STRUCTURAL PERFORMANCE

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When Structural Blast Design Doesn't Really Include Blast Resistant Design

Damage-Limiting Construction and Explosion Protection by Deflagration Venting

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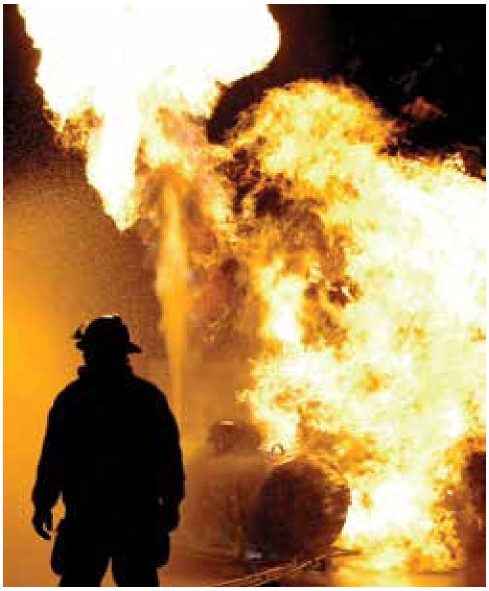
Many chemical, pharmaceutical, laboratory and general industrial facilities have requirements for storage of chemicals, gasses, fuels, lubricants, and other hazardous materials used in everyday operations. When stored appropriately and not subject to puncture, spillage, and exposure to flame or other ignition sources, these materials are benign and safe. However, accidents and events can combine to cause the unintentional release of these materials and their exposure to flame, electrical arc or other ignition sources. In those scenarios, these materials can, in the best case, burn with significant temperature. In the worst case, as the flame front accelerates in the released combustible materials, the transition from burning to deflagration can occur; deflagration being defined as the propagation of a combustion zone or flame front at a velocity that is less than the speed of sound in the unreacted medium (typically air). Further acceleration of this deflagration could reach supersonic velocity, or could cause an explosion, resulting in significant pressure rise and accompanying damage to the structures in which they are stored.

Because the calculation of 1) the release mechanisms (puncture, rupture, spill), 2) dispersion (entrainment in the air or pools) and 3) ignition and flame spread of and in these materials can be very difficult to quantify, industry methods have been developed to limit the effects of "worst case" releases and ignition through what is called "deflagration venting". This approach is essentially equivalent to the installation of a relief valve on a containment structure, where this "valve" limits the pressure buildup inside the structure to a predetermined and safe level. The "venting" eliminates the need to design the containment structure for a maximum credible event or release through the employment of vent panels or explosive vents, areas of the (typically exterior) wall that are designed to open or "fail" at a predetermined opening pressure.

Similar approaches are very often used in industry for mechanical equipment (hoppers, ducts, etc.) when dusts are a byproduct of manufacturing or processing. Dust can be defined as combustible when they constitute a finely divided particulate solid that presents a flash fire hazard or explosion hazard when suspended in air or a process-specific oxidizing medium. Typical combustible dust can occur where processes produce metal dust, such as aluminum and magnesium; wood dust; plastic or rubber dust; biosolids; coal dust; organic dust, such as flour, sugar, paper, soap, and dried blood; and dusts from certain textiles.



Two industry approaches that can be used to determine the venting required for safe storage of hazardous chemicals or dusts for a particular combination of structure type, stored chemical or potential dusts are the National Fire Protection Association's NFPA 68, *Explosion Protection by Deflagration Venting*, and Factory Mutual's FM 1-44, *Approval Standard and Data Sheet for Storage Buildings and Lockers for Damage-Limiting Construction*. Both of these documents provide approaches and guidelines for venting and construction utilizing venting such that structural damage is mitigated by limiting the pressure rise in a material containment or storage room, or facility.

For flammable gasses, dusts or hybrid mixtures, NFPA 68 provides guidance that has been developed over many decades, starting in 1945. Then titled NFPA 68T, *Explosion Venting Standard*, the document was subsequently improved to bring together all the best available information on the fundamentals and parameters of explosions, test data supporting design approaches, and guidance for the use of vents and vent closures for mitigation of those explosion effects. NFPA 68 is presented with both performance-based and prescriptive procedures and contains extensive explanatory material including further descriptions of deflagration fundamentals, measurement and estimation procedures for reactivity of dust and burning velocity of chemicals, and details regarding vent panel configuration and parametric limitations.

To determine required "safe" vent area, the NFPA and FM approaches provide and define methods to quantify and relate critical chemical, geometric, and structural parameters. Critical chemical and combustion parameters include K_{st}, the deflagration index of a dust cloud, S_u, the fundamental burning velocity of a gas-air mixture, ρ_u, the mass density of an unburned gas-air mixture, λ, the ratio of gas-air burning velocity accounting for turbulence and instabilities, and P_{max}, an optimum maximum pressure expected for a given material in a deflagration in a contained volume. Strictly speaking, the volume of the stored chemical would be an important parameter since a stoichiometric mix (combustible mix of fuel and air) must be achieved for combustion to occur. However, in most instances, sufficient material is available in the stored volume to reach this concentration. Thus critical parameters are based on the chemical with the highest combination of S_u and P_{max}. Although, an adjustment to λ and A_v can be determined through a partial volume determination.

Critical geometric parameters include internal volume (V), A_s, the internal surface area of exterior (non-partition) walls, floor, roof and potential venting surfaces, internal volumes segregated by partitions, and A_{obs}, the surface area of internal obstructions including tanks, drums, pipes, and machinery. A_{obs} is critical, as it directly effects λ and the acceleration of the flame front.

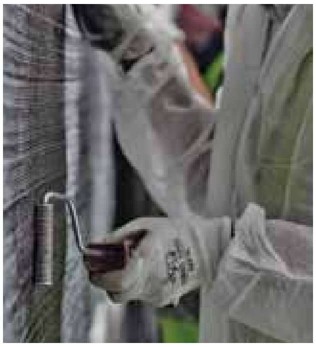
The critical structural and venting parameters are P_{es}, the enclosure strength, P_{stat}, the static activation pressure of the vent, and A_v, the vent area required. The enclosure strength, P_{es}, is defined as the maximum or ultimate internal static pressure that the structure can resist. In the parlance of the structural engineer, this would be an ultimate resistance or capacity of the structural wall, roof, and doors/windows (if included in the resisting portion of the calculation) using expected strengths, but without applying increase factors associated with load rate or inertia (dynamic load factors). P_{es} is further defined as the limiting (typically flexural) capacity of all walls, roofs, doors or windows, or a limiting capacity of any connections between those elements.

The critical chemical/material, geometric, and structural parameters described above are used to determine derivative parameters for vent size determination. One such parameter is P_{red} or the maximum expected pressure inside the containment or storage structure. P_{red} is essentially the pressure for which the vent area and orifices are designed. For relatively ductile structures that can accommodate moderate deformations (as in most reinforced concrete, masonry or structural steel and cladding type systems), P_{red} is defined as follows:

$$P_{red} = \frac{P_{es}}{DLF}$$

Where DLF is the dynamic load factor or the dynamic effect of the rate of rise of the pressure. DLF is further defined as:

$$DLF = \frac{X_m}{X_s}$$



Where X_m is the maximum dynamic displacement and X_s is the displacement produced in the system when the peak load is applied statically. In the absence of detailed analysis using expected pressure rise rate, a DLF of 1.5 can conservatively be used. Similarly, if the structure possesses limited deformation capacity (i.e., where a lack of ductility prevents sufficient deformation before failure), P_{red} is limited to ⅔ of the ultimate strength of the vented enclosure (essentially the same as applying the DLF of 1.5). Other derivative structural calculations might include vent panel reactions and appropriate design for those reactions. If $P_{stat} >= 0.1$ bar, reaction calculations and design are required.

Additional derivative parameters and adjustments might include a further reduction in P_{red} (and a corresponding increase in vent area) if the vents are ducted; i.e., there is a restricted pathway from the vents to the exterior. Minimum distance to air intakes or adjacent structures based on vented fireball diameter must be calculated per the given equations. Acoustic wall linings can reduce λ and a subatmospheric internal pressure can reduce P_{max} and A_v. Vent mass exceeding an upper threshold based on P_{red}, n (the number of vents), V, S_u and λ increase A_v.

Mechanical vents or simple openings can be used to satisfy the venting requirements. Normally open (louvered or hangar type) vents, as well as normally closed panels with pull-through fasteners, shear pins/bolts, spring, magnetic or friction latches, and closed rupture diaphragms can be used. Tethering of vents may be required to protect adjacent equipment or personnel. Hinged devices must be tested to assure the vents do not deform significantly or become detached during operation. P_{stat} and vent area and weight are provided by the manufacturer. P_{red} is also commonly used to specify the vents. Except for pressures below 0.1 bar, P_{stat} must be no greater than 75% of P_{red}.

Two project examples can be used to illustrate the procedure and parameters described above. The first is a relatively large (40-foot x 20-foot x 12-foot high) enclosure at a manufacturing facility that produces a fuel cell hydrogen carrier, where methanol is used as a key component in the development of fuel cells. Methanol is an ideal hydrogen carrier with more hydrogen atoms in each gallon than any other liquid that is stable under normal conditions. This storage room also has propane tanks for heating operations. The proposed storage room walls consist of 8-inch reinforced CMU with #5 bars every other cell, and the CMU is fully grouted. The storage room roof consists of a corrugated steel deck and 6-inch concrete with #5 bars at 6 inches on center each way. The total area of internal obstructions is 250-foot-square, and the vents are not ducted (open to the exterior).

The first step for a quick determination of required vent area is the selection of fuels. In this case, methanol has a higher burning velocity at 56 cm/sec (propane has an S_u of 46 cm/sec); thus methanol controls. Second, P_{es} should be determined for the structure and its subcomponents. The R_u (in this case the ultimate flexural capacity of the CMU walls was determined to be 2.1-psi, while the ultimate capacity of the concrete-over-steel-deck roof was determined to be 2.4-psi; thus the wall capacity controls. Calculating P_{red} and the derivative parameters and stepping through the NFPA 68 procedure yields a required vent area (A_v) of 198-foot-square, or 48% of the wall area, an undesirably large area. As a first revision to reduce that required area, the wall strength is increased by grouting and reinforcing every cell to yield a new wall capacity at 3.6-psi. However, the roof capacity now controls at 2.4-psi. This somewhat higher P_{es} results in a new and slightly lower required A_v of 186-foot-square; still 39% of the wall area. A final iteration simply reduces the storage area (splits the storage into more than one space) to a 15-foot x 20-foot x 12-foot high space. Because of the reduced roof span (and its increased capacity), the wall capacity (P_{es}) of 3.6-psi now controls, and a new P_{red} results in a required A_v of 79-foot-square, or 33% of the new wall area; both architecturally and structurally acceptable.

A second project example concerns ethyl acetate stored at a pharmaceutical plant. Ethyl acetate is used in the pharmaceutical industry as an extraction solvent. In this case, a low-cost exterior "shed" was desired for drum storage. A 30-foot x 10-foot x 8-foot high rectangular building with 8-inch CMU walls (cells grouted with #5 bars at 32-inch on center) and a 3-inch lightweight concrete-on-steel-deck roof supported by open-web steel joists (OWSJ) at 5-foot spacing was desired. The stored drum surface area was 200-foot-square (A_{obs}), and unducted vents were proposed. Based on a S_u for ethyl acetate of 38 cm/sec, a wall and roof capacity (P_{es}) of 2.5-psi and 1.6-psi respectively (roof controls), a vented area (A_v) of 41-foot-square was determined to be required. While acceptable, a second design iteration was performed to see if structural costs could be reduced by replacing the lightweight concrete with a built-up roof over the same OWSJ system, now at a 4-foot spacing. This reduced joist spacing resulted in an increased roof capacity of 2.0-psi, allowing the wall capacity to control the design. The new required vent area was 47-foot-square, still acceptable and with a reduced structure cost.

These examples illustrate the tradeoffs in volume, structural capacity and even combinations of hazardous materials that can be made to generate efficient designs for deflagration venting in damage-limiting construction. While not used directly, concepts and approaches for determination of ultimate capacity used routinely in blast resistant design can support the optimization of vent sizing. The NFPA 68 and FM procedures are tools structural engineers should be aware of when asked to support the industry with safe and efficient structural systems.▪