THE DAVID TAYLOR MODEL BASIN
CARDEROCK, MARYLAND

APPLIED MECHANICS SECTION

RESISTANCE OF STRUCTURES TO EXPLOSIVE LOAD

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APPLIED MECHANICS SECTION
INTRODUCTION TO DYNAMIC TESTING

With the beginning of active preparation for National Defense, this Section enters upon a period of intensive effort and at the same time upon a new field of activity.

We are well acquainted with the way that our structures bend and yield under load; we must now inform ourselves equally well as to the effects of time and of inertia. We must adjust our basic ideas to the fact that every load applied to a ship structure varies with time. We are adjusting our tools and our methods of work to take account of time effects, but the hardest and yet most necessary change is in our ideas.

We must maintain and increase the services of test under steady load, and of clear statement of the results of test in a form useful to ship designers. But we must also discover the results of load variation and point the way for use of these results in ways for which not even nominal methods exist as yet in ship design.

Time variations of load are cyclic and transient, slow and fast.

Slow cyclic loads are not much affected by inertia. Some kind of autographic record is needed, but records by motion picture camera, if synchronized, tell the whole story.

Slow transient loads, as in rolling and pitching, require the same methods as slow cyclic loads, but analysis of the data is harder.

Different means of observation and analysis are needed as soon as rate of load variation rises toward values which occur in vibration of the structure in one of its natural modes.

Fast cyclic loading induces standing waves in the structure, to which all considerations of forced vibration and resonance apply.

Fast transient loading induces wave-like transmission of stress throughout the structure.

When rates of loading rise to values obtained by high order explosion, inertia plays a predominant part.

As the tensile test specimen gives the simplest example of static action, so a straight bar illustrates the kinds of varying action just described.

If the bar is loaded axially at one end by tension and compression, slowly and smoothly alternating, holding it at the opposite end causes a reaction which follows the load. Stress varies with time in the same way throughout, since it also follows the load. The chief question as to the behavior of the bar is concerned with its endurance. Even if the load cycle is not repeated, but follows irregular variation, these results are the same.

If a slowly alternating load is applied in the same way to one end of the bar but the opposite end is not held, the bar refuses to accept the load, but moves in response to the small values of force. Its motion is substantially that of a rigid body and the only forces are those which go with the small accelerations.

But if the cyclic load is speeded up to a frequency near the natural frequency of free oscillation, the bar will ring like a bell, and large loads and stresses can be brought into action. And in particular a transient blow, if quick enough, though it may cause almost no motion at all of the bar as a whole, can easily cause stress exceeding the yield point.

The response of the bar to a slowly applied load is to move like a rigid body and if the bar is not constrained, it will offer little resistance, and so avoid the load. But if the load is applied so quickly or so persistently that the inertia of the bar will not permit it to avoid the load, then it will momentarily accept it. A cyclic load, in unison with the natural frequency of the bar, can thus induce high reactions even though the bar is not held, and the stresses may be much higher than under a static load equal to the amplitude of the cyclic load.

A sinusoidal load, applied for a single cycle only, in unison with the natural frequency of the bar, will start vibration which will continue for many cycles with slow loss of amplitude. But this vibration is accompanied by no motion at all of the center of mass of the bar.

A similar but faster transient load, lasting about a quarter of the natural period of the bar, will excite a continuing vibration in the natural frequency.

But a transient load whose whole duration is much shorter than one cycle of the fundamental frequency, say one tenth or less, has an extraordinary but fundamental consequence.

Upon cessation of the load the stress in the metal adjoining the area where the load was applied also ceases, as might be expected. The stress at such a point quite naturally follows the load, as it would even if the load varied slowly. The curve of stress at this point on time has exactly the same form as the curve of load on time.

The curve of stress on time is also repeated at points more distant from the loaded area, again as if the load varied slowly and again with exact duplication of the details of variation of load with time.

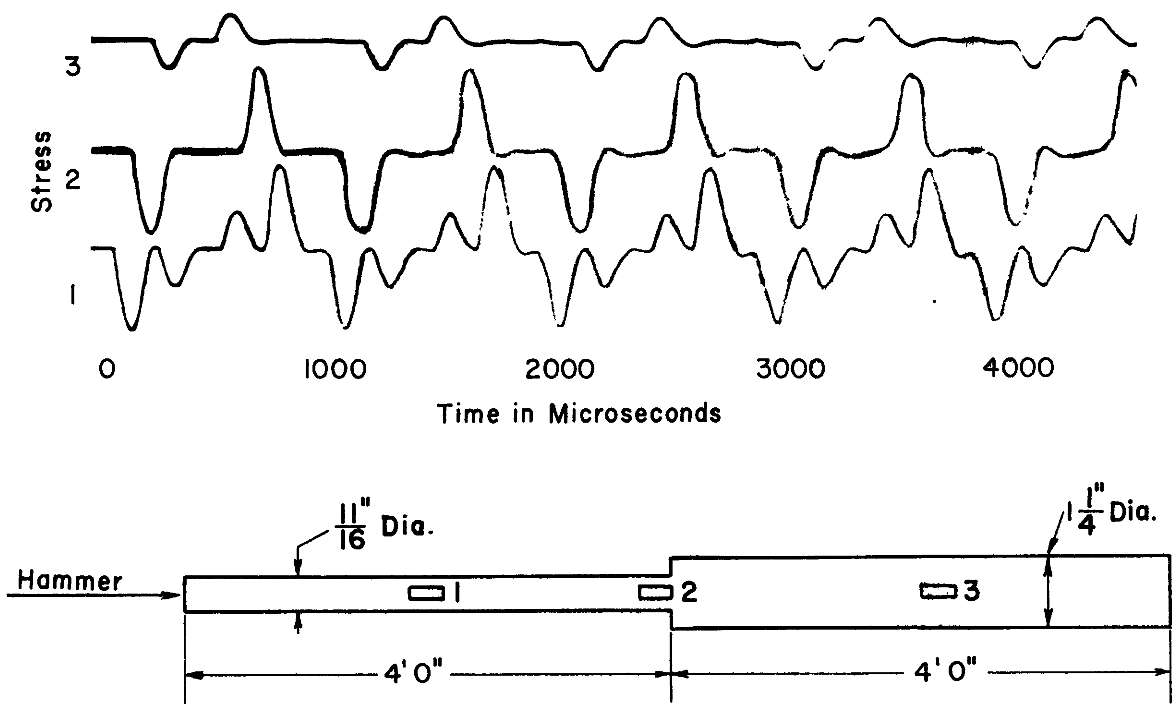
The surprisingly novel feature of what happens at a more distant point is that it all happens at a later time. Stress persists after the load has ceased, although in the locations where this occurs, there may have been no stress at all while the load was acting.

All this is implied in the common statement that stress in an elastic structure at points distant from areas receiving external load is generated by wave action. The curve of stress on time at the point where the stress wave originates is later duplicated by the curve of stress on distance in remote regions of the structure. The function expressing the relation of stress with time and distance always has the form

$$\text{stress} = F\ (ct-x),$$

c being the velocity of sound in steel. The series of values of this function at a given value of x are identical with those at later times at a larger value of x.

Stress in a freely suspended bar caused by a light blow at one end, as observed by the new methods available, is shown in the photographic record herewith. This demonstrates the time required for transmission of stress. The effects of reflection of the stress wave from the ends and from the shoulder are also shown.



Axial Stress in a Struck Bar.

The consequences of stress transmission, as shown here in a simple case, when applied to extended assembled structures, are intricate and difficult to follow. The complications are greater than are those of stress concentrations under static load. However, just as we have learned the nature and the effects of static stress concentrations, so it now becomes our task to reach a similar understanding of the effects of structural practices in the light of the delayed transmission of stresses from transient loads of very brief duration.

APPLIED MECHANICS SECTION
RESISTANCE OF STEEL TO SHOCK LOADS

In continuation of the program of study of properties of steel at high loading rates, Professor de Forest has recently forwarded oscillograph records demonstrating the following high speed phenomena:

(a) Axial stress, axial propagation of stress, and reflection of stress waves in a bar freely suspended and loaded by a hammer blow at one end.

(b) Fluid pressure in a cylindrical tank of water loaded by a hammer blow on the flat bottom.

(c) Hoop stress in the cylindrical wall of a tank filled with water, loaded by discharge of a detonator in the water.

(d) Peripheral stress, axial propagation, and regular reflection (after a period of transient confusion) in a bar loaded by discharge of a detonator in a capsule of water temporarily attached to one end of the bar.

In discussion of these results with Professor de Forest, it was agreed that the bar and the cylindrical tank represent simplified cases well adapted to the study of rapid fluctuations of stress following shock loads. They bear the same relation to assembled structures as does the simple tensile test bar in the case of static loads.

An axially loaded bar serves especially well to demonstrate the fact that when time rates of load variation exceed the time rates occurring in axial vibration of the bar in its fundamental natural frequency, the deferred transmission of stress at the speed of sound enters into the phenomena in a decisive way.

The cylindrical tank, on the other hand, isolates the time variable by the symmetrical disposition which serves to load all sectors of the cylinder equally. The simultaneous measure of hoop stress in the cylinder and of pressure in the fluid offers the best correlative to the stress-strain relation in static testing.

A frequent, possibly invariable feature of load produced by high order explosion in a fluid is the succession of two phases:

Phase A. A very abrupt rise in pressure, in which the maximum is reached in a few microseconds or even more quickly, followed by an equally quick fall, perhaps to negative values, followed by additional usually smaller fluctuations of the same order of frequency.

Phase B. A much more gradual rise of pressure, taking hundreds of microseconds to reach a maximum, and without any ascertained oscillatory tendency.

For preliminary orientation, the following considerations are presented:

1. Axial propagation in the bar, both from hammer load and from explosive load, is observed to follow expectations, both as to speed and to mode of reflection from discontinuities. Stress gradients from explosive load are much steeper than under hammer load.

2. In De Forest's cylinder a mode of vibration in which the radius of the circular section varies cyclically and uniformly, is estimated to have a frequency of about 4000 per second, and a frequency in rough correspondence with this value is observed in hoop strain in the cylinder after explosive load.

3. The B phase of explosive load seems incapable of exciting a vibration of frequency 4000 per second, since its time gradient is relatively so low that it operates like a static load.

4. For a vibration of the type and frequency mentioned, an amplitude which would develop stress approaching the yield point implies accelerations amounting to thousands times g.

5. A shock load applied to an initially undeflected elastic structure (such as a diaphragm) for 1/10 of one cycle of the natural vibration of the structure, and then cut off, starts motion which continues until a maximum deflection is reached, after which return begins. The intensity of the stress accompanying this maximum is of the same order as would occur if the load thus applied abruptly were instead applied statically.

6. The energy content of explosives is small compared with that of coal. Their destructive power undoubtedly depends on the high speed of pressure generation. It would be paradoxical to suppose, however, that brief duration alone could increase the power of a given load to cause damage to a steel structure.

7. But if brief duration is accompanied by high intensity of load, it is possible to impart to the loaded part of the structure a high velocity before its movement has resulted in appreciable deflection; this is termed impulsive loading. The parts of the structure thus set in motion are gradually brought to rest by the elastic constraints in a time equal to 1/4 cycle of the natural frequency.

8. Under impulsive conditions, only the parts of the structure on which the load acts directly are affected by the load intensity directly. Aside from such local effects, the behavior of the structure is determined rather by the time integral of the load. The pattern of stress distribution at maximum deflection may, however, be quite different from that which would be caused by uniform static load. Thus a uniform impulsive load would start the whole area of a diaphragm off at uniform velocity, but since the resistance to motion of the diaphragm originates at its edge, that would seem to be the region in which the stress would ultimately reach the highest value.

9. All of the points mentioned in the preceding paragraphs refer mainly to behavior of an elastic structure within elastic limits. In general the significant consequences of shock load are those which occur above the yield point. Discussion of behavior of structures under shock load causing rupture has hitherto dealt mainly with energy absorption prior to rupture. In order to obtain a more detailed analysis of these phenomena an answer must be obtained to the question: What characteristics of load determine rupture? When that point is better understood, better progress will be made on the main problem: What characteristics of a structure help it to resist shock load?

10. The application of an impulsive load of such intensity that yield point is exceeded in the loaded area must result in plastic flow during the impulse. The impulsive yield point is higher than that which is found by static test, but it is supposed that it is only moderately higher, say double the static value, and that it is definite, so that when and where stress intensity reaches that limit, plastic flow begins and proceeds to a point determined by further interactions between load and structure. A hypothesis as to what stops this plastic flow may be stated as follows:

> When the speed of load application has dropped to a point below the speed of stress propagation in the structure, the stress wave in its A phase detaches itself and moves away from the load. The compressive front of the stress wave is followed by a reversal, if not to tensile stress, at least to great reduction of pressure, and the load is thereby relieved.

11. It appears to be a consequence of this hypothesis that the uniform propagation of the stress wave into parts of the structure at a distance from its origin at the loaded area can lead to plastic flow only where concentrations of energy are caused by discontinuities in the structure traversed by the wave.

12. On the other hand, it is a fact known to all riveters that whereas a hammer that is light in proportion to the size of the rivet is effective mainly in working the metal near the point of impact, a heavier hammer can produce a more penetrating effect. The conditions under which this is done include support for the opposite end of the rivet (holding-on), lateral constraint, high temperature and temperature gradient. These conditions are too intricate to permit simple explanation, but the fact remains that blows can induce plastic flow in regions distant from the point of impact, and this action is favored by increased weight of hammer.

13. And finally, it is an equally clear fact that, by explosive load, rupture can be obtained under circumstances which the foregoing comment fails to explain. If a given charge be detonated in each of a series of cylinders, all, say, 30 inches by 60 inches, with wall thicknesses ranging from high values downward, the result in the heavy cylinders will be simple projection of the water upward, in the light ones destruction of the cylinder. Projection of the water is due to load in the B phase, but in view of the times involved, this is an impulsive load on the water. If the velocity with which the water starts upward is of the order of one to two hundred feet per second, the time required for the water to leave the cylinder is about 0.02 second. The acceleration is thus about 300 g. With the charge at a depth of 30 inches below the surface of the water, this corresponds to a pressure of about 300 pounds per square inch.

Now, on the cylinder, this acts as a static load. The nominal formula for hoop strength of a cylinder of medium steel of 30-inch diameter gives a bursting pressure in pounds per square inch of 4000 times wall thickness in inches.

It is evident that these considerations do not account for the actual effect of the explosive load.

The resolution of these contradictions is the task before us, and our chief resource is the experimental method now available for measurement of strains and pressures. Continued activity will follow the lines, first, of further adaptation of the instruments to the specific problem of the resistance of medium steel structure to underwater explosions; second, formulation of specific questions to which experimental answers can be obtained, for guidance in layout of extended tests. Perhaps the most important need of all is to free our minds of preconceptions so that the data, when obtained, may receive unbiased analysis.

Professor A.E.H. Love, F.R.S., has supplied the following notes:

The immediate effect produced by the explosion is the formation of a "bubble" of gas. The bubble expands very rapidly, especially at first.

The water in contact with the bubble becomes violently compressed, and a compressional wave of finite amplitude is propagated through the water.

The disturbed water, at any instant, is bounded by two surfaces. The outer bounding surface is the "front of the wave"; the inner is the boundary of the bubble. Both are moving outwards.

It is impossible to trace the change which takes place immediately after the explosion, but after a very short time, a regime is established which has definite features. The very short time in question is probably not much greater than the time required to develop the maximum pressure in the gas, almost certainly less than twice this time.

The features of the regime subsequently established are as follows:

1. The pressure of the gas within the inner boundary diminishes as time goes on.

2. The velocity with which the inner boundary expands also diminishes.

3. The velocity with which the front of the wave moves outwards exceeds the normal velocity of sound in water, and it also exceeds the velocity with which the inner boundary expands. As time goes on, the velocity of advance of the front diminishes.

4. The velocity of the water in the disturbed region increases from the value at the inner boundary to the value at the front. The value at the front is less than the velocity with which the front advances.

5. As time goes on the velocity of the water diminishes.

6. The pressure in the water increases from the value at the inner boundary, equal to the instantaneous gas pressure, to the value at the front of the wave.

7. The pressure at the front of the wave diminishes as time goes on.

8. The pressure and velocity at the front of the wave diminish more rapidly than they would if merely affected by spherical divergence, that is to say, more rapidly than would be expressed by a law of inverse

proportion to the distance.

9. As time goes on the velocity of advance of the front tends to a limit, which is the normal velocity of sound in water; the velocity of water just inside the front tends to a limit, which is zero. The pressure just inside the front tends to a limit, which is the undisturbed pressure of water at the depth of any point of the front. It is probable that, if the theory could be worked out by a rigorous analysis, these limits would be found to be attained only after an "infinite" time, but practically attained after a comparatively short time, such as 1/10 second (B.I.R. experiments indicate about 1/500 second for this value).

When the compressional wave reaches a fixed, rigid obstacle, reflexion takes place, as if a wave generated at the obstacle moved inwards toward the gas bubble. Between the obstacle and the front of the reflected wave there is a disturbed state expressed by the proper superposition of the two waves. For ordinary sound waves the effect would be that the pressure against the obstacle would be twice the pressure in the incident wave. For waves of finite amplitude the pressure is more than doubled, though it is impossible to state the ratio in which it is increased. It has been proved that for plane waves in air the ratio may be as much as 8:1. For three-dimensional waves in water it may be higher.

The destructive effect of an explosion at a moderate distance is almost certainly due to the high pressure at the front of the compressional wave, enhanced by reflexion from the ship or other object encountered in the wave.

Most of the observed phenomena, as recorded, for example, by P.F. Chalon in "Les Explosifs Modernes", pages 607 et seq., appear to be explicable on these principles. For example, it is easy to see why floating objects should be thrown upwards before there is any appreciable disturbance of the surface, and why greater effects (e.g., higher column of spray) are produced at the surface by explosions at smaller depths. The multiple sounds heard would be accounted for by reflexions of the compressional wave at the surface of the water and at the inner boundary.

CONFERENCE OF 16 – 20 SEPTEMBER 1940

ON

RESISTANCE OF STRUCTURES TO EXPLOSIVE LOAD

DETAILED TOPICS TO BE CONSIDERED

A period of intensive consideration of resistance of steel structures to explosive load will occur at the David Taylor Model Basin during the week of 16 to 20 September 1940. Its purpose is to clarify understanding of the phenomena involved in underwater attack on ship structure.

An all-day conference will be held at the National Academy of Sciences on Thursday, 19 September. Its purpose is to bring the previous discussion to a rather definitely summarized form, and at the same time to obtain the benefit of comment from others unable to be present except for this day only.

Although it is expected that as many as 12 or 15 persons will be present, the discussion will be held on a confidential basis. It will not be extended, however, to include specific details of construction of underwater structure, but only the general phenomena involved.

The subject matter to be considered has two phases, referring first to the conditions of loading or excitation of the structure, and second to the response of the structure, its strain, plastic deformation, and rupture. The morning session will be devoted to the first of these and the afternoon to the second.

The load to be considered is the pressure generated by high order explosion in water adjoining but not in direct contact with the structure. The variables affecting this load are fairly well known, their functional relationship with load somewhat less so, and the time variation of the pressure only very imperfectly. Theoretical knowledge of explosive pressures needs to be clarified and the valid inferences which may be drawn from general principles by analytical processes need to be made more readily available in physical terms.

The experimental measurement of pressure originating in explosions has recently taken new lines of development through application of electronic methods. These need to be reduced to standarized form and use, with acceptable procedure in calibration. Comparison of older gages of crusher type with newer gages giving the time variation in detail should throw new light on old experimental data, which are very copious. Theoretical study should furnish guidance for design and use of gages, especially in view of the dynamic and non-isotropic nature of the pressure to be observed.

Turning to the response of the structure, it is noted that the new electronic methods are also applied to the direct measurement of strain in the metal, and that these have the merit of almost complete elimination of extraneous inertia in the measuring system. This is the main resource in trying to obtain more valid data than in earlier work, and it is hoped that these may afford a basis for more rational understanding of the basic phenomena in the structure.

The application of the model method is dependent on knowledge of the effects of size and speed of loading on the behavior of the metal, and this is more necessary, as well as more difficult, in connection with plastic than with elastic effects.

While use is made of similitude in current work, it is hoped that progress may be made toward the more intimate understanding of the phenomena that will ultimately permit design by calculation only without need for models incorporating the specific structural details proposed. For such a purpose it is believed necessary not only to deal with total absorption of energy from the explosive load by the structure, but to segregate that part of the energy which precedes the decisive rupture. The variables controlling initial rupture include rate of initial strain, peak value of stress attained, and duration of the load. The task may be defined as the determination of the functional relation of these (and perhaps other) variables with the physical properties of the metal which establish the criterion of failure; and, ultimately, the development of a type of structure which will defer rupture to higher values of these parameters.

These considerations may now be restated in more specific form. We are confronted with the following questions: What is the sequence of events in a fluid medium which surrounds a fully exploded bomb? How does the disturbance in the medium react when it encounters physical objects immersed in the medium? How does the structure encountered respond to the action of the explosive disturbance?

When a structure is distorted, permanently deformed, or ruptured, work has been done upon it. A change of configuration in any system implies the absorption of energy – except in certain hypothetical cases. The essential mystery of indirect explosion damage is that it is caused by a small percentage of an initially fairly small released energy. This indicates that energy flux into the structure cannot account for the observed phenomena in itself. The mechanism of energy expenditure must be the important thing. Force, impulse and power are perhaps the important concepts around which explosion studies must center. All of these quantities can take on enormous values even when associated with moderate energies since they are associated with space and time rates of change of the energy.

$$\text{Force} = \frac{dw}{dx}; \text{ the space rate of change or absorption of energy}$$

$$\text{Power} = \frac{dw}{dt}; \text{ the time rate of change or absorption of energy}$$

$$\text{Impulse} = \int \frac{dw}{dx} dt = m(v - v_0); \text{ momentum changes}$$

If all the energy expended in rupturing the hull of a ship were applied to the hull slowly, it would merely change the velocity and position of the ship slightly. If it is applied rapidly the ship becomes a relatively fixed object as a whole – the effects become localized to the area of energy in flux. The resultant relative motion becomes damage.

What are the important concepts and quantities that should be measured in studying explosion effects?

What instrumentation is needed to measure the significant quantities?

What are the effects of the above mentioned quantities on structures and materials. The resistance of materials to loads and their deflections in the elastic region are well known. The resistance of materials in the plastic region is still the subject of controversy and development even in the region of small velocities of deformation. It might even be stated that the static problems in plastic deformation are so difficult that very few of them have been solved. The field of high velocity and accelerated deformations in the plastic region has remained almost untouched. Finally, the mechanism of complete rupture is not yet fully agreed upon.

These considerations and questions suggest that the specific focal points of discussion could well be:

1. The mechanism of an explosion disturbance in a fluid medium.
2. The interaction between immersed structures and the explosion disturbance.
3. The significant concepts and the quantities to be measured in explosion studies.
4. Instrumentation to measure the significant quantities.
5. The properties of materials in high velocity and accelerated deformation.

PROCEEDINGS OF THE CONFERENCE OF 19 SEPTEMBER 1940

1. This conference on resistance of structures to explosive loads was held at the National Academy of Sciences. It was called by the David Taylor Model Basin to bring together technical personnel from several government agencies interested in this topic from different points of view, theoretical as well as practical, and so to permit an exchange of ideas regarding fundamental features of the problem. It was hoped that the conference would lead to results of value for guidance in the experimental projects at the Model Basin.

2. There were present

(a) from the David Taylor Model Basin:
Capt. H. E. Saunders, USN
Lt. Comdr. W. P. Roop, USN
Lt. Comdr. J. Ormondroyd, USNR
Lt. A. C. Ruge, USNR
Dr. J. M. Frankland
Mr. G. H. Curl

(b) from the Bureau of Ships:
Capt. L. P. Smith, USN
Lt. P. W. Snyder, USN
Lt. H. R. Garner, USN
Mr. E. Rassman

(c) from the Material Laboratory, New York Navy Yard:
Lt. Comdr. J. L. Bird, USN
Mr. J. Lind
Mr. W. H. Hoppmann

(d) from the Ordnance Laboratory, Washington Navy Yard:
Mr. H. H. Moore

(e) from Naval Proving Ground:
Dr. L. Thompson

(f) from the Army:
Col. G. F. Jenks, Ordnance Department
Maj. F. J. Wilson, (CE)
Mr. L. B. Smith, Eng. Corps
Mr. Robert R. Kent, Aberdeen Proving Ground

(g) from the National Research Council:
Dr. R. C. Tolman
Dr. J. E. Burchard

Dr. H. P. Robertson
Dr. W. H. Rodebush
Dr. G. B. Kistiakowsky
Dr. T. L. Davis

(h) from Massachusetts Institute of Technology:
Prof. A. V. deForest
Lt. A. R. Anderson, USNR

(i) from the National Bureau of Standards:
Dr. G. H. Keuligan
Mr. G. W. Patterson

(j) from the Westinghouse Electric and Manufacturing Company:
Dr. A. Nadai

3. Captain Saunders presided over the meeting and called upon Lieutenant Commander Roop who made the following introductory remarks:

"Two schools of thought are represented here, to which the problem of resistance of structures to explosive loads presents itself in different ways.

"All of us desire to learn how to build structures of high resistance to such loads.

"Some of us are familiar with the long history of the problem in its empirical and practical aspects, which goes back to the work of General Abbott of the U. S. Army, seventy-five years ago, and continues right down to the present moment. This arduous process of trial and error has produced results; these are at the moment our main resource, and it will not be possible, on short notice, to obtain much improvement in them. These results are highly confidential and for that reason, as well as others, it is not appropriate to discuss them in an assembly as large and as heterogeneous as this.

"I repeat that it is not the purpose here to deal with the practical problem. That is receiving intensified consideration by other agencies.

"Our actual purpose is rather to clarify ideas. Some of those present, though not hitherto concerned with the need for increased structural resistance to explosions, have information and understanding of the principles and the behavior of the materials involved.

"The purpose of this meeting is to bring these two streams of thought together. Those who approach the subject from the more abstract standpoint may find that the situation with which they have to deal will come to appear to them in somewhat more specific form. For those who have the responsibility for practical developments, it is our hope that this may result in better understanding of the limitations under which they must work, and so of the possibilities which will be opened to them if more rational explanations of the phenomena can be found."

4. Dr. L. Thompson opened the discussion of the mechanism of an explosive disturbance in a fluid medium. Speaking first of the character of the disturbance in air, he said that when detonation is complete in the explosive, a shock pulse leaves the surface of the explosive and is propagated outward, with a velocity which is initially very nearly that of the velocity of detonation in the explosive, that is, from 16,000 to 23,000 feet per second. Although particle velocities in air nearly equal the velocity of propagation of the shock-wave front, they are relatively less than the latter in water because of its greater mechanical impedance, or radiation resistance, measured by the product of density and speed of sound.

Following the shock pulse there is a bodily motion of the fluid pushed out by the expanding explosion products. Velocities of surface upheaval of 1000 to 2000 feet per second have been observed in submarine explosions. Dr. Thompson described an explosion as consisting of three phases:

(a) The detonation wave in the explosive, the character of which plays an important part in what happens later in the surrounding medium.

(b) The radiation of a shock front characterized by extraordinarily abrupt (or even discontinuous) changes in pressure and acceleration and propagated at velocities exceeding the normal velocity of sound in the fluid. The conventional wave equation does not apply.

(c) A wave of pressure following the shock front. The conventional wave equation applies in this case.

The accompanying sketches were given by Dr. Thompson to illustrate his remarks. Figure 1 shows the space distribution of pressure at a time shortly after completion of detonation, and Figure 2 shows the time distribution of pressure at a point several diameters away from the explosive charge.

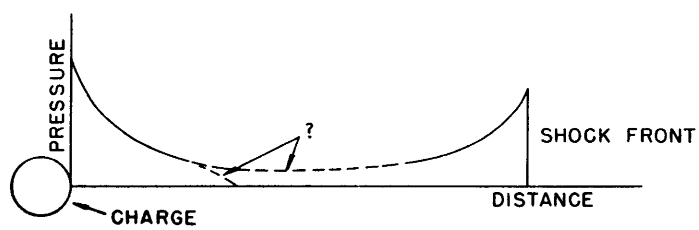


Figure 1

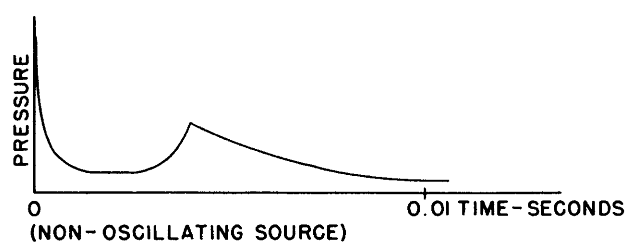


Figure 2

Mr. Kent questioned the details of this picture. He was of the opinion that the work of Riemann and Rayleigh on the problem would indicate that the discontinuity in the shock front was not as sharp as indicated by Dr. Thompson, and that dissipative effects, such as thermal radiation, would operate in the same direction. Dr. Thompson preferred the discontinuity concept and referred to the work of Hugoniot and Rankine, objecting that the authorities cited by Kent had considered the phenomenon as being one of equilibrium. He doubted that equilibrium could be reached under the given conditions. Mr. Kent stated that in his opinion the shock front was followed by a more sustained pressure, probably pulsating, perhaps even reversing*. Dr. Thompson said that present ideas indicated that the explosive source oscillates after detonation and that the picture must be modified with this in mind. Just how this should be done is problematical. He was of the opinion that structural damage was influenced by the shock wave mainly in its relation to the greater actions that follow it. He suggested the occurrence of repeated shock effects, possibly as a consequence of oscillatory reactions, both chemical and mechanical, involving both the compressible fluid medium and the explosive, and partly as a consequence of the impact of the abruptly developed pressure as a phenomenon separate from that of the detonation wave. As many as four peaks of pressure have been observed in water.

The nature of the shock wave received extended attention. A summary of the ideas advanced is given as it came to mind afterward, though it is not possible to give full credit to the various individuals who took part in the discussion. The shock wave is distinguished from ordinary acoustical waves in several important particulars. Its velocity initially exceeds that of ordinary sound by a margin which may be very large. In the case of spherical propagation, this velocity drops off until it gradually approaches that of sound. The wave is not homogeneous as to velocity, however, and the wave front is overtaken by the elements which follow, with the effect of increasing the steepness of the wave front as it advances. In a diverging wave this is accompanied by a diminution of amplitude. Presumably the falling off of velocity is caused by the reduction in amplitude rather than by the increase in steepness and would therefore not occur in a parallel wave.

Extensive theoretical study has been given to sound waves "of finite amplitude." This is understood to refer to amplitude of particle motion, as associated with sounds of great intensity. Such waves have been identified with shock waves having the characteristics mentioned. The disturbance in the medium subjected to explosive action will begin, at a given point, with the arrival of a wave of this nature. What follows at such a point is not clearly understood, and even schematic curves showing probable space and time distributions of pressure and of particle

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* This opinion is plausible by extrapolation from the condition of acoustic waves of small amplitude. Such extrapolation is questionable, of course, but in the absence of other evidence it may be a useful indication.

velocities are not yet agreed upon. In particular, information as to how the pressure varies and how long it is sustained behind the shock front seems to be scanty.

Close analogy between the shock wave in the medium and the detonation wave in the explosive is demonstrated by the following experiment: Explosive in rod form is placed in axial sequence with an air space enclosed in a cellophane tube of the same section, and this in turn is followed by a second rod of explosive like the first. A detonation wave initiated at one end of this assembly traverses the explosive rod at normal velocity, continues without interruption as a shock wave through the air tube, and resumes as a detonation wave on reaching the second rod of explosive.

The attention which has been given the shock wave is partly due to its purely theoretical interest. While Dr. Thompson is of the opinion that it is not mainly responsible for damage to structure, it nevertheless appears as the chief contributor to the reputation which explosive phenomena have for lying outside the realm of ordinary dynamics. Perhaps the shock wave offers the best chance for a rational explanation of these phenomena. Aside from the purely empirical tests of resistance of structures to explosive load, the search for rational explanations of explosive phenomena seems to offer the only prospect for radical solution of the problem. The time has not yet come when consideration of the nature of the shock wave can safely be omitted from further pursuit of this objective.

5. Professor A. V. deForest discussed the phases, mainly experimental, of the problem on which he had been working at the Massachusetts Institute of Technology. He explained the complications introduced by multiple reflections of elastic waves inside of any solid body subjected to shock loading, and the difficulty in interpreting load-time and load-strain data from such apparently simple systems as a tensile specimen broken by impact. As a first step to avoid such complications, he discussed the case of a cylindrical tank loaded by detonation of an explosive at the center. The symmetry of the setup assures that the load is applied simultaneously at all points around the circumference instead of at one end, as in the tensile impact specimen. Even in such a cylinder, however, experiments had shown by such actions as axial propagation and reflection that the strain-time data are still more complicated than had been hoped.

An important experimental difficulty occurs in development of a gage for generating electrical transients proportioned to rapid fluctuations in pressure. The problem of inertialess translation into electric terms of elastic strain has been solved by the metalectric gage, but the problem of conversion of rapidly fluctuating fluid pressure into elastic strain remains.

As a first approach use has been made of a metal or plastic cylindrical bar about a foot long and an inch in diameter, with metalectric wire wrapped around its mid-section. One end of the bar is immersed in the water subjected to explosive load, and the impulse received by the bar from the water is transmitted up the bar and registered as a strain varying with time. Questions about this procedure referred, first, to the fidelity with which time variations in pressure on the end were converted into strain at mid-length, but Professor deForest considered that until the reflected wave from the unloaded end returned to the winding, a record satisfactory in this respect was obtained. The electric impulses generated by such an assembly are to be correlated with the varying pressure on the end of the bar, and it is clear that the coupling includes elements which may prevent the relation from being one of direct proportionality.

An alternative form of gage was designed to make this coupling more direct. It consisted of a disk with the sensitive windings on its periphery, the whole immersed in the water. It was questioned whether this measured direct compressive action on the wires or on the material of the disk or even transverse expansion accompanying axial compression. The idea was advanced that this point was incidental to the fact of observed proportionality with pressure, regardless of the exact mode of action. This idea was found less convincing, however, after the further question as to the directional selectivity of the gage was raised.

This led to further discussion relating to the non-isotropic nature of the dynamic pressure to be measured and to the related question as to the results to be expected if the gage were fixed in position or permitted to move freely so as to follow whatever flow might occur. These questions remained unanswered.

Professor deForest felt especial concern as to the distortion and energy losses caused by reflection of the waves in the fluid from the solid surfaces exposed to them. After some search, he stated, he had found a substance, "catalin," which he considered especially suitable for use as a support for his metalectric gage for pressure measurements in water. This substance closely matches water in mechanical impedance or radiation resistance, and an interface is traversed by a sound wave with a minimum of disturbance. It is not known whether the action in case of a wave of finite amplitude is similar.

A question was raised as to the significance of pressure measurements taken on a gage which had a high reflection coefficient for the shock, as compared with a gage of low reflection coefficient. Kent favored a low-reflection gage, but believed that both types of gages are required. Thompson felt that damage to ship structures would be better represented by readings from high-reflection gages. He was of the opinion that it was important to use a gage having about the same reflection characteristics as the structure which must withstand this shock.

One question in this connection referred to the behavior of such a gage when the expanding "bubble" reached the gage and replaced water pressure by gas pressure. Professor Davis stated, in response to a question, that the boundary between water and gas is probably fairly well defined, but that the flow in any case must be violently turbulent. Dr. Thompson agreed with this view. Reference was made to the results of high-speed photographs, showing that the early phases of expansion (within a few calibers) are very regular.

Application of the metalectric gage to tensile impact studies was also described by Professor deForest. This calls for the design of apparatus in which the phenomena measured are characteristic of the material, the loading, and the rate of loading, and are independent of the geometry of the system. He mentioned that he had under development a promising means for obtaining high velocity stress-strain curves uncomplicated by secondary effects, due to geometrical form. With this means he hoped to shed light on the fundamental problem of damage as affected by rate of application of load.

Professor deForest pointed out that the coupling between two parts of a mechanical system could be exceedingly important with regard to the effects produced when a shock is transmitted from one part to another. He emphasized the dual influence of material properties on the one hand and geometrical form on the other, and expressed the opinion that many of the complications in observed forms of structural behavior were closely related to such purely mechanical effects as multiple internal reflections of stress waves.

6. Professor A. C. Ruge gave a description and a demonstration of his wire-resistance strain gage (the metalectric gage mentioned above). In the discussion of pressure pick-ups, the question was again raised as to the problem of distinguishing between static and dynamic pressure in the fluid. Thompson stated in this connection that the nature of the reflecting surface and stiffness of supporting structure could affect radically the indications of total pressure given by a gage.

7. Lieutenant H. R. Garner described the general characteristics of conventional torpedo protection structures. He showed photographs illustrating the damage to such structures when injured by a contact explosion. Dr. Thompson then showed moving pictures of surface effects due to large charges exploded under water at varying depths.

8. Dr. Nadai briefly described his apparatus for obtaining stress-strain curves at rates of loading up to 900 inches per inch per second, supplementing the data of his current paper published by the American Society for Testing Materials, by detailed comment and by additional unpublished data. This work, though it had a different objective, permits pertinent conclusions as to the behavior of metals under explosive rates of loading, provided moderate extrapolations are accepted. By taking the maximum stress value from each stress-strain curve and plotting it against corresponding strain rate, curves are obtained, for copper and aluminum, which form a consistent family of isothermals at a series of temperatures. Temperature increases considerably during the test, but the information obtained is not materially affected in consequence.

The range of strain rates is extended from low values, corresponding to the conditions of the usual static tests, up to several hundred inches per inch per second. The tensile strength at room temperature, consistently with the isothermals at higher temperatures, is a straight line when plotted against the logarithm of the strain rate within such limits of variation that extrapolation by one power of ten is not considered excessive; this is about enough to bring the rate up to values which occur under explosive load.

Results for medium steel are less consistent, and, more particularly, they are irregular at temperatures at which steel is known to behave irregularly in other respects. At room temperature, however, a curve similar to that for copper is obtained, fairly straight on logarithmic coordinates, and with a very moderate slope, so that the extrapolation would involve at most only a few per cent increase in maximum stress value. For strain rates from 10^{-3} to 10^{0}, maximum stress remains in the range 55 to 60 kips per square inch. At higher strain rates the curve is roughly linear, rising to 80 kips per square inch at 10^{3}. At 10^{4} it is estimated that it might be 86 kips per square inch.

The data supporting these curves are, however, still somewhat scanty. It was noted that the elongation at rupture increased somewhat with strain rate, and in this regard the material can be said to be *less brittle* at higher rates of loading.

The conclusion that the strength of medium steel is not strongly affected by explosive rates of loading is suggested but not proved. Such a conclusion would further suggest that the anomalous effects of explosive loads on structures are to be explained in terms of Professor deForest's "mechanical couplings" rather than on metallurgical grounds

9. Subsequently to the conference, additional comment was received, and this will be briefly summarized. Dr. Rodebush stated his strong conviction that more immediate results were to be expected from empirical than from rational approaches.

Somewhat similar views were expressed by W. H. Hoppmann, who emphasized the point that "the question of how to design a ship to resist underwater explosion remains paramount," and proposed to anticipate the time when fully consistent calibrated gage readings can be obtained and to consider now how such readings can be interpreted. "For lack of a more precise name the physical entity that does the damage to an underwater structure may be called a *generalized force*. If we had a gage that could measure that generalized force we could map its distribution about a given explosive charge and demark the limiting zone of danger for a given type of structure."

He said further that the method of estimating energy absorption (by plastic deformation of bulkheads) to correlate with general damage seems hopeless at present. The ratio of absorbed energy to available energy is fantastically small.

Dr. Thompson remarked independently in this connection that he felt that a pressure gage designed and mounted to operate as far as possible as an instrument to measure the pressures experienced by the actual explosion-resistant structure would be the most direct and important measure of the damaging effects of the explosion.

He believed that current developments in pressure-measuring equipment at the David Taylor Model Basin were well adapted for such use. In this connection it was suggested by Model Basin personnel that a gage of this kind could be made by mounting strain gages at suitable locations in a structure being tested. Dr. Thompson felt that this approach also held promise.

The use of scale models offers a solution of the problem of predicting damage less complete but perhaps more practicable than full scale tests, though there is still doubt as to the exponent of weight of charge which will give results in agreement with full scale. "The gross method now available," said Hoppmann, "is to blow (the model) up and then see what it looks like. We must admit that no one at present seems to know of a better way."

This same problem is discussed by Lieutenant Commander Ormondroyd, who feels that electrical gages present so many unsolved problems that a return to the crusher type may be necessary. "The Hilliar gage," he says, "measures the total impulse $\left[A\int_0^\infty p\,dt\right]$ of the water over the area of the piston where p is the variation of pressure relative to the normal static pressure in the water . . . How (this) is related to actual destruction we do not yet have in mind clearly. The usual methods of comparing the deformation of the gage to that caused by a slowly applied calibration pressure can be very misleading." He proposes extensive use of crusher gages in way of charges in open water to explore distribution of "the quantity measured by the instrument," repeating and checking the work of Abbot, Hilliar, and Shekelton, and especially finding the effect of rigid fixation of the gage in position. He believed that such tests will "give an approximate picture of pressure and particle velocity distribution." If an analytical relation between pressure and particle velocity could be rigorously established, and if a gage existed, say in the form of a sphere, with very high natural frequency and a completely enclosed sensitive element responding only to changes in volume of the sphere, then a single measurement of "static" pressure would suffice to give particle velocity as well. This is a gage of the instantaneous type as contrasted with the integrating type represented by the crushers. He thinks both types may be necessary to a complete solution of the problem, but has a basic skepticism as to electrical methods.

Lieutenant A. C. Ruge made constructive and practical comment on the details of pressure gage practice. He emphasized that the piezo-gage is more sensitive to incidental accelerations and to movement of the leads than is the metalectric pressure gage. He cautioned against the use of grease in the housing of either type of gage between the water and the sensitive surface, and at the same time against air spaces elsewhere in the housing. To avoid both effects a test was made with the housing completely removed. This resulted in an open circuit, although this occurred in the connections rather than in the gage itself. He concludes that high impedance and accelerometer effects make the piezo gage definitely unsuitable, and that the preliminary work already done on the metalectric pressure gage has paved the way for improvements which should lead to definite solution of the problem. Like Ormondroyd, he prefers a type of gage in which the sensitive unit is completely enclosed, though the use of a baked adhesive might afford sufficient protection to permit placing the wires externally in direct contact with the water.

Lieutenant Ruge felt that from the point of view of the gage the argument about the nature of the pressure was somewhat academic, since the gage would recognize only total pressure without separating out any components that might come from different causes. "The dominant problem at this stage is instrumental rather than theoretical, since it is impossible to learn anything about the true nature of the phenomenon from two such irreconcilable methods of observation (as piezo and metalectric gages)."

He feels that basic concepts could be permanently set straight for general acceptance, and recommends a person with geophysical background for the task. That would reduce the problem to one of using metalectric gages for ascertaining facts.

An intermediate position in this matter is taken by Lieutenant H. R. Garner. After long concern with the problem of defensive constructional design on its purely empirical side, and after extended effort in use of piezo gages, he has formulated in his own terms a "mechanical concept of an underwater explosion" which differs in no important particular from that of Dr. Thompson. He considers that following the shock wave the gas globe begins to expand and "the high initial rate of expansion communicates a second shock wave to the water . . . Layers of water . . . are compressed and receive elastic energy as well as energy of translation . . . These waves carry more energy than the (initial shock-) waves by reason of their longer duration," and may be less steep, though "still shock waves . . . waves of finite amplitude."

However, he goes on: "It is difficult to form a clear estimate of the forces or 'pressures' which will result from impingement of first the jet (of flowing water) and then the gas globe on a floating body. Both the velocity and mass of the jet must be fairly large, with large capacity to deliver destructive energy." But "the pressure immediately begins to fall both by expansion of the gas and abstraction of heat" . . . When the wave reaches the surface it produces tensile effects and if the tension exceeds 0.2 to 0.3 tons per square inch, the surface is broken and that is the end so far as shock waves are concerned.

The most significant feature of Lieutenant Garner's memorandum is that after long effort along empirical lines he feels the need of a guiding concept of the sort the theoretical men are doing their best to establish.

10. Lieutenant John Parkinson, USNR, spent a period of about two weeks at the David Taylor Model Basin just prior to the conference, but was prevented from attendance on 19 September. He submitted a memorandum which follows lines diverging somewhat from those already mentioned. He recommends a middle course between the extremes of pure calculation and pure empiricism. Experimental work utilizes either scale

models or coupon models bearing no resemblance to any service structure; in either case theory is necessary to bridge the gap and pass to service structures. Theory, however is still in a somewhat unsatisfactory state and experiments designed to clarify the theory may be in order.

In particular, parallels with the phenomena of sound transmission and absorption are suggestive, both with respect to details of experimental procedure and to the phenomena themselves.

First, as to procedure: In addition to the cylindrical tanks in present use as coupon models, a closer approach to service conditions is proposed in placing panels incorporating proposed absorptive construction in a heavy concrete wall forming one boundary of an extended body of water. The characteristics of the wave need not be determined in terms of any specific physically defined quantity, such as momentum, force, or velocity, but only in terms of destructive power.

This concept approaches the "generalized force" of Hoppmann, but no suggestion is made as to how it is to be measured.

11. Turning to the relations between sound transmission and resistance to explosive loads, a broad contrast may be noted between proposals to protect structure by reflection, and so excluding explosive energy, or by absorbing and converting it into the harmless form of temperature rise. Both methods are used in acoustical practice; acoustical filters are reflectors and blankets are absorbers. Underwater structure in case of contact explosion is probably in no case equal to the task of exclusion by reflection of explosive energy; but important cases of explosive attack have occurred, against which reflection is the most plausible defense, since the effects produced consist of high accelerations of extended areas of the structure rather than of high pressures on limited areas resulting in localized rupture.

Lieutenant Parkinson's discussion of this matter is suggestive. He distinguishes first between damage from the shock wave and that from the surge, and suggests observational methods for determining which is effective in a given case. Since the two phases are separated in time, a determination of the time of rupture would show which occurs first. "As an alternative it may be possible to design structures which are responsive to one effect and not to the other and use them as protective coverings for the test structure in order to determine which part of the disturbance causes the damage . . . A damped resilient system should afford some protection from the shock wave but little from a sustained surge. If such a structure were found to have good protective qualities it would be an indication that the shock wave is the more serious cause of damage." Reference is also made to a remark by Dr. Thompson to the effect that personnel seem less subject to mechanical injury due to blast than is more rigid structure. Blast and shock injury to personnel consist less of broken bones and gross mutilations than of rupture of the finer tissues of the body.

12. Lieutenant Parkinson then states in simple language a basic principle: "If the damage is from the shock wave, a resilient structure which will respond more slowly than the shock impulse and thereby spread out the time of application, is indicated. This may be called a low-pass filter. Experiments on such a structure would begin by increasing the elastic response of the structure, as by staggering supports or increasing the spacing between supports. The next step might be to substitute a material having a lower modulus of elasticity, such as wood, either in the supports or as sheathing material . . . There is a parallel with sound or vibration insulation, in which the best result is obtained by use of reflecting structures whose natural frequency is low compared to that of the driving force. A composite layer of several such structures elastically coupled is much better than an equivalent weight of solid material. The ultimate is complete separation . . . because the compliance of air, unless closely confined, is less than that of any solid material."

Usage in sound insulation, however, is not directly applicable here, because of the high values of pressure and energy. "If materials like soft rubber or cork were used, prohibitive thicknesses would be required. Hard rubber or compressed cork might be suitable.

"The reason why resilient structures . . . are used . . . is because the losses obtainable by reflection are large compared with those obtainable by dissipative effects, 30 or 40 decibels as compared with 10 decibels, or 99.90 to 99.99 per cent loss as against 90 per cent. The transmitted energy would be 100 to 1000 times as great in the latter case.

"If it does not appear practical to store and reflect the explosive energy, some dissipation can be produced by damping. Sand, asphalt, tar, mixtures of clay and oil, gums, etc., are suitable materials. These materials should be applied where maximum velocities are expected . . . Builders of automobile bodies found two thin sheets of metal separated by asphalt many times better than equal weight of steel."

13. Turning to surge pressures, Lieutenant Parkinson thinks they act more like a sustained load, calling for "maximum mass and rigidity. Some benefit will be obtained from resilience through distribution of the load." If both phases of the explosive load are effective, combination of the types of structure described is suggested.

14. Lieutenant Commander Ormondroyd's recommendation is for a "structure which could undergo large deformations without destruction and which embodies the possibility of dissipating large amounts of energy in the form of heat . . . Devices to invoke frictional dissipation of energy are singularly lacking from current designs."

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