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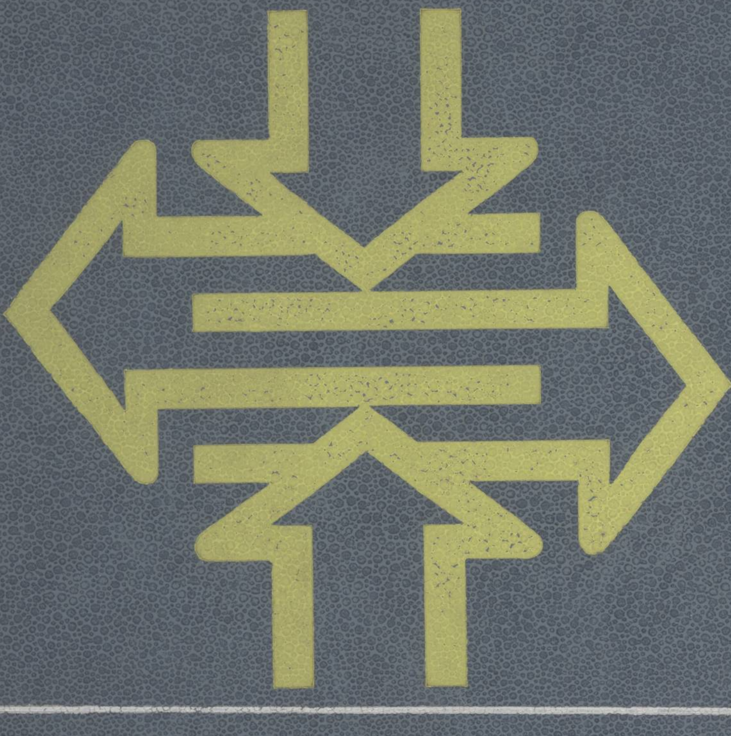

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Strength of Materials

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Основы сопротивления материалов для чертежников-конструкторов

Москва «Машиностроение»

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Strength of Materials

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Chapter One
Basic Concepts

1.1. The Science of Strength of Materials and Brief Notes on Its Historical Development

All structures (such as buildings, bridges, machines, instruments, etc.) are designed so as to satisfy the requirements of strength, rigidity and stability, which is essential for their reliable and safe operation. All structural elements can deform under the action of external forces, i.e. their shape and dimensions can change. In this process, internal elastic forces appear in the elements, which tend to resist the deformation and return particles of a body into their initial positions. The appearance of elastic forces in a body is due to the existence of internal forces of molecular interaction.

The deformation of a body can disappear partially or fully when the external forces causing this deformation are removed. Deformations which disappear upon removal of a force are called elastic and the property of bodies to restore their initial shape on unloading is called elasticity.

Deformations which remain in a body upon unloading are called residual, or plastic, and the property of bodies to retain residual deformations is called plasticity.

Strength is understood as the abilty of a structure or its elements to withstand a specified load without failure.

Strength calculations are aimed at establishing the minimal required dimensions of structural elements which prevent any possibility of failure under the action of specified loads.

Rigidity (or stiffness) is understood as the capability of a body or structure to resist deformation. In rigidity calculations, the dimensions of a structural element are determined so that the changes of the shape and size of the element under the action of working loads were within certain limits and could not disturb normal operation of a structure.

Stability is meant as the capability of a structure to resist the forces which tend to move it from the initial state of equilibrium. Stability calculations should ensure that the elements of a structure will retain the initial (design) form of equilibrium under the action of working loads.

The science that studies the principles and methods of calculation of structural elements for strength, rigidity and stability is called strength of materials. The analytical and experimental methods of strength of materials enable us to choose the kind of material which can be employed rationally in particular structural elements and to select properly the shape and dimensions of cross sections of structural elements to ensure their reliable operation with the least expenditure of the material. The methods of strength of materials are also often resorted to for checking whether the dimensions of a designed structure have been chosen correctly or whether the loads acting on particular structural elements are safe (allowable).

Solutions of problems in strength of materials are based on wide use of mathematics. Mathematical methods, however, cannot always describe properly the phenomena and processes that take place in materials and structural elements under the action of applied loads, especially when the bodies being calculated have an intricate shape. Problems of strength of materials for such bodies are solved by experimental methods: polarization-optical (photo-elastic), radiographic, holographic, extensometric, etc. In some cases, models of a structure or its elements are made and tested in order to obtain data on the pattern and magnitude of deformations, since analytical methods turn out to be inapplicable in these cases.

The course on strength of materials is closely associated with the course on theoretical mechanics. The difference between these courses consists in that theoretical mechanics is based on the general laws of mechanical motion and equilibrium of bodies which are considered to be absolutely rigid, i.e. undeformable, whereas strength of materials takes into account the real properties of materials in structures, in particular, their deformability under the action of external loads.

The methods used in strength of materials are developed and improved continuously.

The first theoretical and experimental studies on the strength of structures which have come to our time were undertaken by Leonardo da Vinci, an Italian scientist, engineer and artist (1452-1519). His works remained unknown for a long time and were interpreted only at the end of the 19th century.

Galileo Galilei, another Italian scientist (1564-1642) is recognized as the founder of the modern theory of strength of materials. In one of his works, dated to 1638, he solved the problem of the bending strength of beams, depending on their dimensions and loads. The statement of the problem and the strength tests of beams, which were carried out by Galileo, gave a strong impulse for development of the science of strength of structures.

M. V. Lomonosov, a prominent Russian scientist (1711-1765), in his treatises on hardness, correlated this concept to the concept of internal forces. He studied experimentally the strength of compressed stands. The theoretical calculation of such stands was made by Leonard Euler, another Russian scientist (1707-1783).

Large contributions to the science of strength were done by French engineers and mathematicians C.L.Navier, A. L. Cauchy, S. D. Poisson, and J. A. Bresse. In 1826, Navier (1785-1836) published a book where the theory of strength of materials was disclosed for the first time and the author made a number of important theoretical conclusions.

It is worth to mention a number of Russian scientists of the 19th century who dealt with problems of strength. Academician M. V. Ostrogradsky (1801-1861) solved some problems in the theory of elasticity. Academician A. V. Gadolin (1828-1892) made extensive studies of the strength of gun barrels. D. I. Zhuravsky, an engineer and bridge constructor (1821-1891) developed a scientifically based laboratory method for determining the properties of various materials and carried out original studies in the theory of bending of beams and bridge trusses. At the end of the last century, important works in the stability of bar structures were done by F.S. Yasinsky (1856-1899).

Complex problems associated with the strength and stability of ship structures were analysed in the works of I. G. Bubnov (1872-1919). Academician A. N. Krylov (1863-1945), known by his works in ship-building, arrived at exceptionally important solutions in the field of engineering calculations of vibrations caused by variable loads. The works of B. G. Galerkin (1871-1945) relate mainly to the analysis of plates and shells. The method of solution of differential equations proposed by him is widely used in the applied theory of elasticity. Some problems of the theory of impact and stability were enlightened in the works of A. N. Dinnik (1876-1950).

Important scientific investigations in strength of materials were done by Soviet scientists A. A. Ilyushin, Yu.N. Rabotnov, S.V. Serensen, E.I. Grigolyuk, V.V. Bolotin, S.D. Ponomarev, A.R. Rzhanitsyn, et al. An appreciable contribution to theoretical and experimental studies in the strength of structures was done by V. I. Feodosyev whose textbook on strength of materials served as a reference book to several generations of Soviet engineers.

1.2. Kinds of Structural Elements and Loads

All structures consist of structural elements which can be reduced to a relatively small number of principal forms: bars, plates, shells, and solid units.

A bar is a body whose size along one of the axes (length) exceeds many times other dimensions (Fig. 1). The geometrical locus of the centres of gravity of all sections of a bar is the bar axis (line *ABCD* in Fig. 1).

Depending on the shape of axis and the cross sections, bars may be straight, curved, with a constant, continuously varying or stepwise varying cross section (Fig. 2). Examples of straight bars are beams and columns and of curved ones, arches and hooks.

Plates and shells can be characterized by a small thickness compared with other dimensions (Fig. 3). Foundation plates and flat bottoms of vessels are examples of plates. Boilers, tanks, reservoirs and aircraft fueselages are examples of shells.

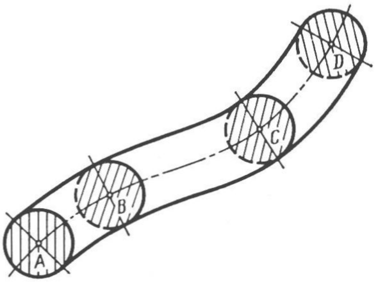

Fig. 1.
Scheme of a bar

A body is called massive if all its dimensions are roughly of the same order (Fig. 4). Examples are foundations of structures, retaining walls, bridge supports (piers), etc. The principal structural element in strength

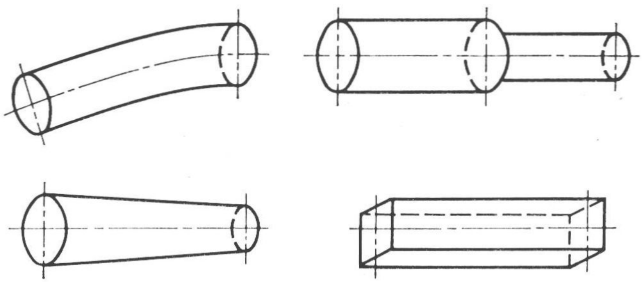

Fig. 2.
Shapes of bars

of materials is a bar which may be called a rod, beam or shaft, depending on the purpose and design.

External forces acting on structural elements are called loads. The external forces which act on a structural element considered include all force actions from the adjacent structural elements of the structure or from any bodies interacting with that structure. Examples of force actions on a structural element are the pressure of

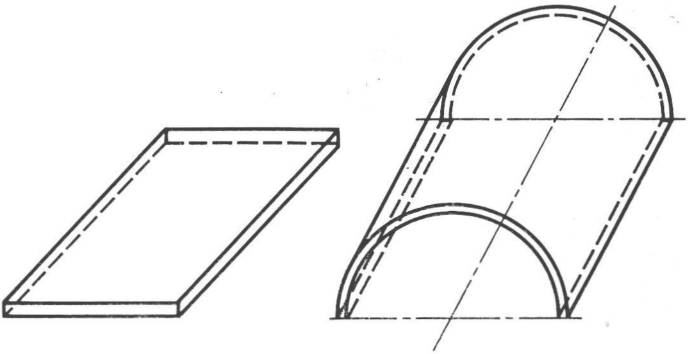

Fig.3.
Schemes of a plate and shell

steam on a piston, the pressure of a liquid on the bottom of a tank. The external forces acting on structural elements also include the weight of the element proper and the reactions of supports (if any).

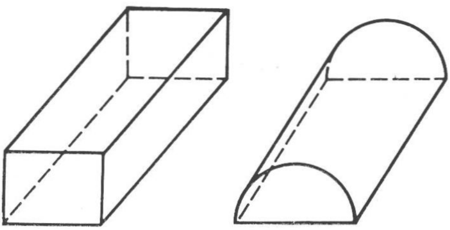

Fig. 4.
Schemes of massive bodies

External forces can be classified by a number of features. Forces which are applied to a body on contact of this body with other bodies are called surface forces (the pressure of wheels on rails, the pressure of water on a dam, etc.). Forces which are distributed over the volume of a body and applied to internal points of the body are called volume forces. Examples are the gravity forces of a structure or its portion, and inertia forces appearing in accelerated motion of a body.

By the method of application, it is distinguished between concentrated and distributed forces. The former are considered to be applied at a point and are vector quantities. Since a force appears due to interaction of bodies and the pressure is transferred from one body to another through the surface of contact which has certain dimensions, concentrated forces are actually non-existent. In cases when the surface of contact is small compared with the dimensions of a body (structural element), the force can be considered to be applied at a point, in particular in the centre of the contact surface. This assumption can substantially simplify calculations. Concentrated forces are measured in newtons. Distributed forces are those which act over a certain relatively large surface of a structure. These loads are measured in pascals (1 Pa = 1 N/m^2). If forces are distributed along the length of a structural element, they are related per unit length. Examples of distributed forces (or loads) are the pressure of water on a dam or the pressure of a gas on the walls of a vessel.

By the pattern of their variation in time, loads can be divided into static and dynamic. By a static action is meant such an action when the load is applied gradually to a structural element and increases from zero to the maximum value and then remains constant or almost constant during a more or less long interval of time. Examples of static loads are centrifugal forces acting on a rotor during acceleration and subsequent uniform rotation. Dynamic loads are characterized by quick variations in time of their magnitude, direction or point of application. An example of such a load is the impact of a hammer in pile driving.

The forces acting on a structure or its elements are mostly determined by calculations, for instance, the pressure of gases in a vessel, gravity forces, or inertia forces.

In some cases, active forces cannot be calculated quite accurately for some or other reasons, say, because of vibration processes involved, and the sole method for determining them is direct measurement.

1.3. The Concept of Design Diagram. Principal Hypotheses and Assumptions in Strength of Materials

The design diagram is a simplified or conditional graphical representation of a structure and the forces acting on it. In the selection of a design diagram, all secondary features and factors which have no effect on the strength of a structure are disregarded.

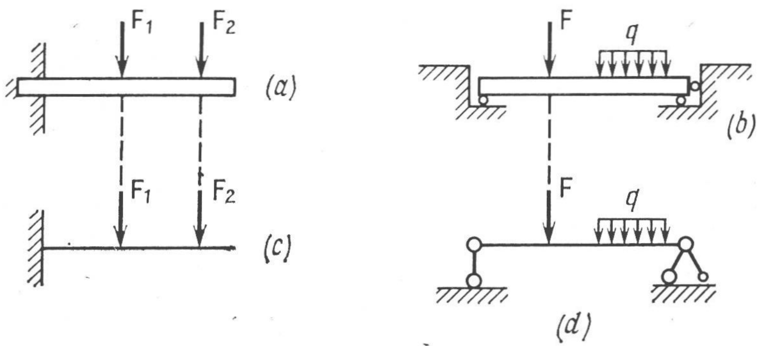

Fig.5.
Loading diagrams and design iagrams

The concept of design diagram can simplify substantially the general calculation methods. For instance, Fig. 5, *a* and *b*, shows two beams with their loads, and Fig. 5, *c* and *d*, the corresponding design diagrams. The design diagram of each beam is given as an axial line with idealized supports. In construction of design diagrams, some deviations from the real conditions of the operation of structures are permissible. For instance, it may be assumed that the load acting on a beam is transmitted to the axis, because of which the point of load application in a design diagram can be determined as shown in Fig. 5, *c* and *d*.

Several design diagrams may be constructed for one and the same structure, depending on what object is to be analysed. On the other hand, several similar structures may have a single design diagram. This makes it possible to obtain solutions for a whole class of engineering problems by studying a single design diagram.

Problems in strength of materials are mostly solved by resorting to certain assumptions and hypotheses on the properties of materials and nature of deformation. These assumptions are such that the conclusions made on their basis agree quite closely with the results of experimental tests. The principal assumptions are as follows.

1. The material of a structure is considered to be homogeneous in structure and continuous at all points of the body. A homogeneous structure implies that any however small particles of a body possess the same properties. Among the materials that are considered homogeneous are metals and alloys, such as steels, aluminium, copper, etc.

2. All bodies are assumed to be absolutely elastic, i.e. their deformations disappear completely upon removal of the load. Actually, this is true only up to a definite value of load.

3. Strength of materials considers all material to be isotropic, i.e. possessing the same properties in all directions. Isotropic materials include metals, concrete, and some plastics. Materials possessing different properties in various directions are called anisotropic. Examples are wood, reinforced plastics, etc.

4. Deformations of elastic bodies under the action of external loads are small compared with the dimensions of bodies, i.e. the dimensions of a body are not changed substantially on elastic deformation. This assumption simplifies substantially the calculations, since it makes it possible to neglect changes in the arrangement of the active forces on deformation.

5. Since deformations considered in strength of materials are small, it can be assumed that external forces act independently from one another, i.e. the deformations and internal forces appearing in elastic bodies do not depend on the order in which the external forces are applied. Besides, it is assumed that the total effect of

the whole system of forces acting on a body is the sum of the effects produced by each force separately.

This assumption is known as the principle of superposition. For instance, for the beam shown in Fig. 6, the

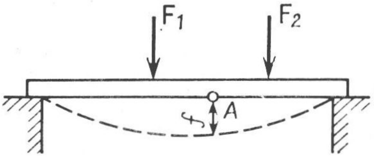

Fig. 6.
A beam loaded by two concentrated forces

deflection at point A under the action of forces F_1 and F_2 is determined as

$$f = f_1 + f_2$$

where f_1 and f_2 are the deflections of the beam at point A due to each force separately.

6. Cross sections of a bar, if they have been plane and normal to the axis before deformation, remain such after deformation.

Chapter Two

Principles of Statics

2.1. Problems and Axioms of Statics. Constraints and Their Reactions

Statics is the part of mechanics that is devoted to the general study of forces acting on material bodies and the conditions of equilibrium of these bodies under the action of forces.

A combination of forces acting simultaneously on a body is called a system of forces. Those systems which produce the same effect on a body are called equivalent.