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Allen, D. E.

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D.E. Allen

This Digest describes the gradual replacement of allowable stress design by limit states design as a basic calculation tool for designing and evaluating civil engineering structures. It also explains the principles and advantages of limit states design.

Background

The successful design of structures goes back to ancient times. For many centuries, structures were designed using common sense, trial and error, and rules of proportion acquired through experience. Their effectiveness depended on the knowledge and skills of master craftsmen.

Industrialization and the mass-production of iron and steel in the nineteenth century led to rapid changes in construction types. This in turn provided an impetus to replace the traditional trial-and-error approach for designing structures, which was slow to adapt to innovations by calculations based on scientific principles. The only scientific tools available at that time for designing structures were Newton's laws of motion and the theory of elasticity. As time went on, these scientific principles were developed into a unified, practical tool for structural calculations called allowable stress design.

In allowable stress design, the adequacy of a structure is checked by calculating the elastic stresses in it due to the maximum expected loads, and comparing them with allowable stresses. The allowable stress is equal to the failure stress of the material divided by a safety factor. Safety factors were first determined by applying allowable stress design methods to successful structures existing at that time. The safety factors for new materials were estimated in comparison with those for traditional materials by taking into account the nature of failure for the new material and its uncertainty or variability. Allowable stress design has formed the basis of structural codes and standards for most of this century.

Limitations of Allowable Stress Design -- Changes in Practice

The allowable stress design method, however, has a number of limitations. These are illustrated by means of an example of a reinforced concrete column under axial force shown in Figure 1. The force in the column is equal to a compression due to the weight of the building plus either a compression or a tension due to the wind load. The column must be designed to resist the total compression, or any net tension if the tension due to wind is greater than the compression due to the weight of the building.

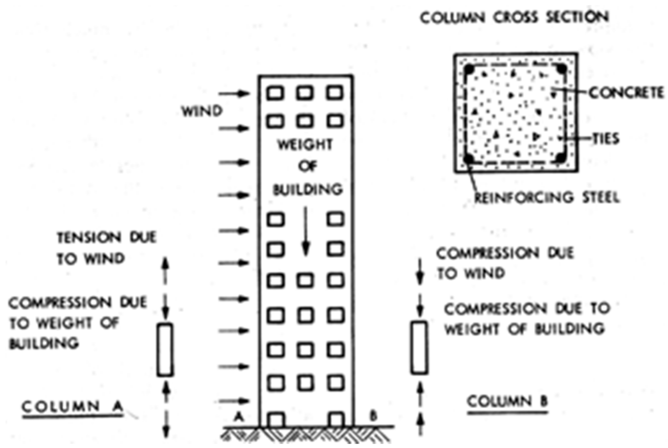

Figure 1. Column forces in a tall building.

Years ago, before much was known about reinforced concrete, the total compression applied to the column was assumed to be carried by elastic stresses in both the concrete and the steel, and the column was designed by comparing these stresses with the allowable values. However, since concrete shrinks after it is cast and creeps under the sustained weight of the building, a large portion of the stress is transferred from the concrete to the steel. Theoretically, then, much more steel must be added to keep the stress below the allowed limit. In practice, however, the yielding of the steel does not cause failure, and the load-bearing capacity of the column is determined simply by adding the crushing strength of the concrete portion to the yield strength of the steel. This, then, is an example in which allowable stress design results in considerable overdesign.

In the case of net tension or uplift, allowable stress design requires that the anchorage steel connecting the column to the foundation be designed to resist the difference between the tension due to wind and the compression due to the weight of the building. The safety factor is therefore applied to this difference. If this difference is small, then a wind load only slightly greater than predicted will cause failure. The risk of failure is therefore high. Thus, there are also instances in which allowable stress design is not safe enough.

Because of limitations such as these, several changes have taken place in design standards over the years. First of all, formulas for calculating stresses based on member strength rather than stress analysis were introduced into standards. Secondly, special rules were established to provide adequate safety for anchorage against wind uplift and overturning. Thirdly, to economize on material, allowable stress design was replaced by methods based on strength theory for specific types of construction and applications. Finally, as structures became lighter and thinner, new serviceability requirements for deflection, cracking and vibration were introduced. All these modifications have resulted in deviations from the unified basis provided by the allowable stress design method for the design of civil engineering structures.

Still other changes are taking place. There is a growing variety of construction types, especially of composite structures made with two or more basic structural materials. In addition, structures are being used for a greater number of purposes and under a wider range of environmental conditions than before. These changes have engendered an exponential growth of structural codes and standards containing a multitude of criteria. The need for a unified basis for design is therefore even greater now than it was in the past. Limit states design has been introduced to satisfy this need.

Limit States Design

All structures have two basic requirements in common: safety from collapse and satisfactory performance of the structure for its intended use. The limit states define the various ways in which a structure fails to satisfy these basic requirements. Ultimate limit states relate to safety and correspond to strength, stability and very large deformation. Serviceability limit states relate to satisfactory performance and correspond to excessive deflection, vibration and local deformation.

Limit states design refers to the calculations made by the designer to ensure that these failures do not occur. The steps involved in checking a structure or its components for any limit state are shown in Figure 2.

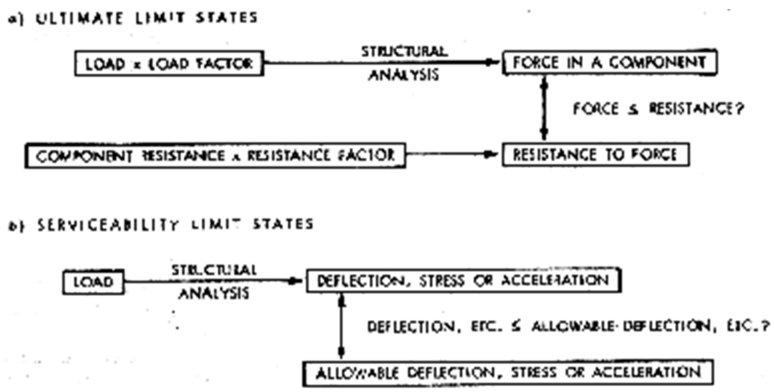

Figure 2. Limit states design method.

In Figure 2 the loads are defined as the dead weight, wind, snow, temperature change, etc., which are expected to act on a structure during its projected life. They are generally specified in codes. Loads generally tend to cause failure, but sometimes they resist failure as in the case of dead weight holding a structure in place during a windstorm.

For the ultimate limit states, the loads are multiplied by load factors which take into account the probability of deviations of the load from the value specified in the code. For example, dead weight is more predictable than wind or snow load so its load factor is closer to 1.0. When a load is combined with other loads, its load factor is decreased by means of a load combination factor to take into account the reduced probability of different loads acting simultaneously. Finally, the load factor may be adjusted by an importance factor to increase the safety of the structure when the consequences of failure are very severe and to decrease it when they are not. Nuclear containment structures, for example, are designed for much greater safety than storage sheds.

All load factors for the serviceability limits states are made equal to 1.0 since these limit states relate to performance under normal use.

Once the loads are factored, the designer then calculates forces or deformations within the structure. These calculations are based on a theory of structural behaviour which appropriately reflects the behaviour of the structure as the limit state is approached. For example, simple elastic theory, which takes into account shrinkage and creep, is appropriate for most structures for the serviceability limit states, whereas simple strength or stability theories are appropriate for most structures for the ultimate limit states.

In the case of the ultimate limit states, the component forces obtained are then compared (Figure 2) with calculated component resistances. These resistances are determined by analyzing the strength of the component as a function of the material properties and dimensions specified in the design. A component may be a member, a connection or a material component in a composite structure, or it may be a mode of failure such as shear or compression. Resistance factors are applied to the component resistances and take into account the variability of material properties and dimensions, workmanship, type of failure, and uncertainty in the strength analysis. For example, the yielding of steel is more gradual and more predictable than the crushing of concrete; therefore, its resistance factor is closer to 1.0. The resistance factor may be further adjusted for certain members to take into account the importance of these members or the greater uncertainties involved in their application. Foundation piles, for example, are associated with greater uncertainties in application than columns in buildings.

In the case of the serviceability limit states, a deflection, stress or acceleration due to the loads is compared (Figure 2) with an allowable deflection, stress or acceleration. The latter are based on user acceptability and specific requirements such as for the operation of equipment.

In order to unify future structural codes and standards and to minimize their number and size, it is planned to adopt the following principle. The loads, load factors and main serviceability requirements depend only on the use of the structure and will therefore be given in the use codes (National Building Code, CSA Standards for bridges, towers, etc.). The resistances, resistance factors and structural theory depend only on the material and type of structure and will therefore be contained in the material design standards (CSA Standards for concrete, steel, etc.).

Reliability

The load and resistance factors in the codes and standards are chosen to ensure a level of reliability (safety) consistent with the consequences of failure for a broad range of loads and materials. Methods for doing this are given in Reference (1). Instead of adopting the load and resistance factors stipulated in the codes, the designer may in some cases calculate the safety factor for an appropriate level of risk. This approach has recently been introduced in the evaluation of existing bridges, where a more precise estimate of strength and reliability is required as a result of the substantial increase in truck loads.

The reliability of structures in service, however, depends not only on design safety factors but also on quality assurance procedures to counteract human error in the design, construction and use of the structure (2). Human error in structural design is most effectively counteracted by an adequate consideration of the way in which a structure behaves and the loads and influences it may be required to withstand (3).

Advantages of Limit States Design

1. The limit states provide a checklist of the basic structural requirements for which design calculations may be required.
2. Limit states design, by providing consistent safety and serviceability, ensures an economical use of materials and a wide range of applications.
3. Limit states design provides both a basic calculation tool for designing and evaluating civil engineering structures and a means for unifying structural codes and standards.

References

1. Guidelines for the Development of Limit States Design. Canadian Standards Association Special Publication CSA S408, Rexdale, Ontario, 1981.
2. Allen. D. E. Structural Safety. Division of Building Research, National Research Council of Canada (**CBD 147**), Ottawa, 1972.
3. Gordon, J. E. Structures (or Why Things Don't Fall Down), Penguin Books, New York, N.Y., 1978.