II

Structural Safety and Catastrophic Events

Sécurité et accidents des constructions

Bauwerksicherheit und -schäden

F.K. LIGTENBERG
Director of Institute TNO
for Building Materials and Building Structures
Delft, Holland

1. INTRODUCTION

In modern theories of structural safety it is customary to assign a certain "probability of failure" (P_f) to a structure. This P_f can be derived from the probability distribution of the strength and the probability distribution of the loads. Failure is thought to occur if the loads exceed the strength.

The intention is, to choose P_f so small, that an economic optimum is reached, where the sum of building costs, maintenance and risk (possibly also remainder value after the end of the fixed lifetime) is made as small as possible.

Many authors have studied the possibilities of assigning a certain value to P_f if the variations of loads and strength are known [1]. Practical application is still difficult, because there is not sufficient knowledge of the probability of extreme loads and extreme material properties. Nevertheless it seems probable that the results of this theory are not completely realistic, because in the theory it is assumed that the structure as a whole - although with an unfavorable combination of material properties - must be able to sustain the normal types of loads (like floor loads and wind), without being damaged appreciably, not even when the loads have an exceptional magnitude. Very little attention has been paid to what happens to a structure that has been damaged locally by an overload or materials defect. For complicated structures, comprising many structural elements this is not satisfactory. Furthermore the theory as usually applied does not allow for abnormal types of load, differing considerably from the standard loads given in the building codes (like explosions, collisions and fire) and of abnormal material properties caused by building errors, chemical attack or fire.

In this paper the author will try to point out some factors that in reality have a great influence on the probability of failure of a structure. For this end he will use on one hand simple statistical considerations, and on the other hand data obtained from building failures.

2. ELEMENTARY STATISTICAL CONSIDERATIONS

For a simple structural element the difference between the strength of the critical cross section and the load can be calculated. This is compared with some quantity (like the standard deviation) that represents the scatter in this difference. The probability that failure will occur depends from the type of frequency distribution and from the ratio between difference and standard deviation.

If the strength of a structure is obtained by addition of the strength of a number of cross sections (like e.g. a statically indermin-ate beam or a rigid block supported on a great number of piles) the scatter in the strength is smaller than that of the individual cross sections. It is not reasonable therefore to calculate statically indeterminate structures with the same "factor of safety" as statically determinate structures.

On the other hand many structures contain a number of elements that are linked in a series, like the links of a chain, the consecutive elements of the cable of a suspension bridge, or the columns that are situated one above the other in a high building.

It is obvious that the chain is no stronger than the weakest link. If mean $\bar{x}_1$ and standard deviation σ_1 of the strength of a single element are known, the mathematical mean and standard deviation of the weakest of a series of n elements can be calculated approximately [2]. In fig. 1 the necessary parameters r_n and S_n are given. The weakest element of a series of n elements has a mean strength $\bar{x}_n = \bar{x}_1 - r_n\sigma_1$ with a standard deviation $\sigma_n = S_n\sigma_1$.

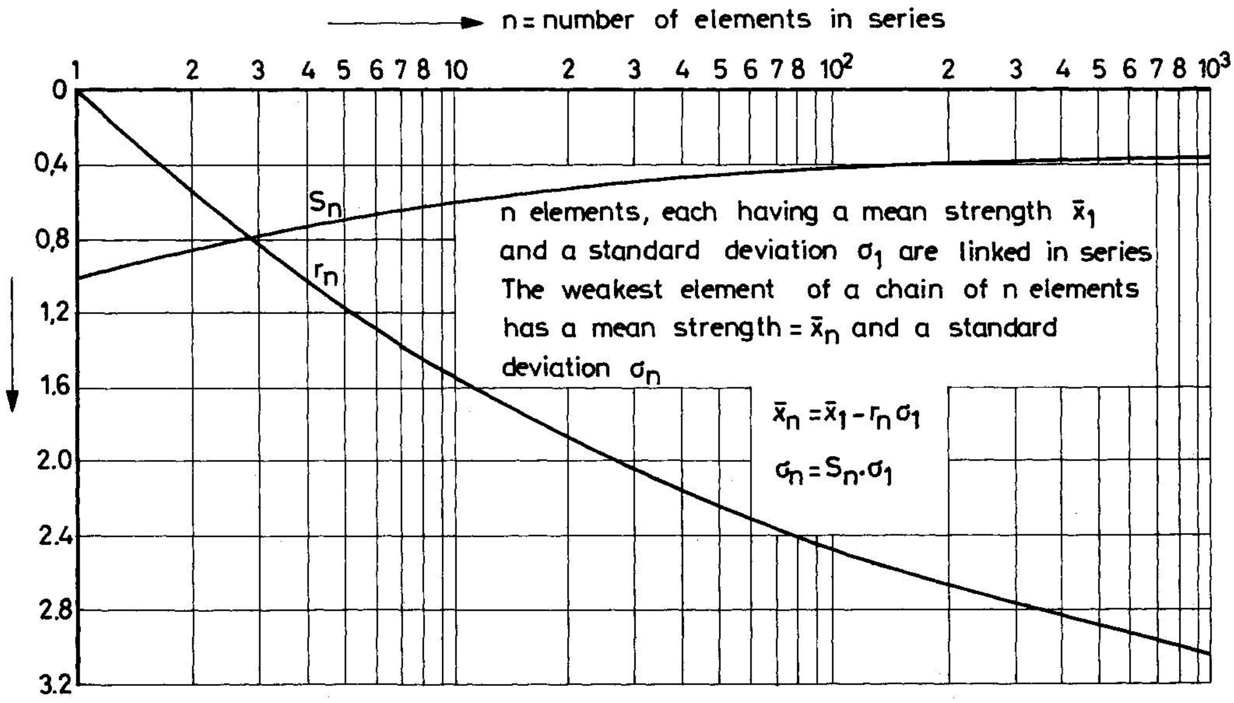

fig. 1 The strength of the weakest link of a chain of n elements

The mean strength of a series of elements is therefore smaller than that of a single element. A greater value of the coefficient of safety will be needed in such cases. This is true especially in cases where the scatter in the loads is relatively great. In cases where the loads are known rather accurately the effect is mildered by the fact that the standard deviation σ_n for the series is smaller than σ_1 for the single element.

The same sort of phenomenon occurs in greater structures. It seems appropriate to consider a greater structure as an assembly of a great number of structural elements. Each of these has to fulfill certain specifications in respect to safety.

Let the greater structure consist of n elements. Each element has a (small) probability of failure = p_1. This does not fix the probability of failure of the whole structure. In the worst case each individual element will by collapsing bring about a total destruction of the whole structure. This is the case for example in a completely statically determinate structure. In this extreme case the probability of failure of the whole structure will be approximately $p_n = np_1$. If p_n must have an acceptable low value, $p_1 = \frac{p_n}{n}$ must be extremely small.

A much more normal situation will be, that only a smaller number of elements (n_2) will bring about a complete failure by failing individually, whereas the other $n - n_2$ elements cause only local damage that can be repaired.

In such a case p_n may be set equal to $p_n = n_2p_2$ (p_2 is the probability of failure of the critical elements). For similar reasons as before $p_2 = \frac{p_n}{n_2}$ will have to be considerably lower than p_n.

The designer has to know what elements are critical, so that he can make these elements sufficiently safe. The safety requirements for the other elements that can cause only local damage may be less stringent.

If there are 100 critical elements in a greater structure, and if $p_1 = p_n = 10^{-3}$, then p_2 will have to be $p_2 = 10^{-5}$. For the normal elements this means that the difference between strength and expected loads has to be equal to 3.1 x the standard deviation, for the critical elements this difference becomes 4.2 x the standard deviation.

Calculations make it seem simple to do this. If the loads and the strength both have a standard deviation of 10 %, the mean strength of the normal elements has to be 1.58 x the mean value of the expected loads caused by the most unfavorable load combination, and the strength of the critical elements must be designed with a factor of safety = 1.90 in order to have $p_2 = 10^{-5}$.

In reality this is nonsense. For not too small levels of probability (order of magnitude 10^{-3}) it is completely reasonable to consider loads and strength as quantities that may vary in magnitude, but retain more or less the same character. If however one has to look for smaller probabilities, the probability of occurrence of completely other types of load (like those brought about by explosions, collisions, inundations, earthquakes, etc.) becomes sufficiently great to make it necessary that these too are considered. The same is true for the strength, where far more abnormal situations (fire, chemical attack, etc.) come within the range of possibilities.

This seems to indicate that it is not sufficient to increase the conventional coefficient of security in order to diminish the probability of failure of a certain structural part below a certain - normal - limit. If this is necessary at least some qualitative insight in the causes of structural damage is needed, as well as some idea of the frequency of occurrence in practice.

3. STATISTICAL DATA ON STRUCTURAL DAMAGE

In the daily papers mention is made regularly of occurrencies where structural damage has been involved. Dependable statistical data are not available. The "news-value" is rather independent of the extent of the damage, so that for a structural engineer the selection by the daily papers seems completely haphazard. Due to the fact that in many cases conflicts arise between several parties on questions of who is responsible for the damage etc., it is not easy to publish freely about specific cases where details are known on causes and extent of structural damage.

This makes necessarily the following statistics a rough estimate. Nevertheless the facts are remarkable enough.

For 1967 the following causes for structural damage in the Netherlands can be enumerated (where in all there are about 3.000.000 houses, flats and other buildings):

15000 fires, known at the fire brigade offices (in 1500 of these fires flameover occurred in at least one room).

200 individual cases, where wind loads caused rather severe structural damage (i.e. more severe than fallen chimneys and roof tiles). Among these was a whirlwind which caused considerable damage to many houses, several roofs were torn of apartment buildings etc., a sport hall was blown over etc.).

200 explosions caused structural damage. Part of them occurred outside buildings (ship carrying ammunition, oil refinery, tank transport vehicle), another part occurred in the buildings themselves (gas explosions of natural gas, sewer gas, acetylene cylinder, gasoline, chemical experiments, detonating gas in an industrial accident, etc.).

100 collisions (ship against bridge, truck against bridge, car or tram against building, building crane falling down on building, airplane against guying of television mast, etc.).

50 total or partial collapses under almost normal circumstances, due to materials defects and/or faulty design.

20 total or partial collapses caused by local overloading (among these a complete roof of an industrial building coming down as the result of an extremely high loading by iron dust on a very small part of the roof.

The total damage may be estimated at H fl. 400.000.000,- (this is about 1/2 % of the national income, and 5 % of the total budget of the whole building industry in the Netherlands). Moreover about 100 people were killed in the accidents described. Roughly one half of the damage was caused by fire.

Another important aspect is that in many cases the indirect damage (e.g. caused by the loss of a vital part of an industrial process) or the injuries to people and the loss of goods that were in the damaged building have caused far greater losses than the structural damage in the building itself.

As far as can be seen this year is not exceptional. In 1968 there was somewhat less damage caused by wind. In the beginning of 1969 some 10 collapses due to snow loads occurred, which had not been present in the previous years.

All this happened without earthquakes, civil war, sabotage, flood disasters, hurricanes and other disasters striking a large area entering the picture.

If it is assumed that only in the case flameover occurs fire causes structural damage, in one year more than 2.000 buildings are damaged in one way or another. This means that from the 3.000.000 buildings in the Netherlands some 100.000 (3 %) will be damaged during their lifetime.

In structural calculations the coefficients of security normally adopted would lead to expect a very low probability of failure (order of magnitude 10^{-4} or 10^{-5}) due to "normal" causes. The designer ought to be more conscious of the adverse possibilities of loading by fire, explosions, collisions, etc. This may be expected to have a relatively great influence on the real safety of structures. Only if this is done, advantage can be reached by using refined calculating methods and quality control.

In the next chapter some more details will help to visualize the risks that a structure runs.

4. CAUSES OF BUILDING FAILURES

There can be discerned three main causes for structural damage:

1. fire,
2. brute violence (explosions, collisions, some cases of wind damage, inundations, earthquakes, sabotage, war actions),
3. an unfortunate combination of material, structural and loads.

Most of the somewhat spectacular failures can be found in the first two categories. In many cases a minute accident triggered off a sequence of events, leading to substantial damage and loss of human lives. Mostly a great total damage occurs when a relatively great part of a building is damaged. Sometimes however even a failure of a minor structural part (e.g. a sewer pipe) can cause considerable damage in the industrial sector.

By fire great losses occur if the room where the fire starts has great dimensions, if the contents are very costly or if the fire can spread later on to adjacent rooms or buildings.

The risk that during the lifetime of a building flameover will occur in one of its rooms may be estimated at 2 %. This makes it obviously a sensible thing to take precautions for diminishing the risk of spread of fire to adjacent rooms. Very large individual rooms should be avoided wherever possible.

Brute violence causes some damage to about 1/2 % of all buildings. Most building codes do not take explicit precautions against this sort of calamities - nor do more advanced ideas on structural design current in the technical litterature. There is no reason to believe that this risk is automatically covered by the conventional coefficient of security.

In normal circumstances quite a lot of communication is needed between the several people concerned with the design and the erection of a building. Even in the design phase no one concerned can effectively supervise all the different viewpoints (economic, heating and ventilation, structural, aesthetic, etc.).

The designer has in mind a definite purpose. Even during erection unexpected circumstances may arise. During the long life of a structure changes in use, additions and internal reorganization may alter the circumstances of several structural parts considerably. It is not to be wondered that in some cases by an unhappy coincidence of structural design, execution and loads part of a structure fails.

This again is an argument, which makes it clear, that in a good design the possibility of a local failure ought to be considered.

5. RISK CONSCIOUSNESS

Especially in cases where a failure may endanger the lives of many people (high apartment building) or where great industrial damage may be caused, it is urgent that methods are developed to make the design "fail-safe".

In aeroplane industry this is commonplace, in shipbuilding watertight compartments have since long been completely normal. Why has it taken such a long time, before the need for "risk consciousness" for the structural engineer became apparent?

Obviously one of the main causes is that for small structures there is not much difference between the extra margin of safety that is obtained by a coefficient of security and by some form of risk consciousness. At this moment however a magnification in scale causes more, bigger and more complicated structures to be built than ever before. In such cases the risk of a complete failure induced by a local failure cannot be covered by the use of a coefficient. The type of design is the only factor that can help without exceptionally high costs.

Necessarily some money will be needed to make a structure so that a local failure cannot cause severe damage to a greater part of the structure. The certainty that a local failure will only cause local damage will make it possible however to choose a higher probability of failure (i.e. a smaller coefficient of safety) for the design of the individual structural elements. This may offset the greater part of the extra costs of the main structure.

In all cases one ought to seek for a solution which makes the sum of building costs, exploitation and risk as small as possible. In a greater object the risk becomes more prominent. As an example a total failure of a normal one family house will cause a damage of say H fl. 100.000,- and there is a reasonable chance that no human lives will be lost in such a failure. If however by a similar cause a high apartment building containing 100 flats collapses, the damage is 100 times as great and there is a reasonable probability that some hundred people will be killed. Moreover the odds that some clumsiness of one of the people living in the building causes the initial calamity is equally great as in 100 one family houses.

This makes it clear that the greater and more complicated buildings and structures that are becoming more and more common now must have some capacity of sustaining completely unexpected loads and local failures. Very accurate calculations seem out of place, but it ought to be investigated at least intuitively and with some rough calculations what can happen in exceptional circumstances.

During the last war prof. J.F. Baker used similar considerations for reinforcing the roof trusses of factory halls. He wished to avoid that a small bomb that e.g. blew away one of the columns would cause the roof to come down completely. In order to increase the risk consciousness of the structural engineers it seems useful to include in building codes and similar documents a sentence like "The structure shall be designed in such a way, that local damage cannot induce disproportionately great damage in the structure as a whole or cause disproportionately great effects on the function of the structure". Such a sentence has effect only if building authorities act upon it.

6. SCIENTIFIC EVALUATION OF RISK

By now the behaviour of most structures under deterministic circumstances is known well enough to enable a specialist to calculate the real behaviour under loads in considerable detail. In many cases it will be possible to calculate the behaviour of a given structure under a given sequence of loads. At the end of this sequence the final state can be described by a number of parameters fixing e.g. the deflections, the crack widths, etc. in a number of typical points. The necessary calculations can be made very rapidly using a computer.

There is a method, called "Monte Carlo method" or "simulation". This means that a rather great number of possible structures is chosen (taking into account the known frequency distributions of material properties, dimensions, etc.). In the same way for each of them a certain sequence of loads occurring during the "lifetime" can be chosen. Some of these loads have exceptional magnitudes - like those due to removal of furniture - others have an abnormal character - like fire, which occurs in varying severity in about 2 % of the cases -. With a computer all the typical parameters of the structural behaviour at the end of the load sequence chosen for that structure are calculated.

The situation of some tens of thousands more or less similar structures under more or less similar conditions can be determined in this way. The data can be evaluated statistically in the same manner as experimental data, and give - within the range of our knowledge of loads and material properties - a realistic estimate of the risk that the structure will become unservicable.

It is obvious that for a complicated structure this type of analysis will be difficult, because so many assumptions have to be made on scatter and frequency distributions of loads, material properties and dimensions.

Even for a rather simple structural part however this type of analysis may lead to unexpected results that can serve as a guide for future work. As an example it would be extremely interesting to investigate in this way the behaviour of a simple reinforced concrete slab. The cover, the quantity and quality of the reinforcement bars, their diameter, the concrete quality and the slab thickness may be taken as design parameters. It seems certainly possible, that this may lead to the conclusion that several normal design procedures are unrealistic (like multiplying body weight and external loads with the same load factor, determining the amount of steel of different qualities from the yield moment at normal temperature and determining the cover from tests in pure bending where the crack width is observed).

It is hoped that this type of analysis will lead in future to methods of structural analysis, where as well the scatter in loads and structural properties as the influence of abnormal loading like fire and structural defects are treated in an orderly way.

7. CONCLUSIONS

Abnormal types of load like fire and brute violence occur too frequently to be neglected in structural design. If these are considered in an adequate manner the real safety of structures can be improved materially. This is especially so for greater structures built from a great number of structural elements.

The probability that in such a building one of the elements is loaded far heavier than normal is so great, that it must be explicitly avoided that any such element causes a complete disaster in failing. This can be ensured by providing alternative paths of load if one element fails. Critical elements must be located and special precautions must be taken to insure their safety.

In most cases rough calculations and qualitative insight will suffice. The more refined modern building codes (like e.g. the CEB regulations) build up a coefficient of security from a great number of separate factors. As a kind of check list on all the influences this procedure may be useful. From a statistical point of view multiplication of a number of these factors is nonsense. Moreover the great numerical accuracy achieved in that way leads to the neglecting of more important aspects of safety.

Good statistical data on exceptional loads and on building failures are not available. For the time being a more realistic approach must therefore make use of extremely rough estimates. Some increase of knowledge in this area will lead to much more increase of structural safety and economy than most of the structural research going on in laboratories all over the world now (including my own!).

[1] See e.g. The analysis of structural safety. Final report of the Task Committee on factors of safety ASCE by A.M. Freudenthal, J.M. Garrelts and M. Shinozuka. Journal of the Structural Division Proc. ASCE, Febr. 1966 (page 4682 etc.) and J. Ferry Borges & M. Castanheta "Structural Safety", LNEC Lisbon, 1968.

[2] Van Douwen, Kuipers and Loof "Correcties op gemiddelde waarde en standaardafwijking bij proevenseries met symmetrische proefstukken" (in Dutch).
Report Oe 5, Stevin Laboratory Technical University Delft (May '58).

SUMMARY

In greater structures there is a difference between failure of a structural part and failure of the structure as a whole. A part can fail by overloading and materials defects but also by fire or brute violence. Statistical data show that this happens during the lifetime of 3 % of the buildings in the Netherlands. A good structure has to be "fail-safe" as well as sufficiently strong in the normal situation. Critical elements must be located.

RESUME

Pour les constructions d'une certaine importance, il y a lieu de distinguer entre la défaillance d'un membre et l'écroulement de la structure entière. La rupture d'un membre peut être occasionnée par des surcharges excessives et par des défauts de matériaux, mais aussi par le feu ou la violence. Les statistiques montrent que 3 % des bâtiments en Hollande subissent un dommage pendant leur durée de service. Une structure bien faite ne doit pas s'écrouler, même en cas d'avarie à l'un de ses éléments. Les parties critiques de la structure doivent être localisées.

ZUSAMMENFASSUNG

In grösseren Bauwerken muss man zwischen dem Bruch eines Gliedes und dem Zusammenbruch des Ganzen unterscheiden. Ein Teil kann sowohl durch Ueberbelastung und Materialmängel als auch durch Feuer und rohe Gewalt versagen. Die Statistiken weisen aus, dass in Holland 3 v.H. Gebäuden innerhalb der Lebensdauer Schaden erleiden. Eine zweckmässige Konstruktion muss bruchsicher und im Regelfall hinreichend tragfähig sein. Die kritischen Teile müssen lokalisiert werden.