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Autor: Forslind, Erik

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L'influence des sollicitations dynamiques sur les constructions

Einfluss dynamischer Beanspruchung auf die Bauwerke

Effect of dynamic forces on structures

ERIK FORSLIND
Swedish Cement and Concrete Research Institute at the Royal Institute of Technology
Stockholm

If a load is applied to an elastic structure very slowly so that the velocity u, imparted to the mass elements of the loaded member may be neglected in comparison to the velocity of sound v, in the material, the load is usually said to be static, otherwise it is called dynamic. The definition is one of practical convenience to be understood in the same sense as the practical definition of the elastic limit. In this paper we shall be mainly concerned with ratios $\frac{u}{v} > 10^{-4}$, in general corresponding to impulses generated by high explosives or impact of missiles.

Shock waves

The velocity of a wave in a compressible medium depends on the density of the medium in the way that increased density corresponds to increased velocity. It is accordingly possible to describe the generation of a shock wave as occurring in successive steps, where each subsequent part of the wave moves in an increasingly dense medium at a greater speed than its forerunners which will be successively overtaken. The steepness of the wave front will consequently increase and would finally become discontinuous, if such a physically instable state were not prevented by heavy energy losses. For the practical treatment of such a wave, however, the wave front may be described as discontinuous.

The shock wave emerging from a detonating explosive may for practical purposes be considered to consist of two parts, extending over different ranges from the center of explosion. In the first range the particle velocity is nearly equal to the phase velocity corresponding to the pseudo-discontinuous wave front and the wave is associated with a considerable transportation of mass. In the second range the particle velocity lags behind the phase velocity and the shock wave is successively transformed into an ordinary sound wave, in which the particle movements may be considered as infinitesimal. The zone of transition between the first and the second range is fairly well defined, as can be seen in fig. 1, showing a photograph taken immediately after that the wave front has left the expanding luminous detonation gases. The steep front of the shock wave may be seen as an oblate halfsphere which after short progress will take the form of a perfect halfsphere.

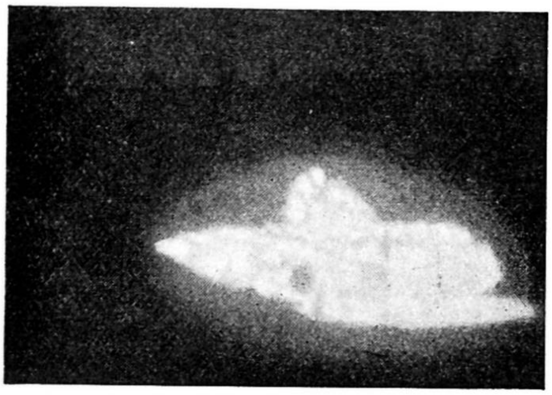

Fig. 1. Detonation of TNT in air. The visible wave front has just left behind the expanding luminous detonation gases.

For the present purpose it may suffice to state that the form of the waves and their impulses can be measured experimentally as a function of time, distance and the amount and type of explosive, and that impulses imparted to structures may be calculated from these data. For most practical purposes it is sufficient to know the total wave-impulse imparted to a plane rigid surface of unit area, while the wave form is unimportant. The last statement is justified by the fact that the time, during which energy is transferred from the wave to the structure, is usually very short in comparison to the transverse vibration period of the most common structures. We shall discuss this question in some detail later together with the characteristics of various types of structures. It should be mentioned, however, that the effect of the blast from an atomic bomb is expected to be different as a consequence of the very large total impulse and its long duration.

Impact

When a missile hits an object, the duration of the impact is determined by the elastic and plastic properties of the two bodies, their geometrical form and extension and the phenomena of rupture that may occur in and around the zone of contact. The impact may under certain conditions develop in a special way that is characterized by a secondary ejection of material from the hit structure. The elastic contact between the two bodies generates a set of compression waves which may be reflected at a free surface of the structure. Upon reflection it is turned into a dilatational wave progressing in opposite direction to the primary wave. A

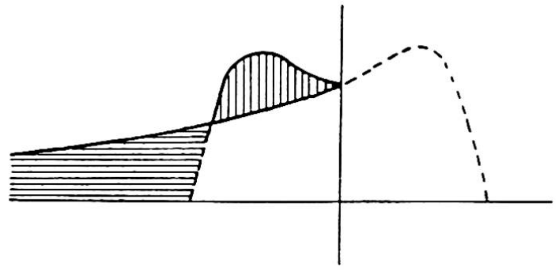

Fig. 2. Schematic representation of the reflection of a shock wave at a solid-air interface.

Compression in the primary wave.
Tension in the reflected wave.

simplified representation of the actually very complicated phenomenon is given in fig. 2. We see that a maximum of tensile stress is to be expected when the reflected wave has penetrated to a certain depth of the material. If the tensile stress exceeds the critical value for the material, rupture will occur and the part set free will leave the structure as a missile, often with a considerable velocity. It is also seen that a smooth wave with small variations in intensity cannot be expected to produce the ejection effect. The effect will generally lead to changes of frequency and boundary conditions of the structural member involved. Similar effects may also be obtained by detonation of explosives in contact with the material.

Behaviour of different building materials

For a heterogeneous and anisotropic material, the modulus of elasticity may be defined by means of the statistical mean value of the velocity of sound waves in the material. For steel this averaging effect may take place over volumes of material that are very small in comparison to the volumes of material used in structural engineering. Steel may consequently be considered as quasi-isotropic and the dispersion of a wave progressing through the material may be neglected. Such materials as brickwork and concrete, however, will require larger volumes for the averaging effect to take place and the dispersion of a wave passing through the material is considerable. This is particularly important to observe when dealing with shock waves, because the wave front will soon loose its steepness and the length of the wave group will be increased after a relatively short passage. By these materials, the elastic constants derived from static or slow loading tests differ considerably from those obtained by dynamic methods, because the plastic deformation which takes place in the former case is substantially eliminated when the test is dynamically conducted. The rate of loading, however, also influences the magnitude of the elastic limit and the rupture strength of the material. The same effect is also observed for steel, although to a smaller extent.

The resistance against local damage from impact is increased both for steel and concrete, if the modulus of elasticity is increased. It is well known, however, that the brittleness of steel increases with the hardness, as well as the risk of secondary ejection of material. A good armour-plate, for instance, must consequently possess good ductility on the rear side. As to concrete it has been empirically observed that the resistance against local damage by impact increases with increasing modulus of elasticity, i. e. with high contents of stone aggregates and increased density of the mortar. As the dimensions of the concrete structure increase, the dispersion of the primary waves will substantially reduce the risk of secondary ejection, which will be easily understood with reference to fig. 1.

The dynamic behaviour of various structural elements

Our discussion may be limited to three types of structural elements, viz. columns, beams and slabs, as the characteristic properties of most structures can be referred to these elements. If such a structural element is subjected to an impulse, a vibrational state is generated that may be considered to be composed of superimposed characteristic vibrations, each corresponding to a discrete energy level and a definite shape of deformation. The characteristic vibration frequencies and the deformation types are determined by the shape and density distribution of the structural element, the elastic and plastic properties of the material and the boundary conditions. A decrease of mass density, increase of the rigidity or reduced degree of freedom will generally increase the frequency and vice versa.

The characteristic functions, or eigenfunctions, are solutions of the general amplitude equation

$$\Delta\Delta\varphi - \lambda\varphi = 0$$

and satisfy the relation of orthogonality

$$\int \varphi_i \, \varphi_k \, d\tau = 0 \ (i \neq k)$$

The physical significance of the orthogonality relation is that the vibrational states corresponding to the separate characteristic functions may exist simultaneously without mutually disturbing each other, i. e. they are linearly independent.

The characteristic functions may be obtained as mathematically exact solutions of the amplitude equation or as approximate solutions to the variational problem. In the case of concrete, the modulus of elasticity determined by dynamical means must be used and the material may be treated as homogeneous and isotropic without consideration of reinforcement and microscopic cracks, provided that the interaction between the concrete and the reinforcement is intact.

A study of the characteristic functions of slabs subjected to various boundary conditions is being made at this institute by Mr. Ödman and it is expected that his work will facilitate the practical treatment of the problem.

Columns and beams

A column is usually designed for carrying an axial load, with due consideration to the question of stability against buckling. In practice, the actual load is either excentric or combined with a bending moment that will produce an initial lateral deformation of the column, whose carrying capacity is consequently determined by the stresses in the external fibres. When a vibrational state is set up in such a column by a lateral impulse, the superimposed stresses may eventually reach the critical value for the material and cause a collapse. Disregarding the practical impossibility of applying a centric load, the excentricity of the external load is always assured for a column of concrete as a consequence of the heterogeneity of the material and its capacity of plastic deformation. The amount of mass per unit length in relation to the surface exposed to the impulse will be greater for columns made of concrete compared to columns made of steel and the response to lateral impulses will be reduced. A design to reduce the risk of buckling will as a rule keep the initial lateral deformations and the secondary additional moments small.

Generally, the impulses corresponding to the second range of the detonation wave have no dangerous influence on the ordinary column, because it is designed for high buckling stability and exposes a small area to the relatively weak impinging wave. The above mentioned effect may, however, occur in the first wave range. For common explosives and ordinary conditions, the duration of the impulse is short enough to make the energy absorption of the column practically independent of its lowest characteristic frequency and we find from the impulse equation

$$mv = \int_{T} p\,dt$$

that more favourable conditions will be produced by increasing the mass of the column which will lead to a decrease of the initial velocity and the maximum amplitude. If the mass increment, however, is associated with decreased characteristic frequency, while the buckling risk at normal load remains unchanged, the favourable effect is counteracted. The mass increment should in other words be combined with increased rigidity. For designing purposes it is usually not necessary to calculate the reactions at the supports, unless the system is very rigid and exceptionally susceptible to shearing forces.

Partial destruction through impact will, as a rule, cause complete collapse of loaded steel columns. In the case of reinforced concrete columns, in which the plastic deformation has caused a transfer of load from the concrete to the reinforcememnt, even a superficial damage to the concrete surrounding the reinforcement may be sufficient to produce partial buckling of the reinforcement bars, which under unfavourable conditions may lead to a sudden collapse of the column. Usually, however, the central part of the concrete column has to be damaged, before its carrying capacity is appreciably reduced. The effect of a lateral impulse located at the base of a column will be discussed later in connection with various structural arrangements.

It is obvious that the behaviour of beams is in principle similar to that of columns, except that the absence of axial load and the presence of a lateral dead load will diminish the probability of damaging effects of lateral shock waves to a considerable degree. It is generally to be observed that damages to beams, due to blast, occur through secondary influence from surrounding structural elements.

Slabs

When a slab is subjected to a shock wave, the excited vibrational state is extremely sensitive to the loading and boundary conditions. It is consequently practically impossible to predict which mode of vibration will predominate, especially as the energy levels sometimes are very close and a sort of degeneracy occurs. Empirically, however, it has been observed that the real behaviour of slabs designed by use of one of the fundamental states is reasonably in accord with theory, provided that the impulse is close to the critical value for rupture.

As for beams it is usually not necessary to consider the reactions at the supports if these extend continuously along the edges. Discrete supporting arrangements necessitate a detailed analysis with regard to shearing effects.

If the slab is subjected to the detonation wave of an explosive in contact with the slab or the impact of a missile, the longitudinal compression wave will produce a local damage around the contact zone, eventually accompanied by a secondary ejection of material from the opposite side of the slab. It has been empirically observed that such local effects have very small influence on the characteristic frequency of the slab and that the damage must be extensive in order to produce an appreciable change. This implies that the structure of which the slab is an integrating part retains its normal function.

Types of structures

As representing the various possible combinations of the aforementioned structural elements three types of structures will be considered, namely the framework, the mushroom structure and the cell structure. All these represent structures which are highly statically indeterminate. Their main dynamical characteristics are fairly well known from the study of earth-quake effects on buildings and we shall limit our discussion to some questions that may be of interest for the planning and designing of factories or other constructions where explosions may take place.

For the framework and also for the mushroom structure a much discussed question concerns the advantages gained by the use of walls consisting of light-weight materials in order to reduce and limit the effects of blast on the carrying structure.

From theoretical considerations it might be expected that impulses transmitted by a shock wave, emerging from the center of a closed room where the distances to all walls are equal, will be absorbed in the same degree, independently of the resistance and the mass of the walls, provided that the fundamental frequencies are low enough to permit the impulses to be considered as momentary. In other words, if one of the walls should be removed without change of the boundary conditions for the remaining walls, the latter would be affected by the impulse in quite the same manner. This has, as a matter of fact, been verified experimentally. Should the intensity of the wave suffice to produce rupture, this could accordingly not have been prevented by making one of the walls less resistant. If, however, the residual static pressure of the explosion gases within the closed space is high enough to produce rupture, the effects will be abated, if one of the walls is easily destroyed. This advantage is, however, only apparent or fortuitous.

In a sufficiently limited space for the static pressure to produce rupture, the impulse by high explosives will be amply sufficient for producing it and the static pressure will be of less consequence as it will only complete the destruction. The explanation of the favourable effect sometimes observed as arising from the premature destruction of one wall may be sought in an inadequate design of the structure supporting the walls horizontally, or the roof vertically. For instance, the tensile stresses set up in a reentrant corner usually start the destruction at impulse intensities far below the intensity producing rupture in the central part of the slab, and a rapid decrease of the static pressure will consequently be favourable. With properly designed walls of uniform and equal strength, no damage at all would have occurred. The guiding principle for the design should be to assure a satisfactory resistance to the shock wave.

In factories and similar buildings, where the amount of explosives contained in a limited space can be controlled, it is technically and economically possible to give the room suitable volume with regard to the permissible static gas pressure. The walls should be designed to resist the shock wave so as to prevent damage to adjoining rooms.

With reference to the discussed questions it will thus be seen that the advantages which are claimed to be gained by framework or mushroom structures are much overrated by this type of load. In our opinion, the most adequate construction is provided by the cellular system as composed of elastically clamped slabs, limiting the damaging effects to the closed cell. Constructional systems of this kind must be considered as the most effective for avoiding total damage by locally occurring explosions and they should be used more frequently for factories and other constructions where risks of explosion are involved at operation.

From a general point of view, and especially with regard to shock waves transmitted through the subsoil, all the structures discussed are particularly well adapted to withstand dynamic action. Even if one or several of the carrying parts are destroyed, the statically indeterminate system will continue to function, causing a redistribution of loads and stresses but preventing the structure from collapse.

Damage to foundations may be caused by shock waves generated in well graded moraine soils. Such shock waves generally occur as longitudinal waves and are easily dispersed by applying a filling of stone around the structural element. If the detonation takes place below a certain depth in layers of plastic clay, however, more dangerous effects may be produced. Besides a primary longitudinal wave, a transverse wave of great amplitude and low frequency is generated, the propagation of which is confined to the surface of the layer. This latter wave, from which damage may arise, resembles the Rayleigh wave, with accelerations comparable to those occurring in earth-quakes. The range of propagation and the energy content, however, are rather limited and depend on the properties of the clay layers and their boundary conditions. The absorption of the wave energy by an ordinary, heavy structure, founded on clay with the load concentrated on pile groups or distributed over a continuous slab, is in general so complete that the wave is extinguished by the obstacle. On

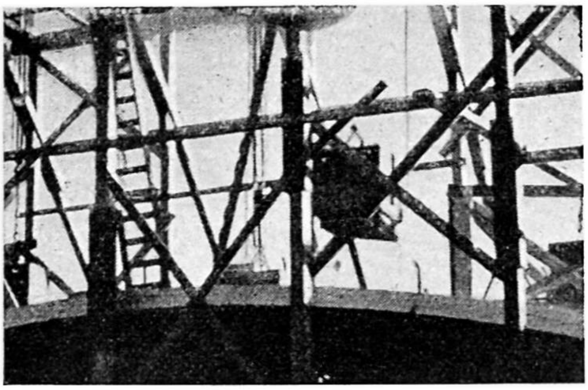

Fig. 3. Impact load on a 9.5 cm reinforced shell roof with a clear span of 14.2 meters. A concrete block weighing 1 000 kgs is released from a height of 3 meters. The picture was taken immediately before the impact.

account of the relatively small energy content of the wave, the effects will only be local and the risks of damage will as a rule be restricted to the pile groups. Rupture would, however, only occur in the immediate neighbourhood of the center of explosion and the risk of damage to the structure as a whole would thus be greatly reduced or entirely eliminated, if the possibilities of redistribution of load from the damaged group of piles to the surrounding ones were assured by an adequate design. Even in this case the cellular structure is less sensitive to local damage of the foundation. Although the framework or the mushroom structure may represent good solutions of the structural problem, the cellular system should be preferred if other circumstances allow it.

In such cases, where a structure is designed for the sole purpose of protecting people or machinery from heavy falling objects, as for instance linings in rock tunnels, the construction should permit a high deformation in order to reduce the risks of damage by piercing.

Figures 3 and 4 show an experiment which was carried out in order to verify the theoretical treatment of local impact on a thin concrete shell roof with a clear span of 14.2 meters and a height at its centre of 1.25 meters. The shell was 9.5 cm thick and was reinforced with 5 mm bars, spaced at a distance of 65 mm. A concrete block, weighing 1 000 kilos, with an effective impact area of 47.5 $\times$ 47.5 cm was released from a height of 3 meters. The two pictures show the undeformed shell, respectively its maximum deformation. The test was repeated with a sharp rock replacing the concrete block and in both cases the missile was arrested by the shell, although a certain amount of local penetration occurred, as is shown in fig. 5.

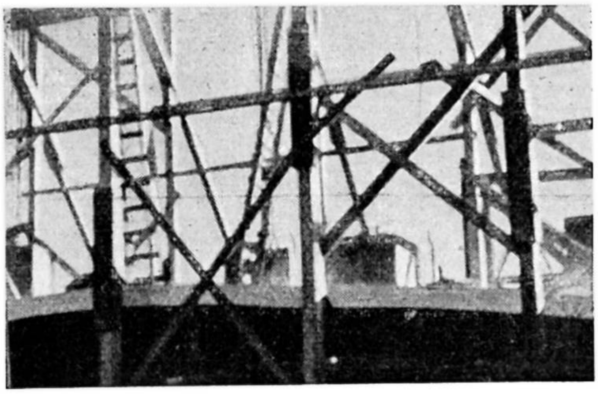

Fig. 4. Conditions as in fig. 3. The deflection of the shell under impact is clearly shown in the picture.

Fig. 5. Local penetration of sharp rock weighing 2 000 kg and falling from a height of 3 meters on the shell roof shown in figure 3.

In another test with a 2 000 kilos missile, the observed vertical deformation, without serious damage to the shell, was 25 cm.

Résumé

La nature des sollicitations dynamiques produites par explosion ou choc est discutée; les propriétés caractéristiques et le comportement de quelques matériaux de construction sous l'effet de sollicitations dynamiques sont étudiés; l'auteur étudie également les déformations subies par trois éléments de construction (colonnes, poutres et dalles), ainsi que le comportement de ces éléments dans diverses constructions.

Zusammenfassung

Die Art der dynamischen Beanspruchung bei Explosion oder Stoss wird besprochen; die charakteristischen Eigenschaften und das Verhalten einiger Baustoffe des Hochbaues unter der Einwirkung von dynamischer Beanspruchung werden in aller Kürze behandelt, ebenso wie die charakteristischen Formänderungseigenschaften von drei typischen Konstruktionselementen, nämlich Stützen, Balken und Platten. Einige Erfahrungen über die Wirkungsweise der besprochenen Konstruktionselemente in verschiedenen Bauwerken werden erörtert.

Summary

The nature of dynamic load as produced by explosives and impact is discussed; the properties and behaviour of some building materials under the action of dynamic load are briefly related and the characteristic deformation properties of three typical structural elements, viz. columns, beams and slabs are discussed, as well as some questions with regard to their mode of function in various structural systems.