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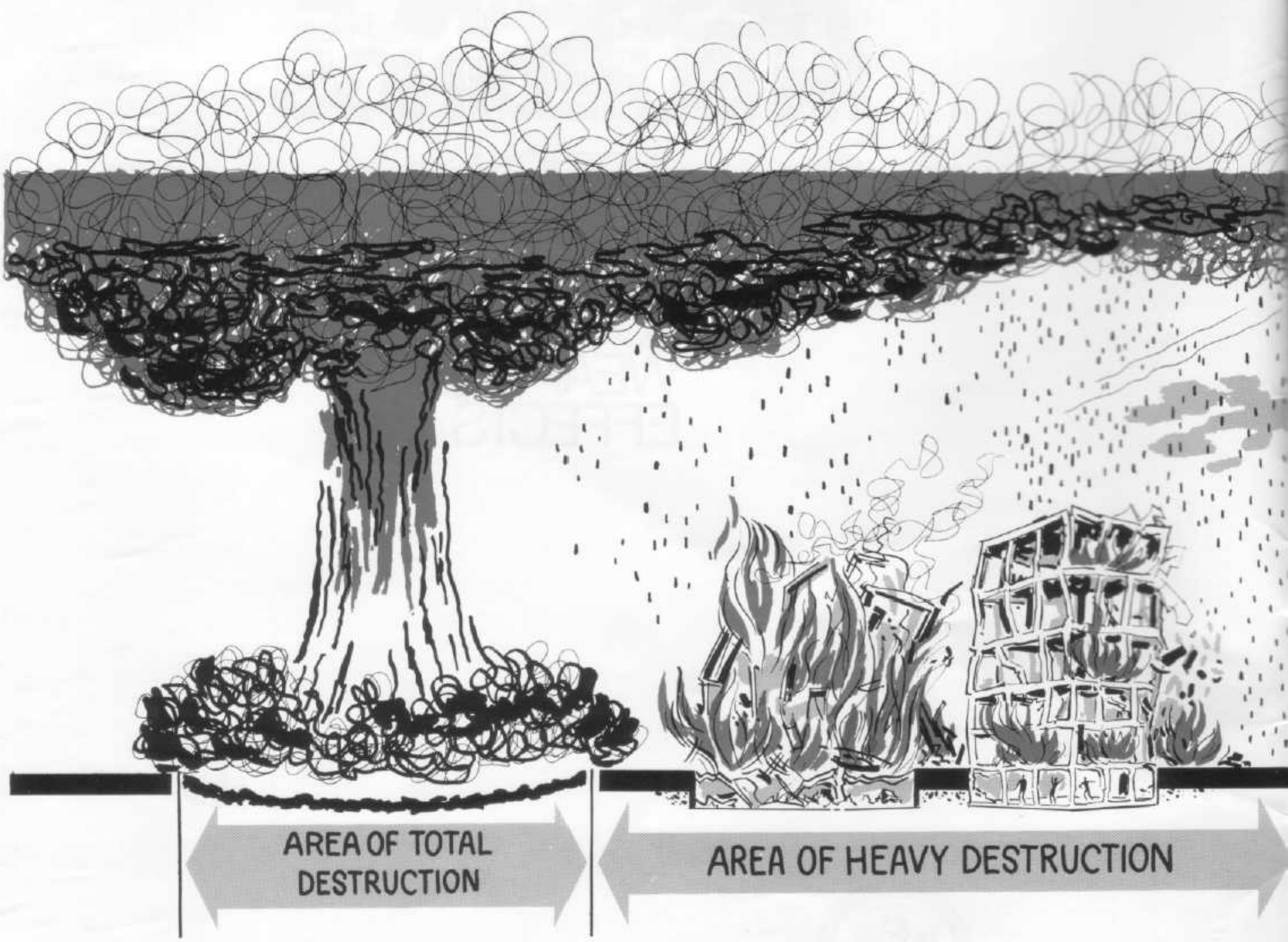
INCREASING BLAST AND FIRE RESISTANCE IN BUILDINGS

DESIGN TECHNIQUES FOR COMBINED NUCLEAR WEAPON EFFECTS

FEDERAL EMERGENCY MANAGEMENT AGENCY

Preface

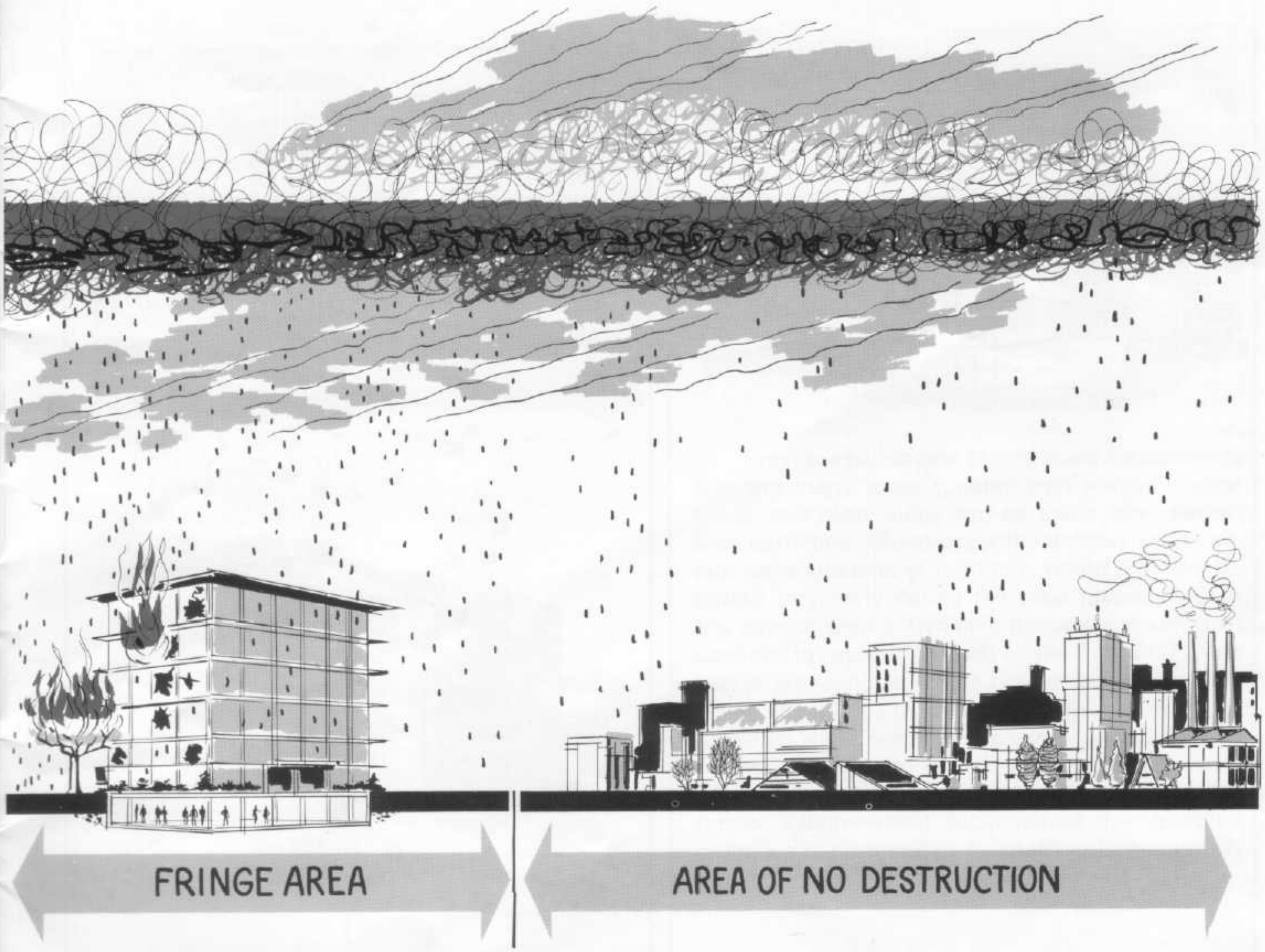
In a nuclear attack against the United States, people very close to an explosion—in the *area of total destruction*—would be killed by blast or by extreme heat of the nuclear fireball. People just outside this area—in the *area of heavy destruction*—would be severely affected by *blast, heat, initial nuclear radiation, fallout radiation* and *fires*. People in the *fringe area* would be subjected to lesser blast, heat and fire hazards. People outside the fringe area would not be affected by the blast, heat or fires. To them and to the survivors closer to the point of explosion (ground zero) radioactive fallout



might be the main danger.

Rational design can enhance man's chances of surviving the hostile environment created by a nuclear explosion. Just as design in some areas takes into account the effects of earthquakes, hurricanes, tornadoes or extreme snowloads, so also may it take into account protection from some of the effects of nuclear weapons. This does not mean the design and construction of special shelter facilities but simply the application of appropriate design techniques to ordinary buildings. Some degree of protection can be achieved without compromising the primary function of the building or adversely affecting appearance or cost. Protected areas need not be recognizable as shelters.

Basic concepts of design techniques for increasing protection against blast and fire effects are given here. Publications presenting additional information on design to resist nuclear weapons effects are listed in the selected references. Detailed design procedures, and the determination of the degree of overall protection, are left to competent consultants.



Introduction

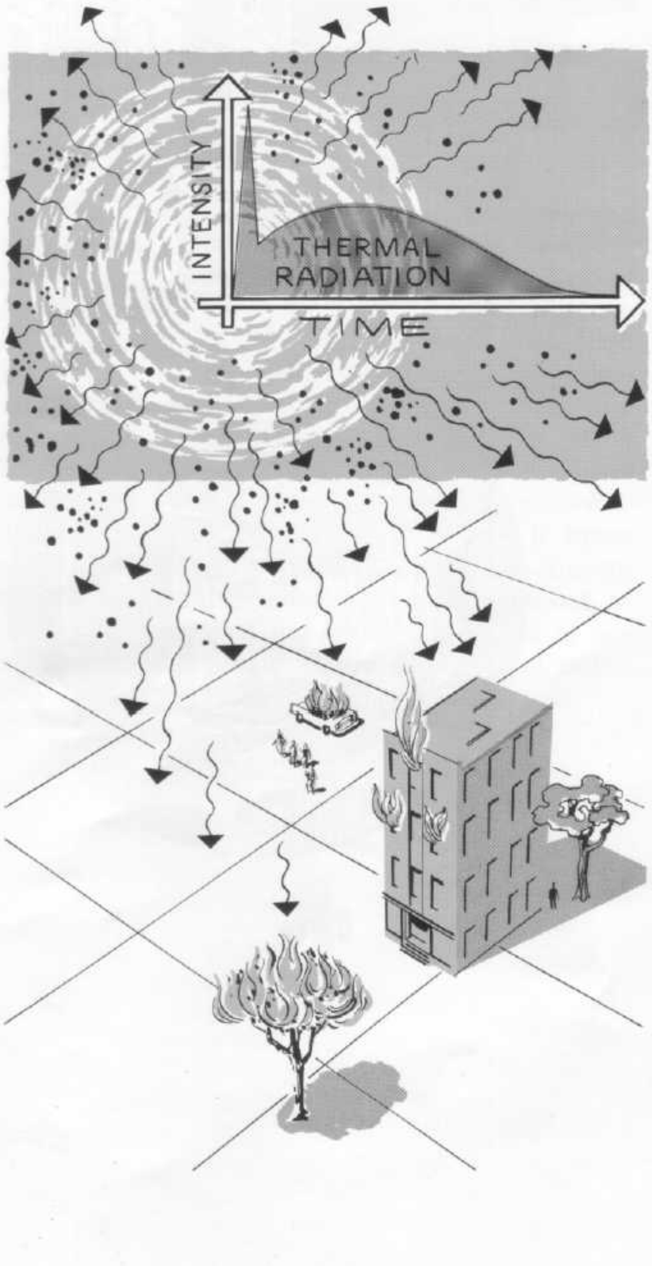
While many buildings afford a degree of protection against fallout radiation—some being better than others—they are vulnerable to thermal and blast effects of nuclear weapons. Most of the United States would not be affected by blast, heat or fires in the event of a nuclear attack. But *a sizeable portion of our population would be threatened by the direct effects of nuclear explosions*. Their survivability can be enhanced by design techniques in new construction to give some protection against these hazards. To explain some of the basic concepts involved, it is necessary to review briefly the environment created by nuclear explosions, the potential hazards, and the response of buildings and their inhabitants to the environment.

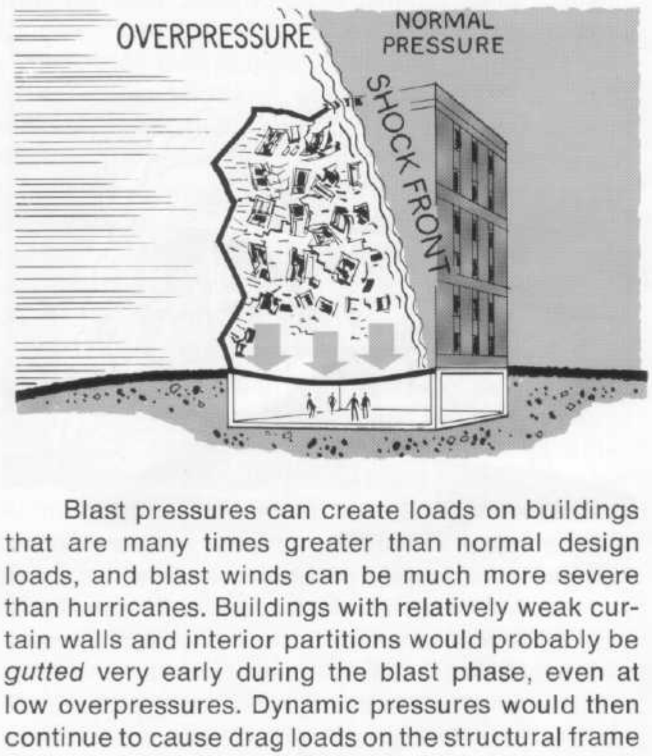
The Influence Of Nuclear Explosions On Building Design

Thermal radiation and prompt nuclear radiation are the first effects to threaten areas relatively close to a nuclear explosion. When thermal radiation strikes an object, much of the energy is absorbed. The amount absorbed determines whether combustible materials will be ignited or whether people will be burned. Thin, highly combustible materials such as paper, window curtains, leaves and dry grass can easily be ignited. They act as kindling for heavier combustible building materials, which fuel major fires.

Intense initial radiation is experienced at locations near the explosion during the first minute after detonation. The effect of this prompt or initial radiation on people and the protective measures to be taken are somewhat different from those for fallout radiation. However, initial nuclear radiation from weapons in the megaton range is not a serious threat beyond the area of heavy destruction.

The effects of the shock wave, which travels away from the explosion faster than the speed of sound, poses the next hazard at close-in locations. The shock front is similar to a moving wall of highly compressed air and is accompanied by blast winds. When it arrives at a location, it causes a sudden rise in the ambient pressure. The increase in atmospheric pressure over normal values is referred to as *overpressure,* and the simultaneous pressures created by the blast winds are called *dynamic pressures.* Both decay rapidly with time from their peak values to ambient pressure and overpressure actually sinks below ambient before equalizing back to normal atmospheric pressure.



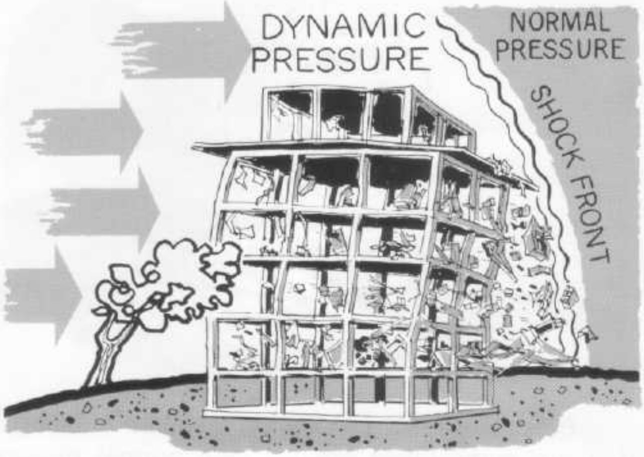


Blast pressures can create loads on buildings that are many times greater than normal design loads, and blast winds can be much more severe than hurricanes. Buildings with relatively weak curtain walls and interior partitions would probably be *gutted* very early during the blast phase, even at low overpressures. Dynamic pressures would then continue to cause drag loads on the structural frame that is left standing. Slabs over closed basements would experience the downward thrust of the overpressure, which would be transmitted to supporting beams, girders and columns. Foundations would experience blast-induced vertical and overturning forces. Failure would occur unless the structural system was designed to resist these large, quickly applied loads.

Structures with load-bearing walls or curtain walls that do not blow out easily could be completely demolished or toppled by blast loads. Such structures would experience the combined loading conditions caused by the incident overpressure, the dynamic and highly transient reflected pressures that develop when the shock wave strikes a surface of the structure.

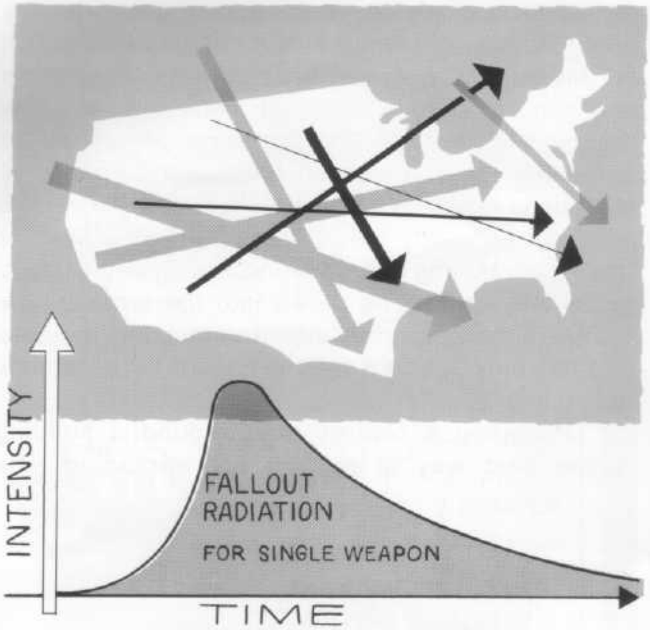
People in basement shelters who are protected against catastrophic structural collapse, high pressures and flying objects would have the greatest probability of surviving the blast phase.

The air blast can penetrate basement areas that are open to the atmosphere causing internal pressures to build up and creating high-velocity jets of air through the openings. Shattered window glass and other objects become dangerous missiles in the air jets. High internal pressures can cause lung damage and eardrum rupture. The air jets, under certain circumstances, can pick people up and hurl them against fixed objects, possibly with lethal effects.



Secondary fires triggered by blast damage such as broken utility lines, overturned appliances, electrical short circuits, etc., present additional hazards to the survivors of the blast and thermal phases of the attack. Flammable building materials, furniture and debris created by the blast can provide the fuel to support fires.

Radioactive fallout particles may drift hundreds of miles from the explosion (ground zero) before falling back to earth. Although higher radiation doses, in most cases, are experienced in the closer-in regions, virtually any portion of the United States may be subjected to a potentially lethal dose of radioactivity in the event of a nuclear attack. Information on radioactive fallout, the effects of gamma radiation and fallout radiation shielding are given in detail in other referenced DCPA publications.



The Plan For Survival

The combination of the thermal pulse and major superstructure blast damage leaves little chance for survival for people in upper stories of buildings within the area of heavy destruction. Basements generally offer the best protection against these hazards and are best suited to protect against the hazards of secondary fires and fallout radiation. Surveys have shown that, while basements are potentially less vulnerable, weak points in their design drastically reduce the probability of survival at close-in locations. If these weak points can be avoided during the design stage, significant protection can be achieved at modest cost against the combined effects of nuclear weapons outside and to some extent within the area of heavy destruction.

Principles of Protective Design

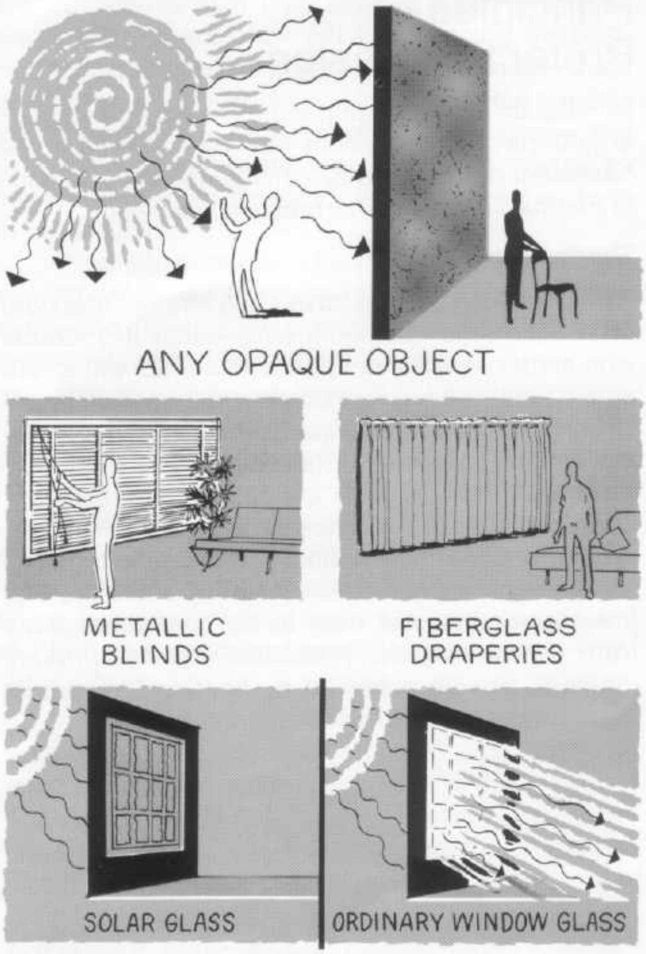
Balanced protection from the combined hazards of nuclear explosions may be achieved in the basement of buildings by considering the influence of *thermal radiation, fires* and *blast* on design.

Thermal Radiation

Thermal radiation travels in a straight line from its source—the nuclear fireball—until it interacts with matter. Any solid, opaque materials will shield against thermal energy. Combustible materials will ignite when the thermal energy they absorb reaches the ignition threshold. Light colors and shiny surfaces will reflect a great deal of thermal radiation; dark, dull surfaces will absorb most of the thermal radiation that strikes them. A thin material is more likely to ignite than a thick material, since there is little opportunity for heat to be conducted away from surface layers. Protection against primary ignitions can be achieved by limiting the radiant heat energy that can penetrate the building.

Metallic blinds or glass fiber draperies over windows will shield combustible furnishings from the thermal pulse. Blinds painted in light colors and having noncombustible tapes will afford protection even though the paint may char. Although transparent materials cannot provide a complete shield against thermal radiation, solar glass will reduce the thermal energy reaching the interior of the room more than ordinary window glass and will have performed this function efficiently before the blast. Avoid combustible draperies and window shades.

As a minimum, shielding against thermal radiation should be provided on the first floor of the building. Since the buildup of fires requires at least several minutes, shelter occupancy plans should also include provisions for fire teams to extinguish early fires.

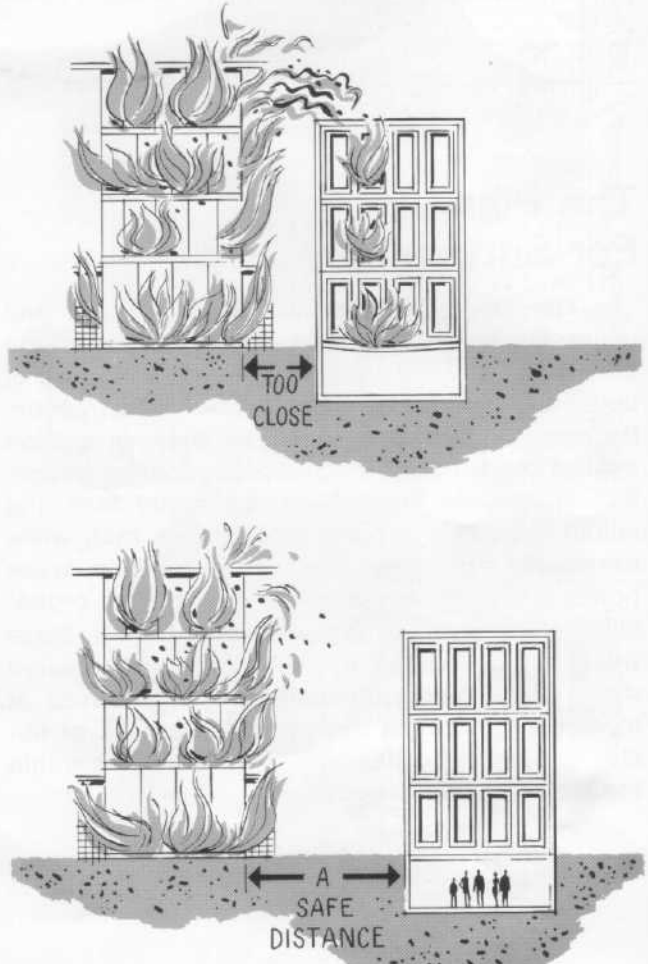


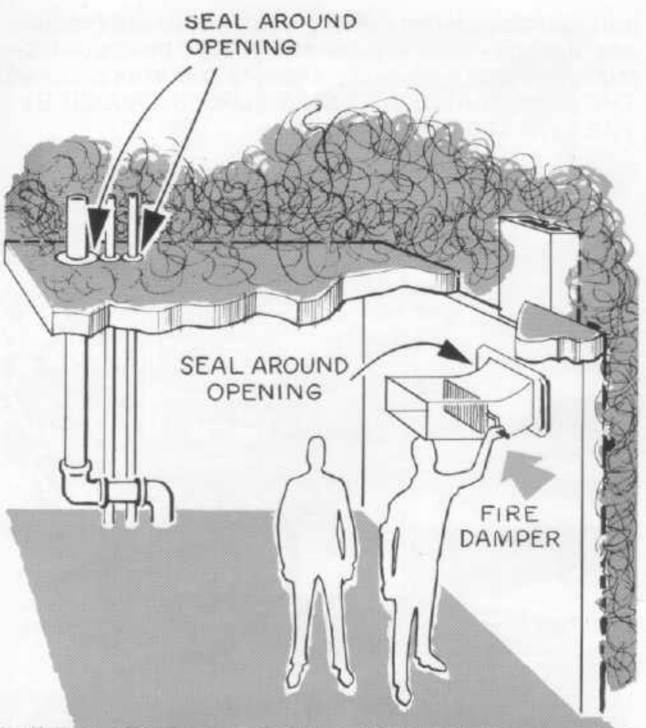
Fires

Primary fires are ignited by the thermal pulse, and secondary fires result from blast damage. These fires then spread to involve other combustible objects and buildings. Regardless of how a fire starts, how much it develops and spreads depends on the amount and distribution of combustible material in the vicinity. Burning buildings produce radiant heat that behaves like the radiant energy of the thermal pulse. Windows and combustible materials increase the amount of radiant heat transmitted from a burning building. The heat intensity reaching an adjacent building depends on the distance between the buildings. Thermal protection devices over windows would be blown away by the blast wave just after the thermal pulse. The building would then be exposed to ignition by the thermal radiation and burning material from adjacent buildings.

Perhaps least known is the nature of the fire problem in a severe-blast-damaged zone. Survival expectancy may be improved in many instances in which blast removes the combustible materials in the aboveground space. The following observations on the behavior of heat and gases generated by fires influence the location and design of a shelter: (1) Although convection heat currents rise, some heat can be conducted through slabs and walls surrounding the fire. (2) Dangerous oxygen depletion and lethal carbon dioxide buildup may occur at elevations equal to or higher than the active fire zone but generally not in areas below the fire. (3) Smoke containing carbon monoxide and other toxic gases may drift or be blown into the areas below the fire, although limited experimental data indicate that this may not be a serious hazard for basement occupants.

Providing a cleared area around a building is the best way to prevent fire spreading. The





building should be sited to provide the maximum separation from adjacent buildings. The greatest fire threat is posed by a building with large openings, combustible exterior walls and large quantities of stored combustibles. Ignition of the roof by heat radiation from taller buildings can be minimized if the exposed roof is Class A or B as defined by the National Fire Code. Fire-resistant exterior walls will protect the building from ignition and, if the building walls are demolished by the blast wave, the amount of combustible rubble in and around the building will be reduced. The window area and openings on the walls facing potential fire hazards should be minimized. If the appropriate separation distance cannot be achieved, there should be a three-hour firewall between the buildings. (Refer to local code requirements.) Fire spread seldom occurs when buildings are separated by distances of 60 feet or more.

Spreading of a fire that may get into the building above a shelter can be limited by reducing the combustible content or by use of fire resistant or fire retardent treated furnishings. Since building use generally governs the fire load, uses that produce the least combustible furnishings and equipment should be planned for areas above or near the shelter. If the first-floor slab is the shelter ceiling, particular care should be taken in selecting furnishings and wall coverings and in locating utilities and equipment so the first story will not be exposed to a rubble fire. Shelter walls and roofs that may be exposed to fires can be insulated to reduce heat flow into protected areas. The use of incombustible materials will help to keep fires from spreading from floor to floor.

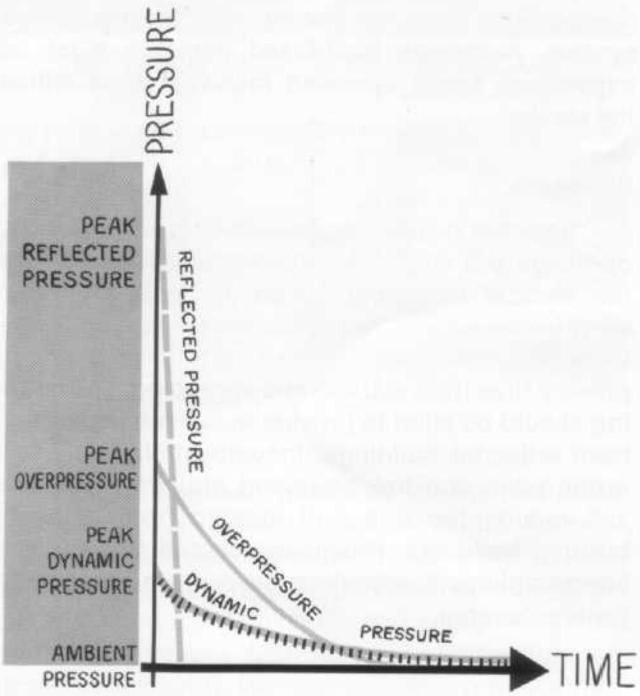
For protection against fires occurring in nonshelter portions of the basement, an airtight exhaust system should be designed to move air in the direction of the nonshelter area. It is likely that, of the usual scattered sources of inlet air, some will be useable for ventilation. If portable ventilation equipment is used, it should be placed so as to pull in air from openings where fresh air is available and exhaust it through other openings. An independent emergency ventilation system designed to provide a positive pressure in the shelter area of one-quarter to one-half inch of water is a good way of keeping out smoke and poisonous gases. To fight infiltration, pipes and ducts that penetrate the shelter walls and ceilings should be grouted or equipped with sealants or gland seals wherever possible. Vaportight fire dampers should be provided in ventilation ducts that extend into the shelter area from the normal building ventilation system. Automatic heat-fused dampers must be capable of being operated manually from within the shelter.

Summary

Thermal protection devices over windows and openings will shield the interior of buildings from the thermal pulse but would probably be blown away by the subsequent blast. The combustible contents of buildings should be kept to a minimum to prevent fires from starting and spreading. The building should be sited to provide maximum separation from adjacent buildings. Incombustible roofs, exterior walls and fire protected structural systems will reduce the threat of ignition from adjacent burning buildings. Provisions should be made to keep smoke and poisonous gases from penetrating the shelter area.

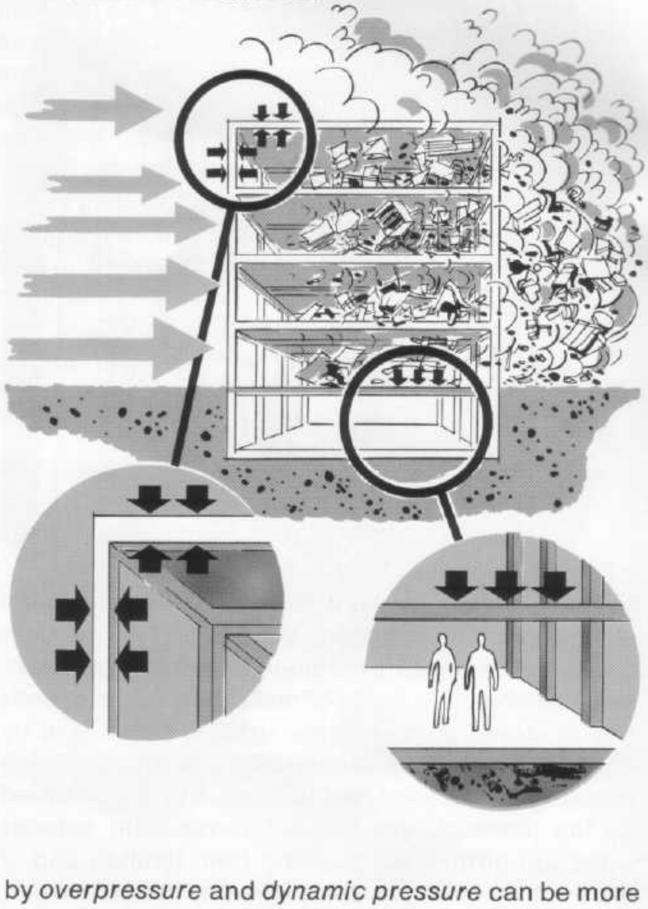
Blast

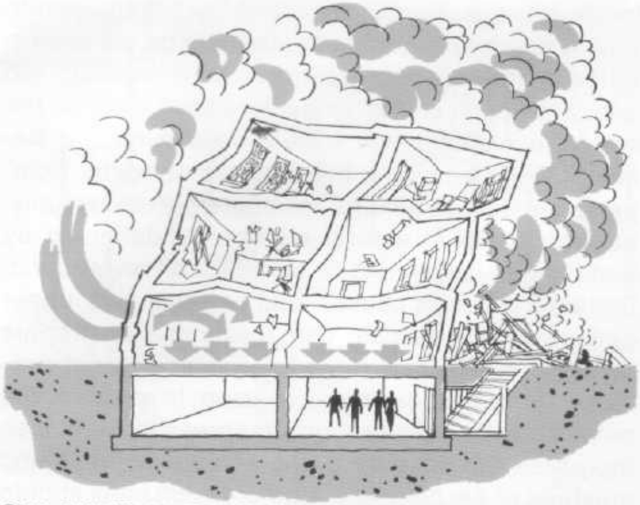
As the blast wave engulfs a building, it produces large pressures on exposed surfaces and penetrates to the inside through openings. The overpressure causes hydrostatic-type loads, and the dynamic pressure causes drag or wind type loads. High reflected pressures are generated on surfaces that the shock front strikes head-on or nearly head-on. At a given distance from ground zero, overpressures and dynamic pressures decay with time but may last for several seconds. The time it takes the reflected pressures to clear a point on a surface depends mainly on the distance to a free edge or an opening and may be one-tenth to one-hundredth of a second. Due to their sudden application and relatively long duration, loads produced by *overpressure* and *dynamic pressure* can be more critical than equivalent static loads, but the damaging effects of the even higher reflected pressures are reduced by their short life. A building with very frangible walls (i.e., walls that are very readily demolished by the air blast) will be rapidly reduced to a bare frame that will experience mostly drag forces. Stronger exterior walls and shear walls will cause the structure to be loaded with reflected pressures, overpressures and dynamic pressures that could cause severe damage or even total collapse.



BLAST PRESSURES CAUSE HEAVY TRANSIENT LOADS ON BUILDINGS -- DYNAMIC RESPONSE MUST BE CONSIDERED IN THE STRUCTURAL DESIGN.

BUILDINGS WITH FRANGIBLE WALLS AND PARTITIONS ARE RAPIDLY GUTTED BY THE BLAST PRESSURES— OVERPRESSURES EQUALIZE AROUND COLUMNS & SLABS. THE BARE FRAME SEES ONLY FORCES CAUSED BY THE DYNAMIC PRESSURE.



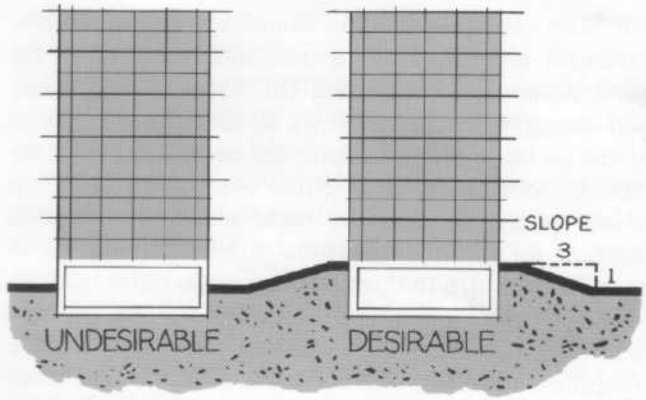


BUILDINGS WITH STRONG EXTERIOR WALLS, INTERIORS, PARTITIONS, OR LOAD-BEARING WALLS WILL EXPERIENCE MUCH LARGER LOADS AS THEY ARE ENGULFED BY THE BLAST.

Frangible upper-story walls and partitions will give way rapidly when struck by the blast, permitting overpressures to equalize quickly around columns and beams and over and below exposed slabs. Consequently, the high reflected pressures will decay so rapidly that the structure will receive little impulse, and the loading on the almost bare frame will be essentially the drag loading associated with the dynamic pressure. The frame and slabs of a frangible-wall structure would probably be left standing with rubble on the slab and around the building. The stronger the exterior walls, the more total load will be imparted to the structural frame. To reduce the amount of rubble on the slab over a basement shelter which has been designed to resist the combined effects, the first-floor walls should be made as frangible as possible.

Slabs over sealed off spaces will be loaded mainly by the overpressure that builds up as the shock front engulfs the building. Basement spaces with openings will be penetrated by the blast pressures, but relief to the slab loading will be negligible since it takes so long for the inside pressures to build up. Jets of air rushing through the openings will exert large drag forces on objects in their paths, although the jets are fairly restricted and short lived.

Blast protection may be achieved in basements through the application of a few basic principles in the design. Design techniques that enhance the strength and ductility of structural elements will increase resistance to blast loads.

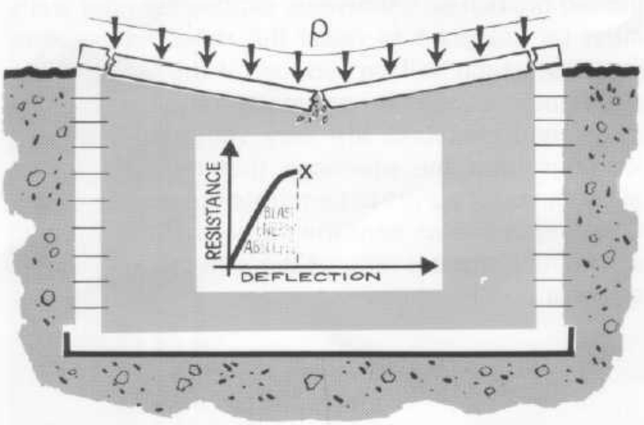


EARTH BERMS INCREASE BOTH BLAST AND FALLOUT PROTECTION

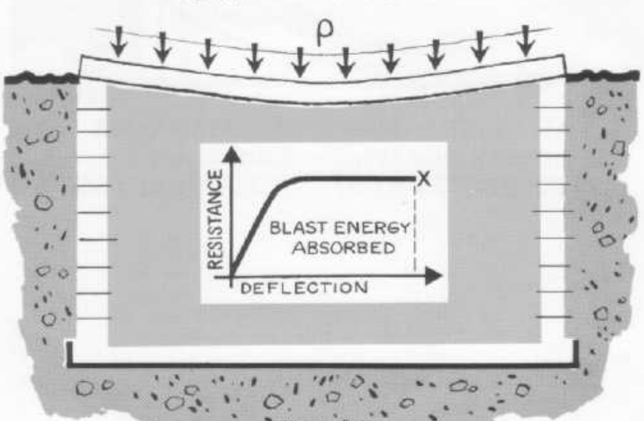
Exposed basement walls will experience the full effect of the high reflected pressures that develop when a shock wave strikes a vertical surface. If the natural topography does not allow the basement to be wholly below grade, earth berms can be used to protect the basement walls from reflected pressures. Otherwise, exposed shelter walls must be designed to resist the reflected-pressure impulse, which will be reduced if the walls of the story above the shelter are made frangible. Outside doors and stairways are very vulnerable to blast loadings, and the openings that they leave can allow the blast waves to penetrate the shelter space. Locating openings near the corners of the building will reduce the duration of the reflected pressures on them.

The need for radiation shielding, fire resistance, strength and ductility favors reinforced concrete as a construction material for floors. Blast-resistant design philosophy allows structural elements to undergo large inelastic (plastic) deformations in response to blast loading. Since blast loads act for a short period of time, the most efficient structural system is one that absorbs the blast energy. A ductile structure that undergoes large deformations without failure can absorb much more energy than a brittle structure of the same static strength. Ductile response of reinforced concrete structures to blast loads may be achieved by applying a few basic principles in the structural design of the building.

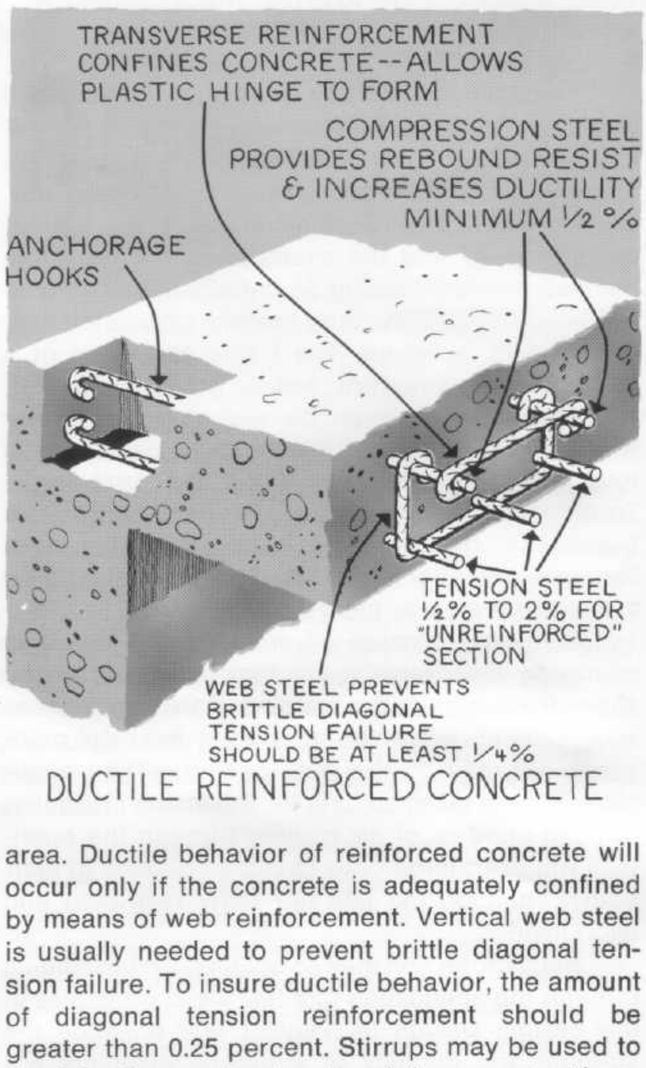
In beams, slabs and other bending members, the relative amounts of concrete and reinforcing steel should be proportioned so that the ductile steel will yield before the more brittle concrete begins to crush. Such an underreinforced *flexural* member will respond in a ductile manner to blast loads. If the section is overreinforced, the concrete crushes before the tension steel yields, causing a brittle failure. *Tensile reinforcement between 0.5 and 2 percent of the cross-sectional area of the concrete element will usually insure ductile behavior* while providing the required strength. Compression steel in flexural members serves two purposes. After a structural member is deflected by blast loads, it attempts to spring back or rebound. Dynamic rebound causes load reversal and, under certain circumstances, can result in catastrophic failure if sufficient rebound resistance is not provided. Compression steel is used to provide the required rebound strength. Compression steel also increases the ductility of the section by inhibiting crushing of the concrete. Compression steel should not be less than 0.25 percent of the cross-sectional area. Ductile behavior of reinforced concrete will occur only if the concrete is adequately confined by means of web reinforcement. Vertical web steel is usually needed to prevent brittle diagonal tension failure. To insure ductile behavior, the amount of diagonal tension reinforcement should be greater than 0.25 percent. Stirrups may be used to provide the required web reinforcement; stirrup ties will aid in confining the concrete.



BRITTLE FAILURE

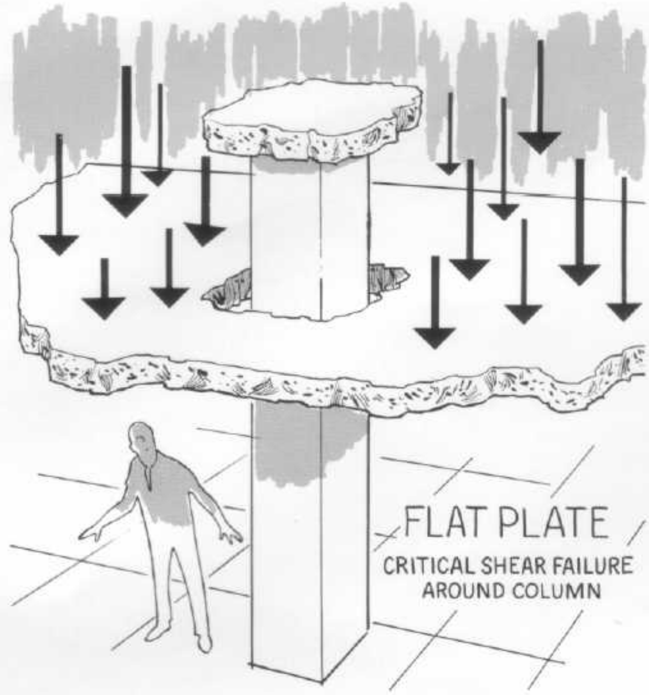


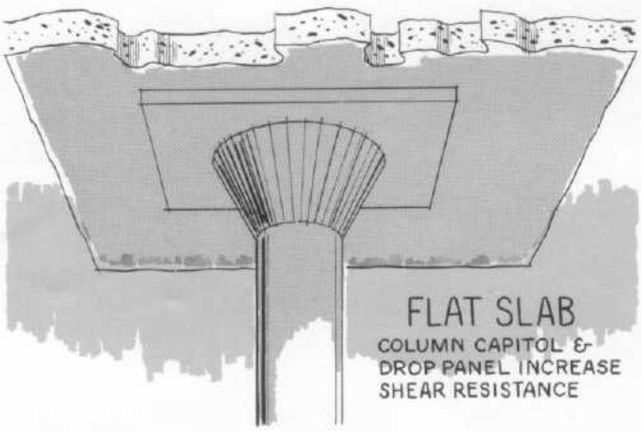
DUCTILE RESPONSE



DUCTILE REINFORCED CONCRETE

There is no advantage in using bent or truss-type bars, so all flexural steel should be straight except for anchorage hooks. Brittle shear failure is avoided in bending members if the section is deep enough for average shear stress on the criti-





cal section to be not more than 20 percent of the compressive strength of the concrete. Because blast loads are always much larger than dead loads, there is no advantage to using prestressed concrete in blast-hardened beams and slabs. If prestressed concrete is used, sufficient unprestressed mild steel should be added to assure ductile response and to provide the required rebound resistance to blast loads.

Column concrete must be adequately confined by means of special transverse reinforcement in areas where yielding will occur in rigid frame construction. Complete continuity is essential for the structure to act efficiently as a unit in absorbing blast energy. The resistance of a tied column will drop off sharply after its limiting static strength is reached, but a spirally reinforced column (with the same area of steel and concrete as the tied column) can undergo substantial deformations before losing its ability to support a load. Since spiral columns are more ductile than tied columns, they are more suitable in resisting blast loads. In view of the particular seriousness of column failures, columns should always have a resistance at least equal to the maximum resistance of the structural elements they support.

Flat-slab floors over the shelter area should have either a column capital or drop panel or both. Flat plates (i.e., flat slabs without column capitals or drop panels) have been shown to be very unsatisfactory in resisting blast loads. Brittle shear failures around the columns can result in the slab punching through at the columns and collapsing into the shelter area.

Summary

The use of frangible upper-story walls and partitions will reduce the probability of a building being toppled or completely demolished by blast. Blast resistant shelters should be below grade wherever possible. Exposed shelter walls and roof slabs should be blast hardened. Ductile reinforced concrete can absorb the blast energy while providing the needed fire and fallout protection. Under-reinforced flexural members with adequate shear, bond and diagonal tension resistance will insure ductile response to blast loads. Flat-plate construction should not be used over the shelter area.

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*These publications are available only to architects and engineers who are certified fallout shelter analysts.

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