Realistic assessment of loads acting on structures with particular reference to snow and wind loads on buildings

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1. The Importance of Loads

It is now recognized that the importance of determining the actual loads to which structures and particularly buildings are subjected has not been appreciated to the extent desirable, with a few notable exceptions (1—6). In view of the increasing attention which has been devoted in recent years to the problem of the load carrying capacity and so to the safety of structures, it is logical to strive for a corresponding advance in knowledge of the actual live loads on structures, since no refinements in the methods of design analysis can compensate for inaccuracies in load assumptions. Recognition of the importance of loads at this Congress of the I.A.B.S.E. is therefore to be welcomed.

Conventional load assumptions and design methods have resulted in safe structures in the great majority of cases. This fact, however, only indicates that caution has been exercised by designers and by the authorities responsible for design specifications and building codes. It is neither proof of the accuracy of design assumptions nor of economy of design. The real degree of safety in many structures is unknown; there are indications that many structures at the present time provide either excessive or non-uniform safety.

Structures are designed to perform a given function adequately, i. e., first, with adequate safety against collapse during their lifetime; and, second, with

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adequate protection against deformations which would impair their service. The former aim, safety against collapse, is generally of primary importance.

The possibility of collapse of a structure depends on a large number of factors which can conveniently be grouped into two main variables: Loads and carrying capacities (strengths). Design loads and design strengths are quantitative values which are selected by the designer or code writing authority, partly based on records of actual loads and of strength properties of materials obtained from tests and partly on the basis of judgement. Since loads and strengths cannot be predicted with certainty but only with some degree of probability, the concept of probability must form a basic part of a realistic approach to design. Design is thus closely tied to the prediction of the variation of loads and of the strength which must be expected. Determination of the probability of coincidence of very high loads with very low strength which will lead to failure, becomes the crucial problem. Notwithstanding the fact that the nature of the problem is probabilistic, the use of theories of extreme values will only find its full justification where factors with a random distribution are involved. This is not always the case and many decisions in design have to be made on basis of judgement and experience. Thus good design will consist of a consideration of the probability of failure by statistical methods, modified by judgement in considering all service conditions of the structure.

2. Recent Changes in Approach to Loads

If the actual loads acting on a given type of structure were plotted in form of a histogram or frequency distribution curve, and if the load carrying capacities or strengths of the same structures could be obtained and plotted in the same manner in the same graph (see fig. 1), it would become apparent that even if a structure is designed very conservatively there will always be a certain, even though very small, chance that the capacity of the structure might be exceeded by the load, as indicated by the intersection F of the two curves. If the design "factor of safety" of the structure is increased, the right

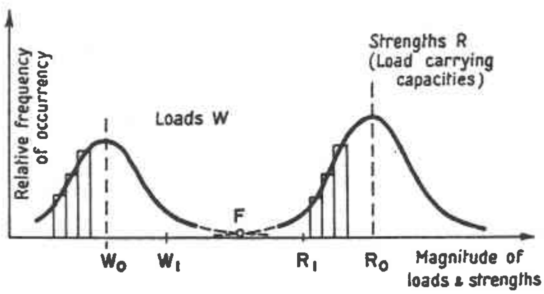

Fig. 1. Frequency Distribution Curves of Actual Loads and Strengths.

hand curve is moved further to the right but the probability of failure does not become zero. In other words, there is no such thing as absolute safety.

What is the factor of safety in the structures of the imaginary example in fig. 1? Is it the ratio of the mean values R_0/W_0 or is it the ratio of a conservative (low) strength to a conservative (high) load R_1/W_1? Great variation in the value R_1/W_1 is possible, depending upon how conservatively the design strengths and loads are selected. Since, frequently, there is no obvious upper limit to the loads and no obvious lower limit for the strength, it is not immediately apparent what the factor of safety really is. It would therefore seem desirable, as pointed out by FREUDENTHAL [7], to establish in principle a procedure in which the conventional concept of the factor of safety does not occur. The "probability of failure" appears to be the only rational quantity defining the degree of safety achieved in any structure.

The concept of safety, however, seems to be so deeply engrained in the minds of engineers at the present time that the idea of working with a "probability of failure" appears to be generally unacceptable. It may therefore be necessary to retain, at least for some time, the concept of safety in design rather than the probability of failure, but it is hoped that more and more engineers will come to view safety in terms of the probability of failure.

In the past, with conventional design, a margin of safety has been achieved by two means — by using an allowable stress, which was a certain fraction of the yield or breaking stress of the material, and by selecting a design load which was set at a certain level above average loads. Both these factors contain a margin of safety; together they determine the true reserve of strength, or the probability of failure. A change in either one of them means a change in the probability of failure. More recently methods of design have been based on ultimate load factors defining the ratio of the collapse load to the assumed working load. No matter what method is used, the real problem of design is the appropriate choice of the probability of failure.

Two approaches can be visualized in the choice of a suitable value for the probability of failure. A theoretical and rational means of determining the probability can be found from purely economical considerations, as suggested by several authors notably TORROJA [8] and JOHNSON [9]. These authors have suggested the principle of making the total cost of the structure (consisting of initial capital cost plus maintenance cost plus the cost of insurance against collapse) a minimum, assuming that the probability of failure can be adequately estimated. As this is not generally possible however, because of the lack of sufficient information, it may be necessary to resort to another method which would be based upon calculating the probability of failure inherent in existing structures. The results might then indicate in a general way what probability of failure society and, more particularly, the engineering profession have come to accept by evolution, through gradual adjustment of design loads and stresses throughout the years. This has been done recently by some authors, their studies indicating that the probability of failure of existing structures may be of the order of one in one million.

In view of the many difficulties encountered in a more rational approach to structural safety, it is not surprising that there are many differing views on the practicability of applying the theory of probability to the calculation of load factors. One point, however, seems to stand out. Since design loads have such a decisive effect on the probability of failure and yet in the past have been selected mainly by estimates, a worthwhile improvement can be achieved by assembling factual information on actual loads. The collection of such information is an undertaking which has been urged by leading authorities such as BAKER, HORNE and HEYMAN [10], PUGSLEY [11], the Institution of Structural Engineers [12], FREUDENTHAL [7] and others. The collection of this information is an undertaking of considerable magnitude since it should be on a national or international scale. It is beyond the means of university research as stated by BAKER, HORNE and HEYMAN.

3. Canadian Approach to Load Determination

In Canada, the vital importance of actual load records for the determination of proper design loads in buildings and other structures has been recognized by the Associate Committee on the National Building Code, the body responsible for the preparation of the most widely used building regulation in Canada. Approximately half of the urban population of Canada now live in municipalities which use the National Building Code. It is thus apparent that the design loads specified in this Code have a significant influence on the cost and safety of a large percentage of all structures being built in Canada.

The Committee responsible for the Code is appointed by the National Research Council of Canada. It is a group of 20 expert individuals — engineers, architects, building officials, builders — who are selected to serve as individuals and not as representatives, on a professional and geographical basis. To assist it in its work, this Committee has set up three Advisory Groups dealing with the three bases of the Code — structural safety, public health and fire safety. The Group concerned with design loads is the Advisory Structural Group, whose terms of reference are, briefly, to keep the Code continually under review with respect to all aspects of structural sufficiency, to ensure that the Code is in accordance with the economical use of all structural materials, to consider new developments in structural design and to suggest to the Associate Committee how best such new developments can be covered in the Code, and to bring to the attention of the National Research Council's Division of Building Research special structural problems which require research and investigation in Canada.

The policy of the Associate Committee is to revise the National Building

Code at intervals of about five years. A completely revised edition of the Code is planned for 1960. The work of preparing revised parts of the Code is being carried out by special revision committees, one of which deals specifically with design loads.

It may be noted that the Advisory Structural Group deals with *all* types of structures and structural materials and thus is unique in Canada in bringing together in a common forum specialists in the various materials of construction such as steel, concrete, wood and other materials. The Group has recognized the fundamental importance of the proper assessment of design loads for structural design, as shown by the Group's recommendation to the Division of Building Research that it should institute a number of special studies of actual loads, particularly snow loads on roofs but also floor loads, earthquake loads and wind loads. These studies are now in progress.

4. Studies of Loads in Canada

Snow loads. Specification of snow loads for design purposes is a most important part of a building code in a country like Canada where snow generally provides the heaviest load to be resisted by roofs. Design snow loads consequently have a significant influence on the cost of construction. A particular difficulty in specifying snow loads in Canada results from the size of the country and its varied climatic regions. The snow cover on the ground during a normal winter varies from a few inches in the southern part of British Columbia, to about 2 feet in the populated areas of southwestern Ontario and Quebec, and to approximately 3 to 4 feet in some northern areas such as Labrador, with much greater snowfalls at high elevations in the mountainous regions of B.C. and Alberta.

In the National Building Code (1953), use was made of detailed snow depth observations on the ground recorded during the years of 1941—1950. The snow loads given in the Code were calculated from the maximum recorded snow depth on the ground, using an assumed average specific gravity, plus the weight of the maximum 24 hour rainfall during March [13]. From these figures, a map was prepared giving snow loads for a horizontal surface in the form of contour lines (see fig. 2). The Code makes allowance for the slopes of roofs and recommends consideration of non-uniformly distributed snow where shape, differences in roof level, insulation qualities, the orientation of a building or its proximity to other buildings may cause unusual accumulation of snow.

Although these snow loads were more rational than in the previous edition of the Canadian Building Code, the fact remains that the loads are based on snow measurements on the ground and thus may not be truly representative of actual snow loads on roofs. Accordingly, the Advisory Structural Group recommended in 1956 that the Division of Building Research should conduct a countrywide survey of actual snow loads on roofs in order to determine the relationship between snow loads on the ground and snow loads on roofs, and to assess factors which affect the accumulation of snow on roofs, particularly the effects of wind, shelter, shape of building, heat loss, and solar radiation. This survey was started in the winter of 1956—1957. Measurements are being made each winter at 66 locations from coast to coast. At some of the stations, complete measurements are made with permanent snow depth gauges installed on flat and sloped roofs and with density measurements taken weekly and after heavy snowstorms. At other stations simpler observations are taken by volunteer observers who merely take depth but no density measurements. Residential roofs and large hangar roofs at airports are being observed. Fig. 2 shows the locations of the various observation stations.

Although full observations for only two winters are available to date, the early results suggest certain tentative conclusions. The assumption of a uniformly distributed snow load on roofs is seldom realized in areas with even normal wind (see fig. 3). The average snow load on roofs is less than that on the ground by an amount which varies widely, depending on wind and other factors. Certain roof shapes tend to develop localized snow accumulations which may be much deeper than the snow on the ground (see fig. 3). This is

Fig. 2. Snow Loads in Canada.

—40— Design snow load on a horizontal surface (lb/ft²) according to the National Building Code of Canada (10 psf ≈ 50 kg/m²).

● Detailed Observations, o Simple Observations } Observation stations of the National Research Council's Survey of Snow Loads on Roofs.

particularly the case on roofs with several levels and upon curved roofs. Heat loss through the roofs and solar radiation reduce snow depth only under favourable conditions.

For determining snow loads for the mountainous areas of western Canada for the 1960 edition of the Code, it is proposed to use a new approach based on empirical relationships between snow load and elevation above sea level within each of a number of climatic zones, similar to the rule followed in Switzerland, France and Austria.

Roof failures due to snow loads are, unfortunately, not uncommon in Canada. The winter of 1958—1959 brought greater than normal snowfall in parts of Canada, particularly in the areas east of Lake Huron, where a number of collapses occurred. One of these failures occurred in a hockey arena with a curved roof supported by 110 ft. span wooden trusses and resulted in the tragic death of seven boys and one adult. Such failures serve to remind engineers of the importance of design snow loads in Canada.

Wind loads. Wind forces on structures result from differential pressures caused by the obstruction to the free flow of the wind. The forces are therefore functions of the velocity of the wind on the one hand and the size, shape and orientation of the structure on the other. Information on wind loads must come from two sources — meteorology and aerodynamics.

At present the wind load requirements of the National Code Building take into account three factors — the gust velocity, the increase of velocity with height, and the shape of the structure.

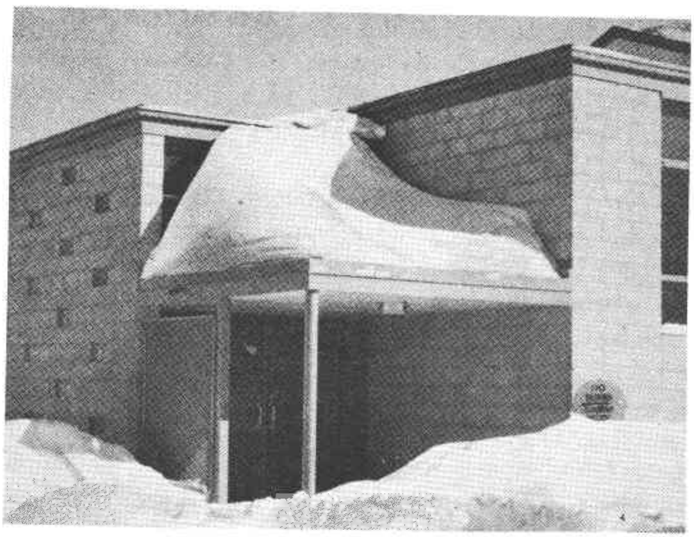

Fig. 3. A Triangular Snow Accumulation (Maximum Load 80 lb./sq. ft.) Resulting From Wind Action on a Building in an Area with a 50 lb./sq. ft. Design Load.

Gust velocities are derived from hourly wind velocities obtained at 200 weather stations across Canada, which are then multiplied by a "gust factor". The gust factor, which increases with the velocity, is based on correlations made at a number of weather stations where both cup anemometers and Dynes tube anemometers are available. The computed maximum gust velocities are shown in the National Building Code by lines of equal velocity on a map of Canada.

For the increase of velocity with height, the $^1/_7$th power law is used, this being a familiar aerodynamic profile in wind tunnel investigations of turbulent flow over smooth boundaries. Experimental investigations have shown, however, that there are many variations in nature to this law. It has recently been proposed by DAVENPORT [14] that ground roughness should be taken into account by using different exponents but the same gradient velocity. Over flat open country an exponent of $^1/_7$th, over rolling and wooded country and the outskirts of large cities 1/3.5, and for the centre of large cities 1/2.5 might be used.

Shape factors are generally based on wind tunnel tests on elementary geometrical models of structures. Attention is drawn to a recent paper by SINGELL [15] in which factors relating to coefficients for various building shapes have been correlated and in which it is suggested that the tables in the Swiss Building Code [16] are the latest and most extensive records available.

Traffic loads at Toronto Subway. The construction of the Toronto Subway by the cut-and-cover method was used as an opportunity to measure actual loads occurring on a temporary road deck supported by steel beams [17]. These measurements, although extending over a limited period only, indicated that the stresses in the steel beams due to traffic loads were very low and that there was considerable room for economies. The published record of this work provides good confirmation of the utility of a statistical approach to load determination. The authors hope to continue this study during construction of further stages of the Toronto Subway.

Study of failures. It has already been noted that design loads and stresses used at the present time are largely the result of "engineering evolution", the values having been adjusted from time to time on the basis of experience and judgement or, in other words, on the basis of a consensus on past performance, taking into account known structural failures or the lack of such failures on the one hand, and the improvement, over the years, of the quality of the construction materials on the other. This approach indicates the vital importance of assembling records of structural failures as a guide for future design. Accordingly, the Division of Building Research maintains as complete a record as possible of structural failures in Canada by collecting printed information on such failures and by conducting its own investigation of such failures whenever practicable.

5. Conclusion

No structure, no matter how conservatively designed or how well constructed, provides for absolute safety. Every structure has some finite probability of failure even though it may be very small, of the order of one in one million. Loads and strengths used in design are quantities whose upper and lower limits can only be stated in terms of probability. The safety of a structure cannot accurately be expressed by a safety factor but only by the probability of its failure. In simplified terms it can be said that if the probability of extreme loads is known and if the probability of extreme strengths is also known the probability of failure can be stated [18]. In reality the problem is much more complicated. The probabilistic approach will, however, allow a gradual improvement in the judgement of those factors affecting safety which can be treated statistically.

Advance in the field of structural design is only possible if advance in the analysis of structures is accompanied by a corresponding improvement of the knowledge of actual loads on structures. Such information for Canada is now being collected by the Division of Building Research of the National Research Council. It is hoped that other organizations will also recognize this need and participate in this important aspect of research, so that results can be shared on an international basis.

References

1. I.A.B.S.E. Symposium on Loading of Highway Bridges. Oporto, 1956, Volumes I to III, Stockholm 1957.
2. M. R. Horne, "The variation of mean floor loads with area." Engineering, vol. 171, Feb. 16, 1957.
3. S. O. Asplund, "Probabilities of Traffic Loads on Bridges." ASCE Proceedings, Structural Division, vol. 81, 1955, Separate No. 585.
4. C. M. White, "Survey of Live Loads in Offices." First Report of the Steel Structures Research Committee, London, HMSO, 1931.
5. J. W. Dunham, "Design Live Loads in Buildings." Transactions, American Society of Civil Engineers, vol. 112, Paper 2311, 1947.
6. I. I. Golden'Blat, B. G. Korenev and A. M. Sizov, "Snow Loads According to Structural Standards and Regulations" (in Russian). Construction Industry 1956, No. 6.
7. A. M. Freudenthal, "Safety and the Probability of Structural Failure." Proceedings, American Society of Civil Engineers, vol. 80, 1954, Separate No. 468.
8. E. Torroja et A. Paez, "Calcul des coefficients de sécurité." I.A.B.S.E., 4th Congress, 1952, Preliminary Publication.
9. A. I. Johnson, "Strength, Safety and Economical Dimensions of Structures." Stockholm, Statens Kommittee for Byggnadsforskning, 1953, Meddelanden, No. 22.
10. J. F. Baker, M. R. Horne and J. Heyman, "The Steel Skeleton." Cambridge University Press, 1956, 408 pp.
11. A. G. Pugsley, "Concepts of Safety in Structural Engineering", Journal, Institution of Civil Engineers, vol. 36, no. 5, 1951.

12. Institution of Structural Engineers, "Report on Structural Safety". The Structural Engineers, vol. 34, no. 5, 1955.
13. M. K. Thomas, "A Method of Computing Maximum Snow Loads." Engineering Journal (Canada), vol. 38, no. 2, 1955.
14. A. G. Davenport, "A Rationale for Determining Design Wind Velocities." Paper submitted for publication, 1959.
15. T. W. Singell, "Wind Forces on Structures: Forces on Enclosed Structures." ASCE Proceedings, Structural Division, vol. 84, 1958, Paper No. 1710.
16. SIA-Normen für Belastungsannahmen, Inbetriebnahme und Überwachung der Bauten. Schweizerischer Ingenieur- und Architektenverein, Zürich 1956.
17. W. R. Schriever, "Strain measurements on the temporary road deck for the Toronto Subway." Proceedings, Institution of Civil Engineers. Part I. Nov. 1954.
18. A. G. Pugsley, "Current Trends in the Specification of Structural Safety". Symposium on the Strength of Concrete Structures. Cement and Concrete Association, London, 1956.

Summary

The Paper points out that no structure, no matter how conservatively designed, provides for absolute safety, because loads and carrying capacities of structures are variables whose upper and lower limits respectively, cannot be predicted with certainty but only in terms of probability. The safety of structures can therefore be expressed truly only by the probability of failure. Advances in structural design must be accompanied by corresponding improvement in the knowledge of actual loads on structures. Canadian studies of live loads on buildings, and particularly a countrywise survey of snow loads on roofs, are described with relation to their application in the National Building Code of Canada.

Résumé

Les auteurs montrent qu'aucun projet, si prudent soit-il, n'offre une sécurité absolue, car les charges et la capacité de charge des ouvrages constituent des grandeurs variables, dont il n'est possible de déterminer les limites supérieures et inférieures qu'avec une certaine probabilité et non pas avec certitude.

La sécurité qu'offrent les ouvrages ne peut donc être effectivement exprimée que sur la base d'une probabilité d'effondrement.

Les progrès réalisés dans le domaine de la construction des systèmes porteurs doivent ainsi être accompagnés d'une amélioration corrélative de nos connaissances sur les charges effectives.

Les auteurs exposent les investigations canadiennes sur les charges utiles des ouvrages et particulièrement les résultats d'une observation étendue sur tout le pays concernant les charges imposées aux toitures par la neige; les résultats de ces investigations sont utilisés dans le Code National du Bâtiment du Canada.

Zusammenfassung

Dieser Bericht weist darauf hin, daß kein noch so sicher bemessenes Tragwerk absolute Sicherheit bietet, da die Lasten und die Tragfähigkeit der Tragwerke variable Werte sind, deren obere und untere Grenze nicht mit Sicherheit, sondern nur nach der Wahrscheinlichkeit angenommen werden können.

Die Sicherheit von Tragwerken kann somit wirklich nur auf Grund der Einsturzwahrscheinlichkeit ausgedrückt werden. Entsprechende Verbesserung der Kenntnisse der effektiven Lasten müssen die Fortschritte in den Bemessungsverfahren begleiten.

In Verbindung mit ihrer Anwendung in den kanadischen Baunormen sind kanadische Untersuchungen über Nutzlasten für Gebäude und hauptsächlich eine landüberspannende Beobachtung der Dachbelastung durch Schnee beschrieben.