a rapid development (horizontal segment of the straight line as shown in Fig. 2.17). The area enclosed by the curve and the straight line signifies the energy (work done by external loads) to produce plastic deformation. This energy is stored within the structure in the form of deformation energy and become reserved bearing capacity after the depletion of elastic bearing capacity.

From Fig. 2.17, we could see that with respect to the ultimate displacement of the structure, the displacement induced by dead load, that induced by a combination of dead and live load and that induced by wind or seismic load are relatively small. It indicates that when the structure is made from brittle material and does not have reserved plastic zone after the depletion of elastic performance, the structure will suffer an immediate loss of bearing capacity at the completion of its elastic performance, which is quite dangerous. At moment like this, displacement of structure is relatively small and the structure suffers a sudden failure before it could absorb a large amount of energy, which might lead to a catastrophic loss of personnel and property. Therefore, the energy reserved in plastic deformation is tremendously beneficial and serves as significant safety reserve against sudden collapse.

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