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Dynamic Effects of Wind and Earthquake

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Introduction

The development of the construction of taller buildings, the tendancy towards more slender forms, the constant evolution of construction materials and methods, and finally the increasing demand for economical and rational construction have resulted in a remarkable effort of theoretical and experimental research with the following aims:

a better description of the limiting forces to which a structure may be subject and a better definition of the behavior of the structure reflecting the true situation as closely as possible and considering precisely the circumstances which used to be relegated to the "margin of safety" or, we should say, covered by the "ignorance factor";

to develop constructive forms, methods of calculation and construction techniques capable of improving the functional qualities and the utility of the structure;

to obtain a proper equilibrium between the requirements of safety and economy using modern concepts based on probability in terms of a scientific evaluation of the risks.

Whereas the empirical methods used to determine the static loading have been progressively, and now almost totally, abandoned in favor of scientifically based studies, the dynamic loading of structures, especially wind and seismic forces, have not been evaluated until recently by more than rough and ready methods using more or less arbitrary figures or coefficients introduced into the usual static analysis.

Certain aspects of the problem of dynamic loads due to these two categories of phenomena and their effects on structures in general and tall steel frames in particular, have, nevertheless, been the subject of some important theoretical and experimental research. Others have not yet been sufficiently studied.

The purpose of the present introductory report is to indicate the essential points of the level of knowledge attained so far by these studies and subsequently to outline the problems which need to be solved or require more profound study, and to suggest, therefore, a desirable course for the efforts of this congress and for research in this domain.

Loading

Wind

Although Galileo and Newton recognised the action of wind its consideration for the design of structures did not take a practical and concrete form until the end of the last century. The effects of these actions made themselves evident with the advent of tall, light-weight and slender structures. The importance of the problem of wind action has therefore coincided with the development of steel framed structures.

It was also at this time that two pioneers of steel construction, B. Baker in Great Britain and G. Eiffel in France, inspired by their intuition and by their understanding of the behavior of structures, set forth two aspects of the problem which are essential to the structural analysis. The first proved, by means of a very simple and direct experiment, that the total effect considered over large surfaces is weaker than the forces measured locally. The second, established by direct measurements on the "300 meter tower" that the maximum displacements of the structure as a whole corresponded to the mean wind intensity and not to the gusts of higher force.

Since then theoretical studies, wind tunnel tests and direct observations have allowed us to gather more precise information concerning the different factors to be considered in structural calculations, such as the variation of wind velocity with height, terrain roughness, distribution of gusts, the difference between instantaneous velocities and mean velocities during a given period, the relationship between rapid and slow variations of velocity, the intensity and distribution of internal and external positive and negative pressures as a function of the angle of incidence, and the possible effects of openings, masking effects, etc...

None the less, as the first international congress on this subject in 1963 made evident, the knowledge of the action of this complex phenomenon is still incomplete and furthermore, obscured by incomplete observations, which were in turn made with not altogether satisfactory instruments placed sometimes in an inadequate fashion. For the analysis of structures it is important to realize the uncertainty which affects the prediction of wind velocities, especially in relation to the site, usually different from that of the weather station of reference, as well as the environmental influence and other local factors. Under these conditions an exaggerated precision in the calculations is misleading and senseless.

It is necessary on the other hand to realize within what limits a given wind is capable of exciting dynamic stresses in the principal members of a multistory steel framed building.

Schematically the normal wind spectrum consists of relatively slow-varying forces, upon which are superposed rapid and generally irregularly varying fluctuations, having, especially near the ground, an uncertain and highly unstable distribution. The result is that the action of the wind has a double effect.

For large buildings the first effect concerns the action as a whole which creates repeated stresses in the supporting elements of the framework which cannot become alternating stresses except to the extent that the whole structure enters into oscillation. The moderate rhythm of the variations of wind force which enter into consideration, and the inertia of the structure as a whole provide, nevertheless, time for the structure to adapt itself as though for quasistatic loads.

The second effect, which is distinctly dynamic but localized and continuously variable, influences mostly the elements which are directly or indirectly loaded and for which this effect constitutes the principal force. Nevertheless, even for these elements, the irregularity in magnitude and direction of this action may limit the dynamic consequences and especially the risks of resonance.

It appears nevertheless that these two fundamental effects recognized by Baker and Eiffel have been ignored for a very long time by the building codes. Actually the reduction of pressures for very large surfaces does not yet appear explicitly except in the most advanced codes. As for the effect noted by Eiffel, it seems to have been completely neglected until recent times, where it is expressed again more precisely in the tentative attempts at dynamic studies of structures.

One must recognize, however, that the limit within which the dynamic effect due to wind may effect the behavior of an entire multi-storied structure has not as yet been determined beyond a doubt and without reference to arbitrary hypotheses. It will only be possible to succeed by reference to experiments on real structures.

Earthquakes

The problem of realizing structures resistant to earthquakes in regions subject to this calamity is as ancient as the memory of man and lead to the empirical development of forms and methods of construction.

Nevertheless, despite the violent, brutal and often catastrophic character of earthquakes the observations of these unpredictable and irreproducible phenomena are, in most cases, insufficient to permit after the consequences a complete a posteriori analysis in terms of the precise responsible movements. It has therefore been necessary to rely on theoretical studies, necessarily based on simplifying assumptions and analogous simulations to determine the behavior of structures and define the methods of calculation.

The movement of an earthquake consists of displacements, velocities and accelerations of irregular direction, magnitude, duration and sequence. The movement thus created takes place along a complicated spatial trajectory which can be decomposed along cartesian coordinates. It is customary to neglect the vertical component which is considered weaker than the vertical forces which a structure normally has to resist. This simplification is generally justified, but it is not evident that is so in every case.

The intensity of the earthquake to be considered in the calculation of structures is established according to the greatest earthquake recorded in that geographic region, which is justified by the catastrophic character of this phenomenon. This intensity is nevertheless defined, lacking more scientific means, with the aid of scales based on subjective observations and the extent of damage, the latter often constitutes the sole precise indication available concerning the earthquake.

Under these conditions the greatest care must be taken in the examination of the data used and in the hypotheses assumed for the application of the theoretical method of calculation in order to avoid any distortion of the results.

G. W. Housner has, however, favoured a method whose principle was suggested by M. A. Biot, which consists of determining the action of the seismic shocks with reference to the records of seismographs.

From the point of view of the manner of loading buildings seismic shocks present several fundamental differences when compared to wind action. They are distinctly and integrally of a dynamic character. In addition, being introduced at the base of the structure, they invariably affect the base in its entirety. They do not act as external forces applied on the structure but as internal inertia forces in relation to the movement of the ground. These forces exercise, therefore, an action as a whole, even if the consequences are localized in this part or that element of the building.

It follows that if the inertia of the masses are opposed to the dynamic action of the wind and considerably reduce the extent of its effect, this same inertia, being a determining factor in dynamic effects, intervenes in the opposite sense in the case of earthquakes. That is why it is recommended to avoid all unnecessary dead weight in buildings situated in seismic zones.

This also explains why, for the most part, the move toward more and more slender structures does not reduce the resistance of steel frames to seismic shocks, but raises new problems concerning their behavior relative to the wind.

Structural Response

The concept of response spectrum

The dynamic response of a structure is a direct function of the static and dynamic characteristics of the building as well as of the configuration of the excitation and of the properties of the transmitting medium.

The first studies of the dynamic effects of earthquakes considered harmonic vibrations of constant amplitude. This simplified analysis proposed by K. S. Zavriev and A. G. Nazarov led only to the avoidance of resonant effects by reference to the resonant frequency of the structure.

Hypotheses which reflect reality more closely were made possible by the introduction of the concept of a response spectrum set forth by M. A. Biot and considerably developed since then, especially by G. W. Housner, in order to take into account the irregularity of the movements which compose earthquakes.

The response spectrum represents the variation of relative displacements, relative velocities or absolute accelerations of the system as a function of the period of its natural frequency and the imposed excitation. It is defined for the most simplified system of one degree of freedom but its application extends to systems with several degrees of freedom by the introduction of integrals of the displacements, velocities and accelerations, inertia forces and shear forces for the different modes of vibration or more simply by the use of factors of equivalence representing the relation of the reduced mass to the real mass. An equivalent spectrum is thus obtained for the structure under consideration.

This spectrum may be established for all forms of excitation, periodic or nonperiodic, whether experimentally using dynamic models or analytically using direct integration or finally by electrical analogue. It represents an aid of primary importance for the dynamic study of structures because it gives the values of the displacements, velocities and accelerations directly, no matter what the rhythm and the configuration of the perturbing oscillation are. It offers, therefore the most simple means to determine directly the necessary resistance and flexibility.

Effects of the mass distribution

The response to seismic shocks being proportional to the inertia of the mass, the importance of the distribution of this mass is evident. For a symmetric building only the vertical distribution enters into the determination of the seismic factor which is the basis of the calculations. It is desirable to have a continuous distribution placing the larger masses (i. e. swimming pools, reservoirs, heavy installations etc.) toward the base of the building as much as possible in order to avoid a concentration of mass at a high level. In any case it is advantageous to place the center of gravity of the building as low as possible.

In asymmetric buildings the excentric inertia of the masses may engender relatively important torsional effects as the result of earthquakes or wind action. Such effects are always to be feared when the center of gravity and the center of torsion of the structure do not coincide. In this case it is absolutely necessary to take this into account in the calculations and in the structural arrangements of the design.

Damping of dynamic effects

The damping of the dynamic effects by absorption of energy constitutes a cardinal element in the behavior of real structures. Indeed no matter what the source of the energy introduced into the structure may be, dynamic wind effects or seismic shocks, this energy must be completely absorbed at the peril of causing excessive permanent deformations or even more severe damage.

Nevertheless in every real system the energy originating from any dynamic loading, a seismic shock for instance, is transformed partially and temporarily into kinetic energy of movement of the mass and elastic energy of deformation of the structural elements, but finally it must all be dissipated by internal friction or, depending on the case, by plastic deformation to the extent that the energy is not returned to the ground by interaction with the building.

In fact it has been proved that all dynamic loading of considerable severity will probably result in creating moments and elastic displacements well above the value normally tolerated, if the nonelastic deformations did not intervene.

The important role of energy absorption by ductility in the dynamic response of frames, no matter what their height or slenderness is, has been revealed recently by studies analysing the nonlinear behavior of systems with one or more degrees of freedom, in particular the studies of G. W. Housner and G. V. Berg.

These studies reveal particularly the fundamental role played by the dissipation of energy in the behavior of buildings subject to dynamic loads. The major difficulty rests in the necessity of knowing exactly the real characteristics of the structure.

In fact, if the input of energy is given, it ought to be recognizable at any instant distributed among the movement of the mass, the internal friction, the work of the elastic deformation and the work in the permanent deformation.

It appears that if the capacity for dissipation of energy of the system is limited, excessive forces may easily be produced requiring an uneconomical reinforcement. One has, therefore, the greatest interest in conceiving structures in such a way that they may absorb a large amount of energy, not only by normal damping, but also by plastic deformations without ruining the building; however in the case of particularly violent forces we may accept certain plastic movements that are not catastrophic but produce damage of limited consequences.

This permits an explication of the good resistance often observed of apparently weak structures having a large capacity for absorbing energy.

The nonlinear analysis which by its very nature is particularly apt to give indications as to the judicious distribution of stiffnesses, has made it apparent that in the normal types of frames the nonlinear deformations are most likely to be produced in the beams. Naturally a reinforcement of the beams will displace this phenomenon to the columns.

It is evident that in the whole process of dampening there is no discrimination such as is suggested arbitrarily by the method of calculation currently used which ignores non-structural elements. All the elements constituting the building, whether they are designated as load-carrying or not, participate in the dampening.

The effects of stiffness, proportion and form of the building

The dynamic behavior of a building with respect to the loads to which it is subject depends primarily on its stiffness and its proportions.

Schematically the limiting case may be considered as an absolutely rigid building fixed in the ground. In this case the forces due to seismic shocks or wind loads would result in a simple decomposition of forces without any attenuation. If on the other hand, the building has a certain capacity to deform, a corresponding amount of energy will be absorbed. This energy may subsequently be released, which is to say one will observe a more or less important phase shift in the loading, which in general has the effect of diminishing the maximum value of the effective forces. Finally, in the case of a slender, flexible building subject to several consecutive cycles of loads, the forces may be amplified considerably.

The height enters both directly and indirectly in the load calculations, but its influence is distinctly overshadowed by that of the slenderness when determining the dynamic response. Only the so-called "whip-cracking" action of the upper stories seems to be aggravated by the height of the building.

The construction of increasingly slender and flexible buildings poses new problems nevertheless, both as to their behavior in earthquakes as well as in wind. Such structures, having a long natural period of vibration, are relatively insensitive to rapid oscillation but may be subject to movements of large amplitude under the influence of heavy wind forces. Moreover a sudden stop of the wind may have the same effect as a result of the energy which may be released.

Important discontinuities in the general form of the structure should be carefully avoided in earthquake zones, because they will influence the dynamic response of the building and may be the source of serious problems at that elevation.

Buildings of asymmetric or complex form such as *L*, *U*, *T* or in the shape of a cross or any other similar form present in general a good wind stability due to the important mutual stiffening effect offered by the different parts of the building. As far as earthquakes are concerned, however, such buildings composed of two or more bodies of different stiffness placed in juxtaposition may pose some serious problems due to the inertia action of the masses. Moreover behavior during seismic movement is very difficult to analyze.

If it is impossible to avoid such forms, for instance when they are imposed by functional necessities or by the wish of the owner, it is up to the engineer to determine in each case the nature and magnitude of the forces created in the planes of contact between the constituent blocks of the building as a function of the individual response of each section to the predicted dynamic loads and to design the connections accordingly. Naturally the best solution is to build the structures with sufficient separation to allow each to vibrate independently. If this is not permissible one must create connections which will oblige the parts to vibrate as a whole.

The influence of the framing system and the type of floors

Of the information acquired from real buildings which have been subject to earthquakes most is concerned with classic frames with rigid joints but some were stabilized laterally by diagonal bracing. The advantage of the first type over the second seems obvious, although there have been no special studies on this point. On the other hand there is no question as to the ability of either system to resist wind loads.

The new conception of "box-type" steel frames for very tall buildings which is the basis for several interesting structures built recently or being built is without a doubt the most rational and efficient design for this type of building for resistance to the dynamic action of the wind. It probably is for earthquakes too. Naturally we have not yet any practical experience with this new type of building, to which, by the way, a special subject of this congress is to be devoted.

The construction of the floors enters into the general stability of the structure by the more or less effective diaphragm effect which they exercise in relation to their natural stiffness, but they have little influence on the lateral stiffness intrinsic in the frame, which depends principally on the columns and their joints.

The presence of solid floors produces, nevertheless, a considerable damping effect on the oscillations by slowing down the accelerations and increasing the period of vibration. Their use has a favorable effect on the behavior of the building as regards the action of the wind. On the other hand the inertial forces produced at each floor level by an earthquake are the least desirable effects sought in an earthquake zone. It would therefore seem that in seismic zone one should give preference to light-weight steel floors, on the condition that a good liaison is assured between all the elements of the frame in such a way that the entire structure reacts as a single body.

The influence of non-structural elements

Neglecting the presence of so called "non-structural" elements, such as walls and partitions, when calculating the resistance of steel framed multistory buildings is one of the aspects which can be most strongly criticized. It may seem surprising to want to take them into account these days when light weight elements, weakly attached to the frame and sometimes even removable, are used whereas they were neglected in the times when, by their very composition, they must have played a much more important role in the rigidity of the buildings. This tendency is justified by the efforts to utilize every possible source of resistance of a building and also by the results of recent knowledge obtained from real buildings.

An example is the measurements made by J. W. Bouwkamp on a steel framed building during different stages of construction. The results revealed that even such weak elements as the window panes could have a measurable influence on the response of the building to lateral loadings in that it modified the natural frequency. This confirms the opinion of S. Mackey and the author who believe that, for modern steel framed structures, the glazing represents a first line of defence against the dynamic action of the wind.

In any case it is important to bear in mind that any real structure which undergoes dynamic loading will behave much differently than any linear oscillator or even any more or less simplified system which is substituted for the sake of calculation.

Practically speaking, the phenomenology of the behavior of the building as a whole indicates that even in the case of a severe earthquake the non-structural elements play a predominant role in the damping of vibrations impressed on the building by absorbing an important part of the energy introduced during the first phase of the response, that is to say when the amplitudes are relatively weak. During a second phase, corresponding to larger amplitudes, these elements are damaged more or less but continue to exert a considerable action in limiting the movements and dissipating energy. It is only after a large amplitude of movement has been reached that this action ceases for all practical purposes and the reserves of plasticity of the frame come fully into play, thus constituting a second line of defence as H. J. Degenkolb remarks.

The case of hybrid structures

The resistance to sway for steel frames is sometimes realized by the use of diaphragms or massive prefabricated panels.

The study of these systems under dynamic loading has not yet been undertaken in an entirely satisfactory manner, especially as to the consequences of the difference in response between these diaphragms and the unbraced parts of the structure and as to the attachment between the solid elements and the steel frame. The possibilities which this type of structure affords would seem to justify a particular research effort, nevertheless, aiming particularly at the very limited capacity for deformation of the stiffening diaphragms.

It has been established, actually, that at every level the distribution of horizontal loads into the vertical elements of a structure is proportional to the stiffness of these elements. A rigid element made of material of lower specific resistance than the other elements may actually represent a weak point because it will be loaded in proportion to its stiffness, whereas its resistance may be lacking. This has been proved by failures observed during several earthquakes.

In certain countries it is common to assure the lateral stability against wind load by means of a central core of reinforced concrete, the steel frame serving only to support the vertical loads. The purpose of the present report is not to examine the economic or fireproofing advantages of such solutions, however it may be noted that a more precise determination of the effects of the wind, allowing a more rational design of the steel structure, would limit the number of cases in which one is lead to envisage such a hybrid solution.

As to this type of building situated in seismic zones, the considerable difference between the response of the rigid part and the metallic part of the building under dynamic loads may provoke very large forces in the planes of contact between the two parts of the system, and therefore produce damage in the connections between the steel structure and the concrete core.

The technical literature does not, to our knowledge, reveal sufficient practical experience concerning the behavior of this type of buildings during earthquakes, and in addition the rigorous theoretical analysis of their behavior proves to be very difficult.

Behavior of Materials and Structural Elements

The essential properties of steel

The essential properties required of materials to ensure their good behavior in frames subject to dynamic loads, whether wind or earthquake, may be enumerated as follows:

elasticity and ductility, qualities necessary to permit an elastic flexibility and an elasto-plastic adaption sufficient to assure a reasonable rate of energy absorption;

good resistance to alternating loads, which implies stresses of the same order of magnitude in both senses and consequently almost the same resistance in tension and compression;

good resistance to fatigue for a low number of cycles.

These properties being admirably united in structural steel it has proved itself particularly adapted for the realization of frames which are to suffer the dynamic action of wind and earthquake.

Nevertheless most of the studies of fatigue performed on steels of all types have been concentrated on the actions under a great number of cycles. The more recent but less numerous research on the effect of a few cycles may not be considered exhaustive, especially in the domain of elasto-plasticity. However it is just in this region that one of the fundamental problems for the calculation of seismic effects on steel frames is found.

On the other hand, despite the repetitive and reversible character of the wind action, it does not seem, lacking evidence to the contrary, that fatigue should enter into the calculations of supporting elements of the usual type of multi-story frame buildings, particularly in view of the low values of stresses in question.

Such a criterion should be considered in any case for those elements subject essentially to fluctuations of the wind and principally designed to resist these loads, for example secondary façade elements or certain struts for wind bracing.

Behavior of beams and columns

We have already spoken of the predominant role played by the beams in the non-linear behavior of the normal types of steel frames. The analysis of this behavior takes on therefore primary importance.

Such a problem may not be properly solved without experimental evidence but, nevertheless there has been but little research on this subject. The most revealing and the best adapted to this purpose is no doubt the research done by E. P. Popov, which indicates that the threshold resistance of such an element is determined by the local buckling of the flanges under the effect of a number of cycles which depends on the maximum stress reached each time. It seems, actually, that under this type of loading the protection against buckling of the flanges is even more important than the fatigue resistance of the material itself, this buckling being favored as soon as a previous cycle has been able to produce a slight deformation.

This phenomenon of the accumulation of deformations is liable to constitute a limit to the degree of energy absorption, which one wishes to keep as high as economy permits.

In a system of multi-storied frames with rigid joints, the lateral displacement of the frame under the action of lateral loads is a function of the stiffness of the columns and their connections. Furthermore, this lateral displacement being a determining factor for the response of the building to dynamic loading, its importance is evident. Being elements subject to both bending and compression, their behavior is similar to that of the beams, but their capacity for the absorption of vibrational energy depends largely on the applied axial load.

The behavior of connections

A frame being constituted of elements connected together, it is important that the behavior of connections is well understood, as these represent points of discontinuity in the beams and columns of constant cross section. Their behavior under dynamic forces require particular attention. Such a study proves, however, to be impossible on the theoretical level in view of both the complexity of forms which make it difficult rigorously to determine the stress distributions and also the many different means of assembly such as welds, bolts and rivets, each with its individual characteristics and the secondary stresses which they may create.

Here again the experiments of E.P.Popov on different types of welded and bolted connections subject to alternate loads giving elongations up to 1½ to 2% offer particularly clear and significant results which may serve as a basis for the study of the behavior of real structures. Naturally they also permit a closer approach to reality by introducing their results in the simplified systems which one takes as a basis for theoretical studies.

In fact these experiments indicate a very favorable behavior for all the connections tried, as reflected by the remarkable stable hysteresis curve, which shows that the energy absorption is practically constant for each successive cycle.

These studies need to be completed and utilized, but in the meantime it is possible to draw the general conclusion that for steel framed structures subject to dynamic loads it is sufficient to design neat, correctly fabricated connections of the normal types whether welded or bolted, and above all not to resort to special complicated devices which may not only be useless but possibly even unfavourable. In fact the observations made after several earthquakes have shown that wherever there were failures in the connections it was due to defects in the design or fabrication. It is desirable for example to avoid the devices which produce a sudden change in the stress distribution in the cross section, or an undue stress concentration which may reduce the resistance of the joint to alternating forces in the elasto-plastic range.

In any case safety considerations require that joints should be designed and fabricated in such a manner that they do not fail before the elements which they connect.

Behavior of Entire Frames and Buildings

Effects of the wind

Exhaustive wind tunnel tests on models have permitted an enormous increase in our knowledge of the pressure distribution on the surface of buildings as well as of certain localized actions as a function of a specific wind velocity, and have allowed the verification of the application of aerodynamic laws in this particular domain. In modern wind tunnels it is even possible to reproduce certain environmental conditions of a particular building under study in order to obtain the most faithful reflection possible of the real conditions of turbulence.

Measurements made on real buildings have, however, revealed important differences in the magnitude and distribution of pressures as compared with those obtained from models, which proves the necessity of complementing the research made in wind tunnels. Such measures, insufficiently realized in the past, are actually being taken, in particular by C. W. Newberry.

Nevertheless this research concerns only the first part of the problem. The second, the effective behavior of the structure, cannot be accomplished with models, which cannot faithfully reproduce the reaction characteristics of real buildings. Only measurements on a building itself may reliably answer the many questions concerning it. Nevertheless, with the exception of early studies, this domain remains unexplored to this day.

A remarkable study was undertaken in Canada by R. Crawford and H. S. Ward on an 18 story steel framed building using electromagnetic seismometers recording vibrations due to wind action on magnetic tapes. Even though it was only an attempt to verify the results concerning the natural frequencies obtained from mathematical models, and despite the presence of a central core of steel and concrete slab construction, which detracts part of the significance of the results for the point which concerns us, the research did not fail to allow us to make certain interesting observations.

It was therefore made apparent that strong winds have a tendency to provoke vibrations following the first mode, whereas light winds tend more to excite the higher modes. The author feels that this corresponds well with our knowledge of the wind spectrum.

Earthquake Effects

The rigorous determination of the exact dynamic behavior of a real structure is pratically impossible. In fact the behavior is controlled by the natural frequencies determined by the various modes of vibration of the structure, and in addition it is affected by the damping due to the technological characteristics of the structure.

The calculation of the natural frequencies of a system of n degrees of freedom, implying the determination of the amplitudes of all the modes of vibration, is out of the question for practical cases. Even for the simplest system, a beam on two supports, the degrees of freedom are infinite.

It is nevertheless possible to refer to very simplified "equivalent" systems, without departing too much from reality. Such a simplification would be to consider the masses of the system concentrated at certain points and to apply the appropriately modified loads at these points. Naturally, the choice of the simplified system requires a very thorough knowledge of the real behavior of the frame in order to assure a sufficiently faithful replica.

Some approximate methods giving the fundamental frequency corresponding to the first mode of vibration with reasonable accuracy have been developed by Dunkerley and by Rayleigh. The latter method, based on the principle of the conservation of energy, is best applied using the simplifications suggested by J. A. Blume and by M. Ifrim. It should be noted that Dunkerley's method always gives lower values and Rayleigh's method higher values than the exact ones so that one may bracket the true values by applying both methods. Using a matrix of displacements, S. A. Bernstein has established a "spectral function" permitting the determination of two values bracketing the desired frequency. Finally the iterative convergent method of Vianello-Stodola, which has become classic, allows the determination of the deformation of the system by successive approximations, departing from an arbitrarily chosen deformation thus leading to any desired accuracy.

However, one must realize that the exactitude of the calculations of natural frequency is in fact illusive because it depends on the mathematical methods used. Also several more realistic research workers have been led to propose simple empirical formulas based on the results of experiments or on theoretical considerations to express the natural frequency of structures.

The formulas proposed by T. Taniguchi, by the U.S. Coast and Geodetic Survey and by E. Rosenblueth respectively give the value of the natural frequency corresponding to the first mode of vibration as a function of the number of stories. Those of I. L. Korchinski, of F. P. Ulrich and D. S. Carder and of M. Takeuchi refer to the height of the buildings, whereas the formula of the Joint Committee ASCE-SEA, widely known under the name of "San Francisco formula", refers to the proportion of the same building height to the square root of the building width measured in the sense of the vibrations under consideration.

By applying the general theory of vibrations and the principle of d'Alembert and introducing some simplifying hypotheses, mass concentrated at each floor and infinitely rigid beams, M. G. Salvadori has established a formula giving the natural frequencies for all the modes of vibration of a multi-story building. A similar formula has been proposed by R. G. Merritt and G. W. Housner.

Based on the notion of a seismic shock spectrum and the natural frequency of a building, some very important research work has been undertaken, especially with the use of analogue simulators, in order to clarify the different aspects of the dynamic behavior of structures.

Diverse methods have been developed using various hypotheses concerning the type of simplified model of the frame and concerning the conditions of behavior in the non-linear zone. Among these one of the most general is that recommended by N. M. Newmark.

Besides the experimental studies mentioned on isolated elements and their joints, some tests have been undertaken, in Japan and the U.S. in particular, on real buildings subjected to excitation by pulsators installed at various levels. The information thus furnished concerns above all the determination of the natural frequency of real buildings. They are already numerous enough to have a certain statistical value.

Some tests, very much limited in number and scope, have even been made using explosions to create shocks in the soil.

This research, as useful as it may be, cannot replace observations (still missing) of buildings during a real earthquake.

Lessons Learned From Practical Experience

Wind

For long centuries practical experience has constituted the only source of information for the conception and the dimensioning of structures. In order to reconcile daring and safety one had to aim like artillery, first on this side and then on the other side of the limit of resistance.

Even today experience constitutes a valid source of information as a last resort, to confirm or destroy the hypotheses of the calculations and the value of the structures. The most instructive cases are those involving failures, that is to say accidents.

The information which one can gather in this way on the stability of buildings as a whole is nevertheless scarce enough, since there is no case of a collapse or important failure due to the wind in this type of structure. This proves that the present calculations are on the safe side. But by how much?

The scientific means available today should make it unnecessary to aim above the limit of resistance and permit us to reduce the margin of safety if research should show that it is excessive.

Earthquakes

Despite the numerous investigations undertaken on a theoretical level which have allowed us to explore the principal aspects of the problem, the safety of structures against earthquakes is still essentially based on empirical considerations. This is due not only to an insufficient knowledge of the forces and the complexity of the response of buildings, but also and above all because of the impossibility of establishing a precise relationship of cause and effect between the two for most known earthquakes for lack of necessary information.

The inquiries made after earthquakes have nevertheless permitted us to draw the conclusion that the safety of structures does not rest on conventional calculations alone, but also on their design and construction.

For example an essential condition to assure good earthquake resistance of a building consists of securely tying together all the constituent elements. This observation recures constantly in all the cases examined where often one encounters buildings which do not conform to the conditions of the calculation but have nevertheless resisted well. The author, incidentally, has been able to verify this personally during the catastrophic earthquake in Bucarest which he witnessed in 1940 and whose consequences he had to analyse, since no building with a steel frame suffered serious damage although the calculation of the frames were not made for such forces.

The consequences of several recently recorded earthquakes and the behavior of the buildings have been related to their type of construction and the materials used and, even more, the construction methods. Even though these studies can tell us nothing concerning the response of the building to a certain given force, they still offer valuable information relative to the adequate design and construction of buildings in earthquake zones.

Calculation and Design

Wind effects: a critical examination of the actual conditions used for calculation

All structural calculations necessarily include two fundamental parts which are also complementary: the determination of the forces, and with reference to these, the structural analysis. We shall briefly see how these points are treated as far as the calculation of multi-story framed structures with wind loading is concerned.

A critical examination of the basic data offered in the codes of different countries makes it appear that they have a more or less arbitrary character and therefore lack a precise probabilistic significance which is indispensible for a rational design. In fact no measures capable of realizing such design in the sense of a well controlled safety factor may achieve their aim so long as we do not dispose of data for wind action based on satisfactory observations and defined by precise criteria of probability and uniformly accepted at the international level.

As to the classic conditions for the calculation of frames in wind we see that they are based on a series of simplifying hypotheses: the introduction of loads in the form of static loads, action on an idealized frame with purely elastic behavior, a building without inertia, nonstructural elements included for the loads and neglected for their resistance, etc. It is possible that one or the other of these hypotheses is justifiable practically, but there is no incontestable proof of the cogency of such a calculation.

Nevertheless, despite the gaps in the basic data and in the fundamental methods of calculation the most recent construction codes have not failed to follow the progress recorded in the knowledge of aerodynamics and meteorology.

Thus we have seen the introduction of the notions of "normal wind" and "exceptional wind" which, if they really correspond to definite probabilities, constitute an important step ahead in the direction we have described.

The irregular wind distribution across large surfaces is expressed by a reduction factor which is a function of the dimensions of the surface acted upon.

Finally, the rapid variations of pressure which constitute a characteristic dynamic action, are expressed by a magnification factor which is introduced into the traditional calculations for the affected elements. Certain codes have recently extended the application of this factor to the calculation of the stability of entire multi-storied buildings. Nevertheless the basis of this measure does not seem to have been proved.

In any case the dynamic magnification factor should be applied only to values of pressure corresponding to the mean during a certain determined period of time.

The effects of earthquakes: A critical examination of the basis for calculation

In the case of multi-story buildings the determination of the permanent or live vertical loads does not present any problem. The determination of the wind loads, although still marked by certain inadequacies, should be capable of solution, provided that the required research is undertaken. For earthquakes, on the other hand, in view of their nature and the manner of their occurence, it is difficult to imagine, at least in the present state of our knowledge, obtaining precise information which would indicate clearly the relationship of cause and effect and which would have sufficient statistical value to "stick close to reality" in the building codes.

Moreover the calculation and the achievement of structures erected in earthquake zones must always be able to provide the resistance with a sufficient margin of safety against all the catastrophic consequences of some possible earthquake.

As for the structural analysis it must be noted that they are performed with the use of a seismic factor which is supposed to take into account all the influences that are present (i.e. force of the shock, nature of the soil, interaction of the soil with the building, distribution of mass, etc.) but whose value actually rather arbitrary and should be subjected to cautious interpretation. It is certain that the general conception of the frame, the joints, and to the same degree, the nature and method of attaching the so-called non-structural elements represent as important a factor which is not taken into consideration in the evaluation of the seismic coefficient but which exerts a far from negligible influence on the behavior of structures.

Introduction to the elements of probability

The dynamic calculation of a structure makes use of both the characteristics of the applied excitation as well as those of the structure itself in order to determine the response.

The essentially uncertain character of the parameters which define the telluric and aeolian phenomena and the complexity of the factors involving the behavior of structures subject to the actions of these phenomena indicates a perfect example of the application of the methods of probability. It is evident nevertheless that this sector is not up to date as compared to the present general orientation of structural calculations toward the methods of probability.

The explication is to be found, no doubt, in the lack of indispensable statistical data relative to the loads, on the one hand, and, on the other hand, in the difficulty of describing statistically in a sufficiently succinct manner as complicated a problem as that of the dynamic behavior of structures. Nevertheless in this case the methods of probability offer the only means of making a reasonable approach to reality. In addition the methods of statistical mathematics allow us to level off to a certain degree the blanks in the data, and offers us the means of obtaining a certain precision with a reasonable number of judiciously chosen observations.

In fact the problem which faces the engineer is that of achieving a reasonable factor of safety and at the same time considering the dictates of economics. In order to reconcile these two opposed considerations it is necessary to find a relationship between the loads defined in the stochastic sense and the behavior of the structure with reference to a fixed criterion of failure, the final aim being to obtain a margin of safety corresponding to the type of loads and the admissible risks for the structure.

Some notable contributions to the solution of this problem for loads of seismic origin have been made in particular by E. Rosenblueth, M. F. Barstein, V. V. Bolotine, N. M. Newmark and H. Tajimi. One approach to the same problem for the wind has been outlined by A. G. Davenport.

Nevertheless the question is a long way from being solved, not for lack of research, but because of the absence of statistical data capable of furnishing a valid basis for calculations.

Margins of safety

A calculation based on the consideration of probability must lead, as a function of the given conditions of the problem, to a well defined margin of safety for each category of risk, taking into account the probability of its occurence and the seriousness of the possible consequences.

For the buildings with which we deal we may classify the risk schematically in the following four categories:

uncomfortable sensation for persons inside a building;

minor disturbances involving limited material damage particularly in secondary and non-structural elements;

serious damage to secondary and non-structural elements and possible disturbance of the main structure, but involving practically no accidents to personnel;

serious damage to the main structure capable of causing partial or total failure of the building by static or dynamic instability, by plastic collapse or by fatigue which threatens to provoke accidents to persons.

As far as wind is concerned, the calculation must provide for all these risks for the case of velocities which are considered normal and for which the frequency of occurence is relatively large, but a certain perceptible movement may be tolerated in an exceptionally strong wind.

As for earthquakes, which in any case are much less frequent than the wind, and which have, by definition and by their very nature, the character of a calamity it is allowable to tolerate minor material damage for a relatively weak shock for the seismic zone under consideration and more serious damage for a relatively strong earthquake, all being a function of an economic study made in the same sense as that for an insurance policy for which one must decide deliberately to accept or reject such and such a risk rather than a higher construction cost. The final result is an economic consideration based on technical data.

Finally, all risk of the loss of humain life due to a collapse must always be rejected as a result of any reasonably predictable forces.

Studies Which may Contribute to the Advancement of our Knowledge

The effects of wind action

The effect of wind action as a whole on multi-story buildings are determined according to actual practice by hypotheses which have not been sufficiently established. It is indispensable to perform observations on real buildings including measurements of displacements, accelerations and stresses with simultaneous recording of the wind velocity and direction in order to determine the real correlation between their magnitudes as well as between their spectra. This research must be of statistical character and extended over a sufficient length of time and including several buildings of different characteristics in order to constitute a basis sufficient to formulate design rules and in particular to verify the application of a dynamic coefficient to the action of the whole building.

A particular attention should be devoted to the sensitivity of structures as a whole to gusts in order to determine their threshold with respect to duration and to verify the validity of the reduction factors for large surfaces.

For this it is necessary to undertake some systematic investigations, on actual buildings for example, in order to better define the relation between the durations of the gusts and the possible consequences of their action on structures. This relationship is still poorly understood and therefore not considered sufficiently in the present regulations for calculation.

The local action of the wind may create in certain zones of façades high and low pressures which may attain many times the value of the basic dynamic pressure.

A study using wind tunnel tests to corroborate the measurements on real buildings could be used as the subject of a systematic analysis of local pressures on the most exposed parts of building façades as a function of their form. The most favorable forms with reference to the whole as well as to the shape of the edges could be recommended.

The effects of earthquakes

If despite all the research undertaken on the subject, the design of earthquake resistant buildings is still made according to largely empirical criteria the principal cause is, without doubt, the lack of information on recorded earthquakes up to the present time. With some rare exceptions there have been no records which allow a valid interpretation of the damage observed during even the most recent earthquakes. Nevertheless only a direct confrontation of known loads and their effects could permit a conclusive comparison.

The impredictable character of telluric phenomena does not permit us to envisage a very systematic observation, this being always a function of the chance of having recording apparatus at the site of the next earthquake.

Some installations including instruments capable of recording the characteristics of possible seismic shocks and the response of the structure at the same time have been placed in several buildings in Los Angeles, San Francisco, Mexico City and Tokyo. Despite the high cost of these installations with respect to the probability of recording an earthquake at the chosen place it seems possible to create by international accord a regular network of observations by thus equiping a larger number of buildings with metal frames situated in regions notoriously subject to seismic shock. The chances of obtaining the missing information on the response of real buildings to a well defined earthquake within a reasonable length of time will be considerably increased. In addition a portion of the same instrumentation could be used also for the observation of the effects of wind on the same buildings.

Without awaiting the realization of such an important but not at all utopian action we could begin immediately to use the existing information to the maximum. Certain recent earthquakes have been the subject of very interesting descriptive studies despite the absence of the corresponding recordings of the shocks. Nevertheless a general study comprising a very large number of observations, even incomplete, would without doubt reveal some practical and useful lessons.

It would therefore be desirable to proceed on such a study of the synthesis of all the data which have been able to be collected in the world, if not during at least after the known earthquakes.

Perfecting the methods of calculation

During the course of the last years the methods of the dynamic calculation of structures have been subject to a spectacular development in the sense of precise analysis of the phenomena concerned. Nevertheless this precision is more or less clouded by uncertainty due to the simplifying hypotheses which these methods must use. Besides these methods neglect certain parameters whose influence is nevertheless considerable or else they are included in too imprecise a manner.

The perfectioning of the calculation methods should have as its objective the most faithful approach possible to the behavior of the real structure under consideration, taking into account not only the type of frame as well as the distribution of mass and stiffnesses but also the intrinsic character of the frame material, the dynamic behavior of the structural elements and their joints and of course the consequences of the presence of non-structural elements on the behavior of the whole.

The calculation methods should be developed in accord with the results of research undertaken with the aid of analog computers and with ample use of the possibilities offered by digital computers. Studies on hybrid computers allowing reference to all real recorded earthquakes or any "custom-made" fictitious shocks and permitting the consideration of all desired parameters providing that they are well defined, open very interesting prospects for research.

Naturally all kinds of calculations made in this way must be compared in the largest possible way with direct observations on real buildings since they are an indisputable source of information in the last resort.

Exploitation of the reserves of resistance in the non-linear range

Despite the importance assumed by the absorption of energy for frames in the non-linear range before reaching the ultimate strength, the behavior of multi-story frames undergoing cyclical loading in this zone has not yet been studied experimentally. Such studies must be undertaken, among others, in order to verify the evolution of the rate of energy absorption as a function of the applied loads, to determine the effect of successive plastic deformations following load reversals, and to observe the phenomena of hardening which may be produced and their influence on the strength.

The result of this research should furnish a basis for the consideration of this important reserve of safety in the rules for the calculation of structures for earthquakes.

Moreover, even considering the state of our present knowledge, these rules are seriously at fault with regard to this aspect of the problem, since the seismic factor does not satisfactorily take into account the inherent capacity and the characteristic of each type of construction. The regulations should, nevertheless, as is remarked by G. V. Berg, "reward" the capacity of energy absorption and penalize its absence.

An experimental investigation could be undertaken in the laboratory on steel bents with different types of fillings or façades in order to determine the influence of the latter on the behavior under dynamic load.

Joints

Even though it is recognized and experimentally proven that all well designed steel joints which are normally dimensioned and reasonably fabricated can resist dynamic loads of the same order of magnitude as the frame itself without damage, it seems worthwhile to proceed with further systematic studies to determine the characteristic limits of resistance of each of them and to classify them and possibly to develop new types which correspond better to the required qualities.

These studies should be directed at all the means and procedures in common use for joints and should consider distinctly the pieces of moderate dimensions and reduced thickness and those of large dimensions and greater thickness.

An individual study should be devoted to the specific behavior of joints using high strength friction grip bolts, a method in full development whose resistance against loosening has already been proved for other types of loads.

Properties of materials and of the structural elements

The primary qualities which are required of the metal for the type of loading with which we are concerned, ductility, resistance to alternating stress over a small number of cycles and for certain elements fatigue resistance, have already been widely studied for structural mild steel.

The use of new grades of steel having higher mechanical properties which are beginnig to find use in the construction of the frames of tall buildings incites us to investigate to what extent these qualities are still to be found in the new steels.

The phenomena of instability which can be produced in the elasto-plastic range under the effect of repeated or alternating loads has already been the subject of studies. These do not seem to have exhausted the subject when seen from the point of view of the behavior of frames as presented in this report. One of the points to be clarified is the influence of the extent of vertical static loading of columns on their resistance to transverse dynamic effects.

Conclusion

The problems concerning dynamic loads and their effects on tall steel framed structures have been raised only recently in all their complexity. Nevertheless the modern methods of research have permitted investigators to attain a wide knowledge of the phenomena which they involve.

Still this vast domain requires more supplementary information, especially on the basic data concerning the effects of wind and earthquakes and the effective behavior of real buildings, with all their structural and technological characteristics are difficult to include in a simple formula.

The orientation of future research should be toward a closer approach to reality for the benefit of safety, economy and the progress of construction.

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