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Allen, D. E.

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Structural Safety

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D. E. Allen

Please note

A basic requirement of any civil engineering structure is that it does not collapse, causing death, injury or economic loss. It is a requirement that cannot he made absolute. Structures have collapsed, and even with improved technology they will continue to do so. This Digest will consider the risks involved, the main reasons for structural collapse, and how risks are taken into account by structural engineers in design. Finally, as an aid to designers and builders, the Digest will include a list of specially vulnerable situations that have caused most structural collapses in Canada.

Risks

There is everpresent risk of death or injury from structural collapse, but it is not as great as that from building fires, automobile travel or cigarette smoking. Table I compares existing death rates per year for a "typical" Canadian. The individual can reduce most risks by resorting to various defence mechanisms, for example. by avoiding cigarette smoking or swimming more carefully. His control over structural collapse, however, is very limited and the risk of death per year should be kept very low, say no more than about one in a million. Although risk of death from structural collapse in Canada is generally very low once a structure has been completed, the risk is high during construction and many construction workers have been killed or injured during this period. (Table I).

Table I. Risk of Death Various Activities

Activity or danger	Deaths per Million People per Hour of Exposure	Hours of Exposure per Year for a "Typical" Individual	Risk per Year per cent
Automobile Travel (International	1.04	340	0.036

Figures)			
Swimming	3.50	20	0.007
Cigarette Smoking	2.60	200	0.052
Building fires			0.003
Structural collapse (1) Construction workers (Ontario)			0.003
(2) All others (Canada)			0.00002
Total (1) For smoking construction worker			0.101
(2) For non-smoking office worker			0.046

Newspaper clippings record far more structural collapses in Canada than there are deaths from these causes: three deaths per year, excluding those of construction workers, compared with more than 50 collapses. One reason for this difference is the fail-safe nature of design, where total collapse is prevented or sufficient warning is given for escape.

Structural Failures and Causes

Most notable structural collapses in the world have occurred under catastrophic conditions such as major earthquakes, floods, hurricanes and tornadoes. Less notable because they occur sporadically are collapses during construction, under heavy snow loads, during thunderstorms, or, more often, as a result of faulty design or manufacture. The major causes of collapses include the following:

Excessive loads during catastrophic events

At one time it was thought that nothing could be done to prevent the catastrophic effects of large earthquakes, hurricanes, tornadoes or floods, and they were generally regarded as acts of God. It is now recognized that deaths or injuries resulting from catastrophic events can be reduced drastically by proper design and construction. A fairly severe earthquake in Iran killed about 10,000 people mainly because buildings were of adobe construction, the worst type from the point of view of earthquake resistance. A similar earthquake in Los Angeles killed 60 people, most of whom were inside old buildings not designed to resist earthquakes.

Even with proper design, a really severe overload or unusual load such as an explosion or crashing aeroplane will undoubtedly kill or injure some people. Nevertheless, this risk can be kept small in comparison with other risks that are faced every day (Table I).

Insufficient Knowledge

In the past, many failures have been the result of inadequate technical knowledge. Insufficient knowledge of the strength of latticed columns contributed to the collapse of the Quebec bridge. Insufficient knowledge of aerodynamic instability led to the collapse of the Tacoma Narrows suspension bridge. Other examples occur in the areas of fatigue and brittle fracture, for example the failure of Liberty ships during World War II.

In a few cases misleading code rules have been partly to blame. The collapse of the Ferrybridge cooling towers in England during high winds was largely attributed to strict application of allowable stress design, which does not provide sufficient safety in cases of stress reversal, for example, where wind load tension overcomes dead load compression.

Errors in design or manufacture

As technical knowledge improves, errors are becoming by far the major cause of known structural collapses, particularly in technologically advanced countries like Canada. An error in this context is a gross error or mistake, not a minor calculation error or construction deviation. These errors are made by individuals - by designers, manufacturers, builders or authorities responsible for checking a design or inspecting a construction. In most cases not one but a number of errors have contributed to collapse, and usually more than one person has some responsibility since checking and communication are necessary features of design and construction. Notable examples of structural collapses attributed to errors include the collapse of the Heron Road Bridge, Ottawa, in 1966, the Second Narrows Bridge, Vancouver, in 1958, the Quebec Bridge, in both 1907 and 1916, and the Union Carbide Building, Toronto, in 1958.

Safety in Structural Design and Construction

Until about two centuries ago all structures were designed and built according to experience. A concept was tried, and by experience involving sometimes fatal accidents the design and construction method were modified until a satisfactory solution evolved, i.e. until the structure proved economical and its chances of falling down or becoming unusable were remote. This method of design and construction was then repeated for many structures, perhaps with minor alterations, and it was passed on from generation to generation by the method of apprenticeship. Notable examples of this approach include the medieval cathedrals of Europe and Roman bridges and aqueducts. Many empirical rules were developed in this way; to the credit of early builders, some are still used. The time required to develop the design and construction method, the likelihood of fatal construction accidents during the trial period, and the difficulties in extending experience to new types of construction or unusual structures are obvious drawbacks.

Today, most structures are designed by a more rational, direct method involving an understanding of Newtonian mechanics, external actions or loads acting on a structure, and material behaviour. The basic idea is to make the structure sufficiently strong to withstand the loads that will be applied to it. Loads and structural strength are, however, to some extent unpredictable and this is where the risk comes in. To reduce risk of collapse to an acceptable level, safety factors - ratios between calculated strength and applied loads - are introduced and stipulated in building codes and structural standards. Table II gives some of the safety factors used in the National Building Code of Canada 1970 (1). They have been arrived at primarily on the basis of experience, and have been gradually reduced over the years through improved knowledge and workmanship.

Table II. Safety Factors in the National Building Code of Canada 1970

Type of construction	Basic Safety Factor
Steel and Aluminum	
Yield or plastic resistance	1.67
Elastic Buckling	1.92
Bolts	2.50
Reinforced	1.7 to 2.0

Concrete	
Beams and slabs - bending	1.8 to 2.1
- shear	2 to 2.4
Columns	
masonry	3 or more
Wood	Allowable stresses are based on experience
Foundation	3

There is now a considerable research effort aimed at basing safety criteria more directly on risk and consequences of failure. It should be realized, however, that errors are the major cause of structural collapse, and that safety factors, no matter how they are derived, are of little help in preventing collapses resulting from them.

Errors

Errors leading to structural collapse are made by those who design, build or use the structure, or by those who demolish it or excavate near it. It is essential that these people should have the best information available and the experience to make use of it.

Structural engineers responsible for design must understand how the structure works, and this requires a fundamental knowledge of statics, dynamics, material behaviour, structural strength and ductility. They should also be familiar with the concept of fail-safe design, which is implicit, for example, in earthquake design or in resistance to progressive collapse (1, p.605). As there are so many ways for mistakes to be made, especially with new or unusual structures, there should always be an independent assessment of a design. This applies not only to the final structure but also to the temporary supports, which can themselves be very complicated structures. Some catastrophic failures, especially of temporary supports, have occurred because previously successful designs have been transferred to new situations without any realization that this has caused a fundamental change in the over-all structural behaviour.

Building codes and structural standards specify minimum loads and safety factors and contain detailed rules embodying the best structural knowledge available at the time of writing. Except for small, conventional structures, which are covered by empirical rules, structural standards must only be applied by competent engineers. Further discussion of the role of building codes is given in **CBD 114**.

Good communication and inspection are very important in preventing errors from occurring. Inadequate communication can be in the form of unclear specifications or contract arrangements. drawings that do not give sufficient detail, or inadequate understanding of drawings and specifications. Lack of positive communication between the structural engineer and the builder or architect is a potential source of trouble. Communication is essential in coping with such contingencies as errors in design drawings, alterations in the construction method, and changes required by the owner or architect. Inspection by the structural engineer is necessary to make sure the constructor builds what is required. Perfection is not a human characteristic.

A list of the more vulnerable situations follows, based on a study of past structural failures. It excludes ground failures which have been discussed in earlier Digests (**CBD 29**, CBD 80, **CBD 81**,**CBD 143**).

Problems during design

It should be realized that most small buildings in Canada do not require attention by a structural engineer. They are controlled by empirical rules such as those specified in Part 9 of the National Building Code of Canada (2).

1. Lack of competent structural engineering design in structurally important situations has produced more cases of collapse in Canada than any other single source. Examples include inadequately designed large-span roofs, in particular arenas and curling rinks. Over 100 Canadian buildings of this type failed in the winter of 1970-71 under heavy but not unexpected snow loads.
2. Inadequate wind anchorage. This applies particularly to wind suction on roofs of nonengineered buildings, to wall and roof panels, and to large signs (see **CBD 68**). Light buildings such as mobile homes should be anchored to resist overturning and sliding.
3. Detailing. In design offices, most errors leading to structural failure occur in detailing: insufficiently detailed drawings; insufficient consideration of statics in the design of details; insufficient anchorage or bearing distance to allow for construction tolerances; connections so brittle that failure occurs due to indeterminate forces or small impact. Special considerations have to be given for earthquake resistance.
4. Choice of materials. Examples include selection of excessively brittle materials, metals subject to fatigue failure under cyclic loading or to brittle fracture at cold temperatures, or metals not suitable for welding, materials which by their location may be subject to corrosion, rotting (e.g. condensation in roofing systems, **CBD 112**), more recently developed materials subject to solar or chemical attack (consult **CBD 115**, **CBD 116**, **CBD 117**, CBD 120, **CBD 121**, **CBD 122**, **CBD 123**, **CBD 124**, **CBD 136**).
5. Assessment of loads. As a rule, loads are adequately taken into account in design offices, but errors can occur. Examples include: forgetting changes in dead load or partition loads; possible effects of temperature change, shrinkage, differential settlement; concentrated snow loads on canopies, etc.; wind uplift or overturning, ponding loads, ice loads or snow slides, accidental loads such as explosions or impact which might lead to progressive collapse (1, p. 605).

Problems during construction

In Canada this has been the source of greatest trouble in the past (Table I), mainly owing to a lack of competent structural engineering in the erection procedure or in the design of temporary supports and bracing.

1. Temporary supports. Some of the worst disasters have occurred as a result of inadequate temporary supports. In most cases, lateral bracing to prevent buckling was either absent or not sufficient. Another error that occurs in reinforced concrete construction is too-early removal of temporary supports before the concrete has become sufficiently strong to carry construction loads.
2. Bracing or guying during construction. There are many structural or building elements which are, by themselves, unstable or incapable of resisting moderate wind loads until the structure or building has been completed. Elements subject to wind collapse include free-standing masonry walls and inadequately connected steel or wood frames and trusses. There have been many collapses of this type in Canada. Elements subject to instability include plate girders, long-span joists and walls that function as beams in the completed structure. All such elements must be braced or guyed temporarily. Construction cranes subject to wind collapse can also be included.
3. Workmanship. There are some manufacturing processes for which fairly strict control and inspection are needed to prevent serious defects in workmanship. Examples are welding, glue laminating in timber construction, curing of concrete during cold weather, and toe-nailing wood rafters for wind anchorage.

Problems during use or demolition or from adjoining excavation

1. Deterioration, brittle fracture or fatigue. Catastrophic structural collapse resulting from these phenomena can be reduced considerably by inspection and maintenance. Inspection includes looking for dangerous cracks, rot, corrosion and other material changes. Although bridges are usually inspected carefully, this is not generally true for buildings. Special maintenance is needed for certain types of structures, for example, air-supported structures (**CBD 137**).

2. Change of use, alterations. Sometimes a change of use can cause overloads; for example, new heavy trucks crossing old bridges on secondary roads, use of office space for heavy storage, shovelling snow from a high roof to a lower one. Sometimes thoughtless alterations can drastically change the structural capacity: cutting of reinforcing steel, re-roofing without maintaining the required lateral support to the roof structure.
3. Excavation nearby. There have been many collapses of walls and other parts of buildings into adjacent excavations. Usually the fault is obvious, but with some old buildings it is difficult to know what the existing foundations are like.
4. Demolition. Unwanted collapses during demolition usually occur because of inadequate understanding of structural behaviour. In one case, cutting the upper chord bracing of a truss bridge led to the sudden premature collapse of the bridge.

Conclusion and Recommendation

Compared with that from other sources, the risk of death or injury from structural collapse is generally now very low in Canada, although structures under construction are a source of risk about equal to that from building fires. Almost all recent structural collapses have been the result of errors.

The Division is anxious to collect information regarding significant structural failures and the reasons for their occurrence. This information is available at present only from isolated reports, occasional articles in the technical literature, and newspaper clippings which are generally not structurally informative. Designers and builders are urged to report significant failures and the reasons for them.

References

1. Canadian Structural Design Manual, Supplement No. 4 to the National Building Code of Canada. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, 1970 (NRC 11530).
2. National Building Code of Canada 1970, Part 9, Housing and Small Buildings. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa (NRC 11246).