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Technical Report

R 611

ACTIVE SYSTEMS FOR BLAST-RESISTANT STRUCTURES

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ACTIVE SYSTEMS FOR BLAST-RESISTANT STRUCTURES

Technical Report R-611

Y-F011-05-02-356

by

W. J. Nordell

ABSTRACT

A conceptual study was undertaken to develop systems which could be activated in emergencies to provide additional resistance to nuclear blast loadings. Participants in this study included engineering consultants, teachers, and researchers. The concepts with the greatest potential were found to be those utilizing internal pressurization or movable structural elements. However, "slanting for blast" will usually be a more effective approach than active systems in the design of blast-resistant structures.

INTRODUCTION

For blast-resistant structures, the exceptional (blast) load governs the structural design; consequently, the members are overdesigned for normal working loads. It would be desirable if, in designing new protective construction or hardening existing structures, active systems (defined below) could be utilized to "reinforce" the basic structure during an emergency. This "reinforcement" could be in the form of a structural assembly which would enhance the resistance–deformation characteristics of the basic structure, or a system which would attenuate the energy or peak loads applied to the structure.

The objective of this work unit was to investigate the use of active systems to provide protection to structures subjected to blast loads. This report summarizes the results of the investigation's initial phase, which was concerned with devising and evaluating concepts of active systems.

An active system is defined as a system which is manually or automatically activated before the structure or element is overloaded or deformed excessively to protect that structure or element from failure. Thus, it is meant to provide a means of producing a temporary increase in strength or "effective" strength for infrequent, relatively short-duration loads. Active structural assemblies could utilize fluids, gases, and/or additional mechanical or structural elements to resist a portion or all of the applied blast loads, by prestressing critical elements or by transferring the blast loads directly to the foundation.

The remainder of this report is divided into four sections: (1) background information, which includes descriptions of some existing active systems and some previously proposed concepts, (2) the approach used in formulating concepts, (3) a discussion of the concepts, and (4) the conclusions and recommendations.

BACKGROUND

The use of active systems, as defined, to provide protection against dynamic loads is not new. Concepts have been proposed by others, before the present undertaking. Furthermore, active systems have been utilized in practice. Therefore, for the reader's interest and to provide background information, some of these systems are described below; references containing further information on these systems are cited.

Water Door

To attenuate blast pressures in a tunnel, Brode[1] proposed the water door (Figure 1), which provides an effective closure for a protective shelter at the end of the tunnel. To keep the water from being driven down the tunnel at high speed, the depressed portion of the tunnel would have to be approximately 100 feet or more long for an incident pressure of about 150 psi from a 10-megaton burst. The proposed system is both efficient and reliable because the tunnel is filled and drained by gravity flow and because the reservoirs' size may be such that a dependable, small-capacity pump can be used.

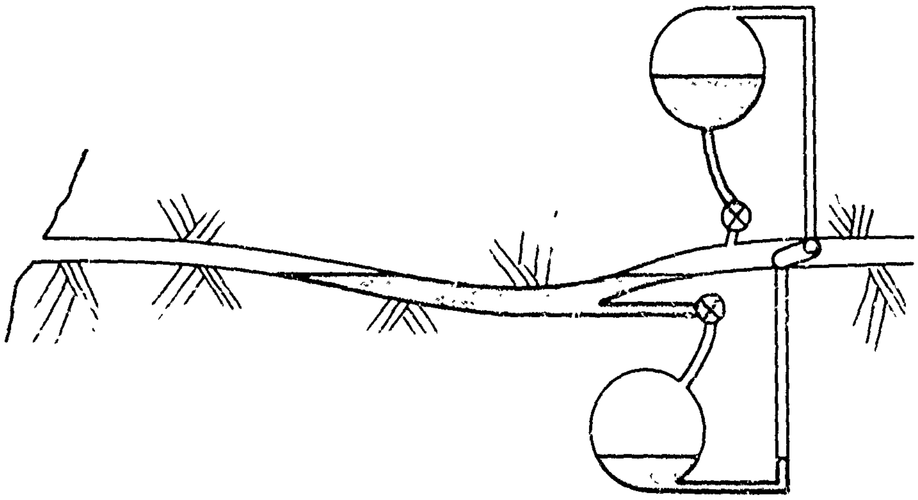
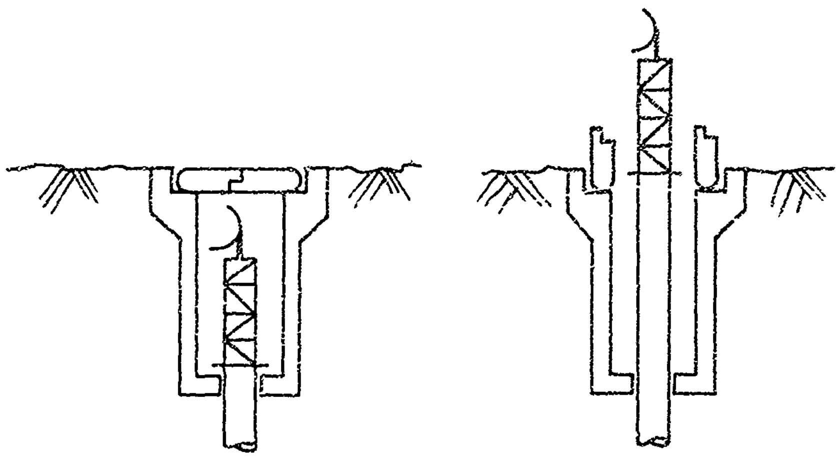


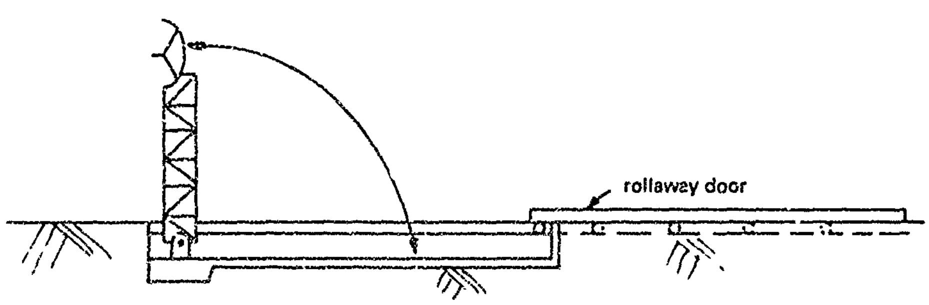
Figure 1. Water door

Antenna Hardening

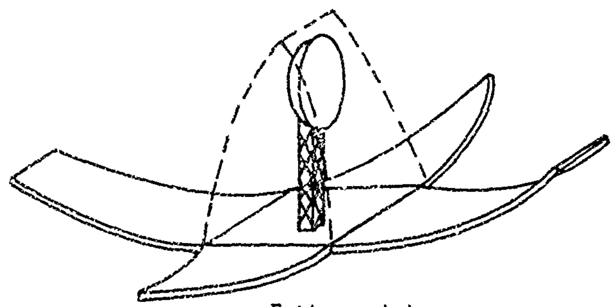
To provide effective protection for antenna systems, Cohen and DiNapoli[2] have noted or proposed telescoping, tilt-up, and fold-away antenna systems such as those shown in Figure 2. Retractable or telescoping antennas have been utilized.[3] The problem involved in antenna designs is that both structural and electronic criteria must be satisfied. What is good from a structural point-of-view is not always suitable from the electronics viewpoint The systems noted by Cohen and DiNapoli provide efficient solutions to the problem. They can be considered as active systems because the structural system being subjected to the blast pressures is not the same as that during the normal operational phase



a. Telescoping antenna system



b. Tilt-up antenna system



c. Foldaway shelter

Figure 2. Antenna protection systems.

Bubble Screens

Bubble screens have been utilized to protect underwater structures from shock waves generated by TNT explosions [4] These screens reduce the peak pressure by an amount which is dependent upon the air content of the screen, the screen thickness, and the incident shock wave pressure level

With respect to the attenuation of nuclear weapon effects, the cost of the equipment to produce an adequate screen would be great Nonetheless, this is an example of an active system which has been found to be effective under certain conditions.

Crushable Shields

Another example of an active system is the use of crushable materials as shields to protect structures against blast loadings. The crushable shield is not a part of the structural system resisting loads under normal conditions, but it can be effective in absorbing the energy of a blast pressure wave. The important properties of the shield are the crushing strength and the thickness of the shield. The effectiveness of the shield, however, is reduced greatly if the shield is completely collapsed.

The shield acts to modify the blast wave impinging on the basic structure. Essentially, the shield is used as an energy absorber.

For protection against the long-duration pressure waves from nuclear weapons, this system may not be feasible because the thickness of the shield would be prohibitive.[5]

Shock Absorbers

Automobile shock absorbers, water-filled bumpers,[6] and pneumatic bumper systems on piers and wharves are additional examples of active systems. Like the crushable shield these systems are effective only for short-duration loads.

APPROACH

Blast loads can be divided into two categories; short- and long-duration loads, the time reference being the natural period of the structure. For relatively short duration loads, impulse governs the response and a fixed amount of energy can be assumed to be imparted to the structure. To avoid failure of the structure, the maximum strain energy must be greater than the imparted energy. The available strain energy may be limited by (1) the maximum permissible deflection, (2) failure of a portion or all of the structure, or (3) type of response desired—elastic versus inelastic deformation. No limitation need be placed on the maximum resistance of the structure.

However, for long-duration loads, the required resistance diagram must be defined further because in addition to the energy considerations, the maximum resistance must be greater than the applied load for equilibrium to occur.

In the case of nuclear blasts, the load duration is long so that the maximum resistance of the structure or element is important. There appear to be two approaches to solving the problem of providing adequate structural resistance for a given design: (1) increase the maximum resistance of the basic structure to the degree necessary, and (2) reduce the peak pressure by an amount such that the existing resistance of the structure will be adequate. Active systems were devised considering both of these approaches.

Because this phase of the study dealt solely with formulating concepts, a large input was desired. This was accomplished by soliciting ideas from many persons. Three contracts were negotiated in order to get opinions and ideas from outside sources. Two were engineering consultants, John Blume and Associates[7] and T. Y. Lin and Associates,[8] and one university group, the Civil Engineering Department at the University of Illinois.[9] At NCEL, there were three meetings of engineers from the Structures Division during which ideas were presented and the problem discussed. Also the author had informal discussions on this subject with persons at other facilities including the following: Illinois Institute of Technology Research Institute; Naval Facilities Engineering Command, Structural Design Division, Washington, D. C.; U. S. Army Mobility Equipment Research and Development Center, Fort Belvoir, Virginia; Naval Postgraduate School at Monterey. The remainder of this report presents a summary of these contracts and discussions.

DISCUSSION OF CONCEPTS

The discussion of the concepts is divided into two sections. The first is blast-attenuation systems and includes those systems which act to reduce the blast loading on the structural system. The second is structural reinforcement systems and includes those concepts which act to increase the resistance of the structure.

Blast-Attenuation Systems

Damped Systems. Damping devices can be used as active systems in parallel with structural elements to reduce the response of the structure to dynamic loads, but to do so requires that the damping devices also transmit force. Therefore, a question arises as to whether it is more effective to use a damping device or to increase the elastoplastic resistance of the elements by an amount equal to the peak force transmitted through the damping device. An analytical study was made to answer this question, and the results indicate that it is more effective to increase the elastoplastic resistance or the elastoplastic energy-absorbing capacity of the structure.[5] Damping devices in parallel are useful primarily in dissipating energy from cyclic loads, as automobile shock absorbers do, and thus, are not effective in providing additional resistance to nuclear blast loadings.

Crushable Materials. Such materials were discussed previously. Essentially, they shield the structure by reducing the magnitude of the blast load imparted to the structure. For the long durations typical of nuclear blasts, the use of crushable materials has limitations. For example, to protect a glass pane having a 1/2-psi resistance against a triangular pulse with 5-psi maximum side-on overpressure and a 2-second duration, a shield about 1,500 feet thick is needed.[5] On the other hand, crushable materials have been found to be successful against short-duration pulses. Also, these materials have served effectively as liners or packing around buried structures.

Controlled Atmosphere Systems. These schemes are intended to alter the atmosphere in the vicinity of the structure so less of the kinetic energy of the blast wave will be imparted to the structure. One concept proposed to eject a water vapor cloud into the atmosphere for several hundred yards around the structure.[8] Another scheme used jetted air instead of water vapor,[8] and another used a sheet explosive at a shallow depth in the soil.* The explosive is ignited at the appropriate time to create a dust storm. In each of these cases, the results would be similar to those obtained by releasing air bubbles underwater (noted earlier), essentially, the rise time is increased, and for short-duration pulses the peak pressure reduced somewhat. To design these systems to be effective against long-duration (nuclear) pulses would not be practical.

Electromechanical Generators.[5] The conversion of the kinetic energy of the blast wave into electrical energy instead of strain energy by electrical generators is a means of reducing the blast loads applied to the structure. However, such a system would be ineffective because large forces would have to be transmitted through the active system, it would also be expensive and not too reliable.

Aerodynamic Design. Structures could be designed to reduce reflected pressures and drag forces.[5,8] Although this approach does not necessarily utilize active systems, one concept proposes the use of an inflatable membrane around the structure (Figure 3).[5] In the active state, the membrane would

* NCEL concept.

assume a cylindrical or airfoil shape having a lower drag coefficient than the actual structure. With this system there would be problems in providing ventilation and entrances to the structure. Also, the cost and maintenance of the membrane and inflation equipment would be expensive.

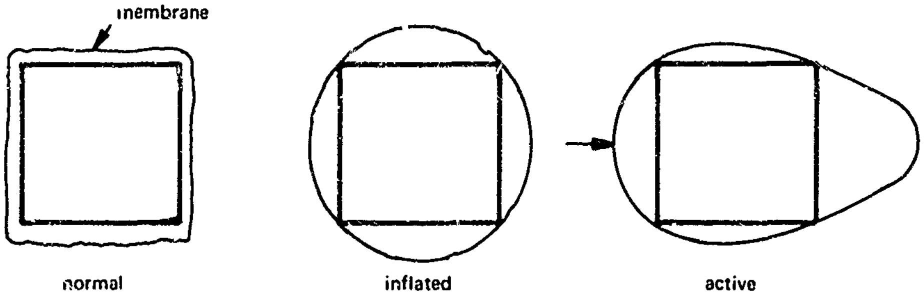


Figure 3. Drag-relieving membrane.

Structural Reinforcement Systems

Electromagnetic Force Activated Systems.* These systems would use magnetic forces to strengthen structural elements by transient prestressing. The magnitude and duration of this type of prestressing load could be controlled easily. However, magnetic forces decay rapidly with distance from the generating source, and to develop the required forces for the time duration of a nuclear blast would require an enormous amount of power and would be very expensive.

Thermally Activated Elements.* Thermal radiation travels at the speed of light whereas the shock wave travels at the speed of sound so that it is possible for a significant amount of thermal energy to reach a particular location before the blast wave. If this thermal energy is used to develop thermal stresses or deformations which would counteract the stresses or deformations of the blast wave, an advantage through thermal prestressing could be realized. For example, thermal buckling of plates in a deformation pattern opposite to that developed by the blast wave, and prestressing or predeforming of bimetallic plates could be used to provide lightweight doors for protective shelters.

There are many problems associated with this type of system. One of the biggest problems is that the amount of thermal energy actually imparted to such a structure within a specified time interval is too variable, having a potential range from an insignificant amount to too much. The amount of thermal energy reaching a given structural system depends on the range, the degree of shielding between the system and the point of burst, and the clarity

* NCEL concept

of the atmosphere, the amount actually absorbed depends on the thermal properties of the system. Therefore, it is not a reliable quantity. This problem could be overcome by providing an independent heat source, but this makes the system undesirable from a cost viewpoint. It would be cheaper to provide a stronger door or a deformed door such as is often used in hardened structures.

Preventing a buildup of pressure on the interior of the structure could be an additional problem because movement at the supports would occur, requiring special edge details to prevent openings from developing. The effect of temperature on the material properties, although not a serious potential problem, would have to be considered

Internal Pressurization. The use of pressurization to increase blast resistance was recommended by NCEL and others [5,8] Pressurization of underground structures appears to be beneficial, whereas pressurization of aboveground structures does not. In the case of aboveground structures, the resistance of roofs to suction loads would be reduced, and leakage losses would be great, requiring extra expense to eliminate or compensate such losses. For underground structures these disadvantages are negligible.

By means of a simplified model it has been estimated that an inflated flexible cylinder buried under a soil cover equal to the cylinder radius and in a cohesionless soil with a friction angle of 30 degrees could resist surface pressures eight times the magnitude of the internal pressure [5] The strength advantage is obtained through the increased resistance of the preloaded soil around the structure.

For manned structures, the physiological effect of pressurization must be considered. The Navy Diving Manual[9] indicates that no decompression is needed if the maximum pressure is less than 13 psi (30 feet of water) Therefore, assuming a factor of 8 increase in capacity of the inflated flexible cylinder from internal pressurization, it would be possible to resist surface pressures of slightly over 100 psi without concern for decompression

No decompression is required at higher pressures if the time spent at the higher pressure does not exceed a specified limit For example, persons could be subjected to pressures equal to 40 psi for 30 minutes without requiring decompression If the time limit was exceeded, decompression equipment and procedures would have to be provided.

An alternative solution to decompression would be a one-atmosphere personnel shelter within or attached to the main structure This could be a small hardened enclosure which personnel would occupy for the duration of the attack. For unmanned structures, pressurization provides no such disadvantage, and therefore it would have greater feasibility An investigation (not associated with this study) is underway to determine the feasibility of pressurized underground fuel storage tanks [10]

In most cases, it would be more economical and reliable to have the structure pressurized at all times.[5] Rapid pressurization of a structure would be difficult and would require more elaborate equipment than that required for constant pressurization.

Movable Elements. Most active systems are uneconomical, because it usually would be cheaper to use members which were designed to carry, in addition to their normal operating loads, that share of the blast loadings which would be resisted by the active system Thus, active systems are not practical on the basis of cost alone. However, when other factors are important, active systems may be advantageous. For example, when efficient space utilization or serviceability requires relatively large unobstructed areas under normal operating conditions, a design which provides these areas and movable elements to strengthen the structure in emergencies would be a potential solution Some examples of such elements are given below. These elements also could be used to harden existing structures without affecting the existing functional requirements.

Two concepts for movable diagonal bracing are shown in Figures 4 and 5. These bracing schemes would be manually activated Automatic emplacement of the hinged bracing is possible but complex, and it would increase the cost significantly. A problem with the hinged bracings would be to provide an adequate and reliable means of securing the bracing in the active state It is estimated that tensile bracing having an area of 4 $in.^2$ and a yield strength of 40 ksi would increase the lateral resistance from about 3 psi to 10 psi for a structure consisting of two 10-foot stories (8-foot clear story height) and two 20-foot bays with frames spaced at 20 feet [5]

Similar concepts for movable columns, walls or trusses are possible.[5,7,8] an example is shown in Figure 6 As with all movable systems, the problems which have to be considered are clearing the swept area, designing adequate connections, and providing equipment to assist in emplacing heavy elements The wall and truss systems would increase both the lateral and vertical resistance

A foldaway king-post beam, as shown in Figure 7, was thought to have potential * However, for a system which was to be activated manually, the benefits were estimated to be negligible In particular, for a span length of 30 feet and a load area of 600 square feet, a beam was assumed to be reinforced by two 1/2-inch cables to be stressed to 50,000 psi The increase in strength was estimated to be about 0 5 psi Increasing the cable tension increases the resistance proportionally, but it also makes manual assembly of the active state more difficult

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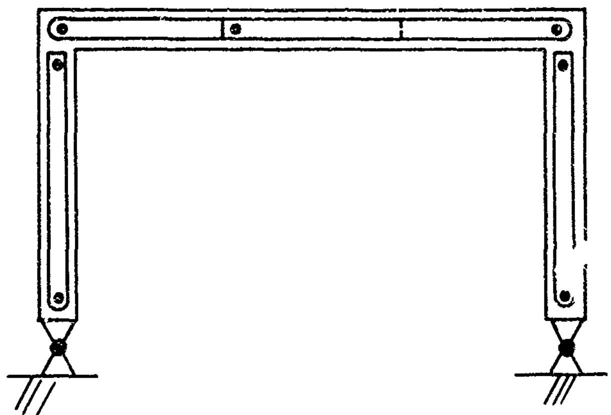
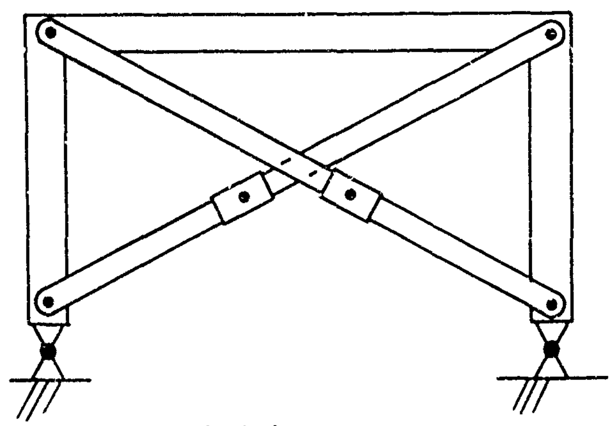
* NCEL concept



a. Inactive state



b. Active state

Figure 4. Frame with foldaway bracing.

A comparable scheme for doors, however, appears to have potential, a sketch of such a system is presented in Figure 8.* An ultimate strength about six times that of the unreinforced door was estimated for a 3/4-inch-thick, 4-foot-wide steel door having a yield strength of 40,000 psi This strength advantage can be obtained because it appears to be possible to develop a relatively large force in the tension plates with respect to the external load area. This was not practical for the king-post beam because of the large load area.

* NCEL concept.

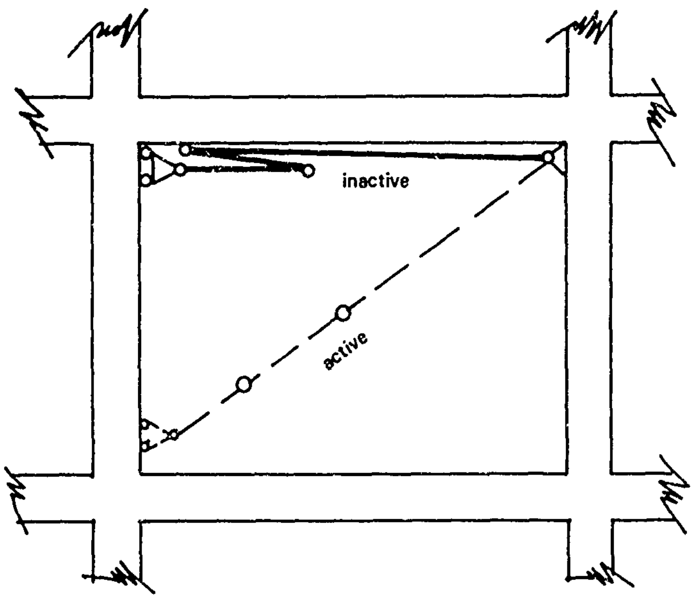


Figure 5. Hinged bar bracing.

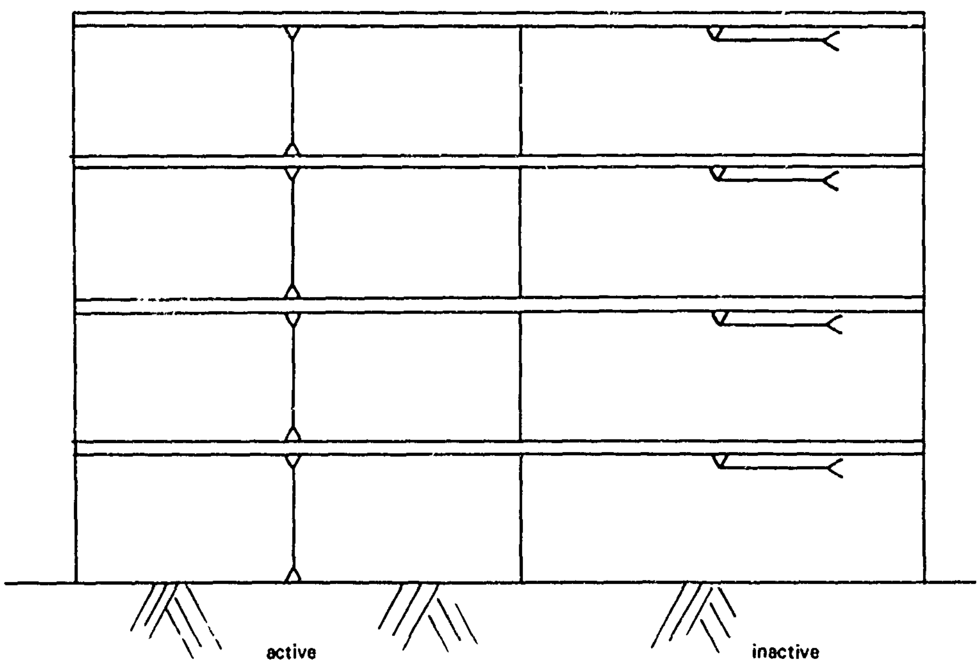
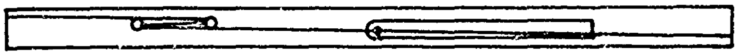
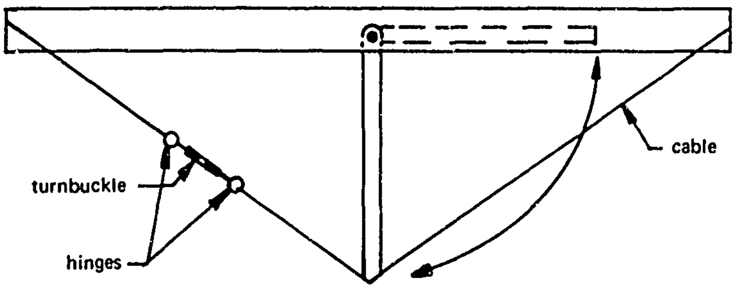


Figure 6. Movable columns, trusses or walls.





b. Active state

Figure 7. Foldaway king-post beam.

Another type of movable element is the retractable cylindrical column (Figure 9), which can be used to provide additional support for beams, floors, or roofs. Activation of the column is achieved by means of pressurized gas or controlled explosives.[5,*] This concept provides unobstructed floor space for normal operating conditions, and the column itself could be stored out of view in a hidden ceiling if desired.

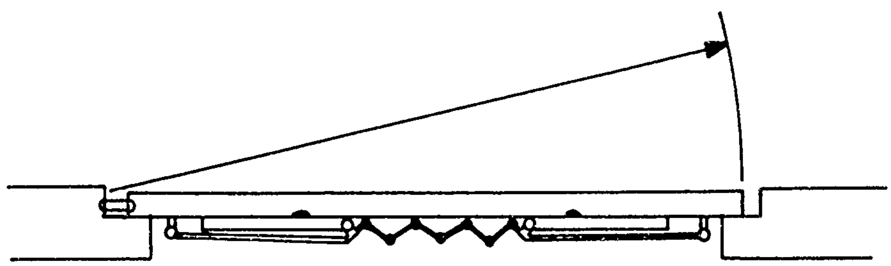
This concept has a number of drawbacks. One, of course, is that the floor area below the column must be cleared before activation. If an explosive-type activator is used, the apparent danger of accidental activation would preclude personnel working in the immediate vicinity of the column. Gas inflation would be slower but safer. However, the greater the activation time, the greater the warning time must be. Rapid inflation would require expensive and rather elaborate equipment.

CONCLUSIONS

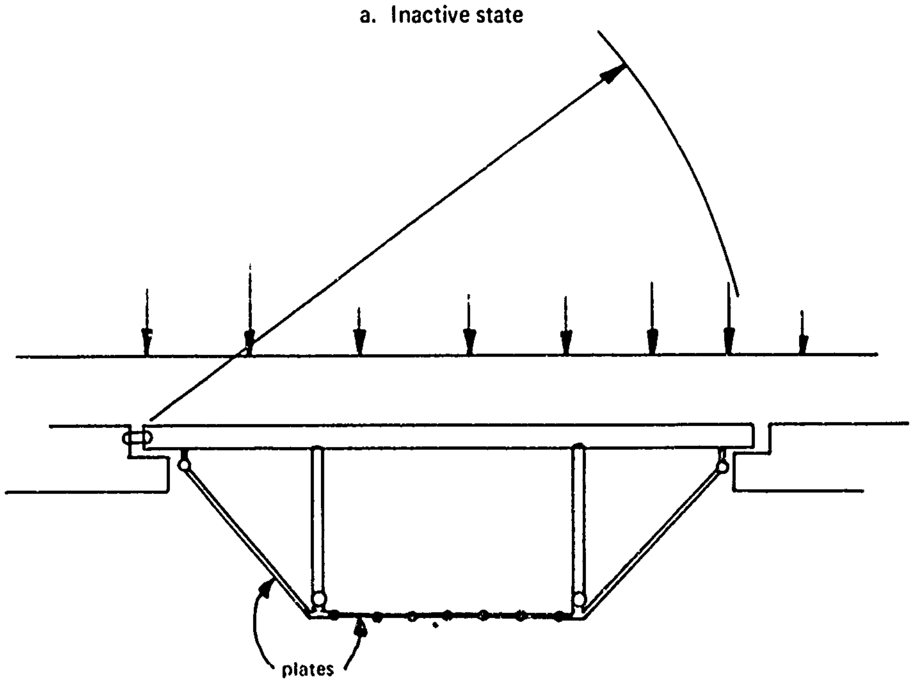
A structural system coupled with an active system which resists all or part of the blast loading is not as economical nor as reliable as a structural system designed to take the total load. The cost of providing the necessary equipment and material to construct and maintain an active system is generally

* Suggested by representative from Naval Postgraduate School at Monterey

greater than a "brute force" approach of increasing the size of appropriate structural elements (beams, columns, and slabs). Active systems may be practical only when factors other than cost are equally important. An active system which would provide greater functional benefits than a structural system by itself might prove to be practical. However, such benefits could be offset by likely disadvantages of an active system, such as low reliability, greater maintenance, and long activation time.



a. Inactive state



b. Active state

Figure 8. Door with foldaway reinforcement.

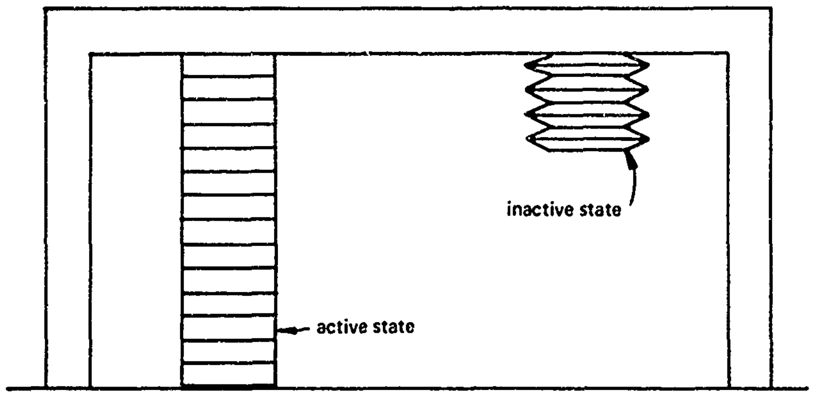


Figure 9. Retractable column.

A more effective approach appears to be "slanting for blast."[5,*] Relatively minor design modifications or improved structural details will generally be the most effective solution to providing additional hardness. This technique is already used to a certain extent in designing structural connections to maximize strength and energy-absorbing capacity, but this approach can be extended further. For example, using soil-cement as backfill over buried structures would be a method for providing additional hardness.[8] Structurally upgraded temporary and permanent "nonstructural" partitions which are secured adequately to the main structural members is a possible method of increasing the lateral resistance of certain structures.

The active systems which appear to have the most potential are internal pressurization and movable elements. Internal pressurization is a relatively reliable scheme which can provide significant additional strength at a moderate increase in cost. Movable elements provide additional strength when it is needed, the cost for constructing the elements may be partially offset by the greater versatility of the structure's use and improved space utilization.

* "Slanting for Blast" is the incorporation of certain engineering features in the design of new structures or the modification of existing structures to maximize protection against blast without significantly increasing the cost and without adversely affecting function.

RECOMMENDATIONS

1. The results of the underground fuel storage tank study, previously noted, should define the potential of internal pressurization. If the results of this study are favorable, internal pressurization should be considered as an alternative approach in future designs of underground unmanned facilities. Furthermore, a study should then be undertaken to determine the feasibility of pressurized manned underground structures.

2. The "slanting for blast" approach should be given preference over an active systems approach.

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13 ABSTRACT

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Internal pressurization						
Bubble screens						
Crushable shields						
Shock absorbers						
Damping						
Electrical-energy conversion						
Aerodynamic design						
Thermal activation						
Thermal prestressing						
Bimetallic plates						
Movable bracing						
Gas-pressure activation						
Controlled explosive activation						

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