Fire Research Note 759

FIRE RESEARCH STATION

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THE RELIEF OF GAS AND VAPOUR EXPLOSIONS IN DOMESTIC STRUCTURES

by

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1. Introduction

1. Following the publication of the Report on the Enquiry into the collapse of flats at Ronan Point, advice was sought from the Joint Fire Research Organization on the pressures which might occur in domestic structures during explosions involving fuel other than town gas. In particular information was sought on the conditions under which the maximum explosion pressure on external loadbearing walls may be reduced to specific values lower than 35 kN/m^2 (5 lb/in^2). The point was also made that it was difficult to design for the removal of more than one external loadbearing wall in a flat and the question was raised under what conditions more than one loadbearing wall might be removed in an explosion. This note is concerned with the provision of this information.

2. When an explosion takes place in a flammable gas or vapour in a closed compartment a pressure up to 700 kN/m^2 (100 lb/in^2) may be reached in that compartment. This, of course, is vastly greater than pressures to which normal buildings can be designed. The fact that the maximum pressures that are reached in explosions are far less is usually due to the fact that the pressure in the explosions has been relieved in some way. As a rule, gas and vapour explosions take place substantially more slowly than explosions involving high explosives such as T.N.T. The most explosive mixture of a fuel vapour and air in a volume of 30 m^3 (1050 ft^3) will contain about 2.5 Kg (5 lb) of fuel. The energy potential of this will be equivalent to that of 20 Kg (45 lb) of T.N.T., but the pressure pulse with the gas explosion would last several hundred milliseconds and with T.N.T. only about one millisecond. The gas explosion is thus usually slow enough to allow time for the gases produced in the explosion to be pushed through an opening in an outside wall in the compartment. Explosion relief, therefore, consists of spaces in the exterior walls which may be opened by the explosion pressure at an early stage in the explosion and before other walls in the compartment are affected. Windows, doors and light walls are examples of such spaces. The availability of such spaces determine the maximum pressure under otherwise constant conditions of explosion.

3. Most of the experience available at the Fire Research Station is concerned with the relief of gas, vapour and dust explosions in industrial plant and buildings. These are usually single volumes. Domestic premises differ in that they consist of a series of rooms, etc., joined by doors and this highlights a new problem in explosion relief which has not in the past received much attention. In general it is not possible to keep the flame and the pressure effects of an explosion in one room either

because the flammable gas may be present initially in a number of rooms, or because it is pushed from one room to another in the course of an explosion.

Explosion relief at Ronan Point

4. To pinpoint advice on the questions raised consideration was concentrated on the design of flat in which the initial gas explosion took place at Ronan Point. A visit was made to a similar flat on the 29th November, 1968, and an estimate was made of the potential explosion relief in the flat. On the basis of this, and on general principles for explosion relief developed below, estimates have been made of the maximum pressures that might occur in explosions ignited in different parts of the flat.

5. Details of the layout of the Ronan Point Flat have been given in the Report on the Ronan Point enquiry [1]. The possible explosion reliefs in the flat may be listed as follows:-

(a) Living-Room door leading on to the veranda. The dimensions of this door was 0.6 m x 2.0 m (2 ft x 6 ft 6 in). It had a glass window 0.5 m (1 ft 6 in.) square. It opens outwards and is held by a simple catch. It was estimated its weight was less than 15 Kg/m^2 (3 lb/ft^2).

(b) The two windows in the living-room. These were double-glazed with a gap of about 75 mm (3 in.) between the glazing. They were in wooden frames and measured 1.1 m x 1.75 m (44 in. by 69 in.). They swung round a central pivot and were held by five bolts bearing on $\frac{1}{8}$ in. metal catches. The bolts were operated from one handle.

(c) The kitchen window measuring 1.15 m x 2.3 m (45 in. by 90 in.). This consisted of two parts, three-quarters of the length of the window was double-glazed, like the living-room window, but one-quarter of the length of the window had the panes sealed together to form double thickness glass. The dimensions of this double thickness pane was 0.55 m x 1.05 m (21 in. by 42 in.). This window looked out onto the veranda and over the top of the balcony.

(d) The bedroom window measuring 1.3 m x 1.15 m (52 in. by 45 in.) similar in construction and operation to the living-room windows.

(e) The rest of the non-loadbearing wall in which the kitchen windows were inserted. This non-loadbearing wall was described as consisting of a sandwich of 50 mm (2 in.) polystyrene (foam) with 3 mm ($\frac{1}{8}$ in.) plywood on the inside and 6 mm ($\frac{1}{4}$ in.) asbestos on the outside. However, the extent to which this could act as a relief was severely limited by the presence of the balcony on the veranda.

(f) The front door of the flat leading onto the corridor and measuring 0.3 m x 2.0 m (2 ft 9 in. x 6 ft 6 in.). Although the door was not an external door, the combination of the facts that the partitions in the corridor were flimsy, that the corridor was partly open at both ends, and that the volume of the whole corridor was large in comparison with the volume of the hall in the flat, allow the inclusion of the external door in the corridor as explosion relief.

6. To be most valuable an explosion relief should be as light as possible and should be secured with a minimum force which should rapidly disappear when the vent begins to move. Viewed at from this basis, the only really satisfactory explosion relief in the flat is the door leading from the living-room to the veranda. The fact that the windows are pivoted about their centre prevents the force of the ~~explosion opening the windows, i.e. the windows cannot be easily converted into a~~ swinging panel type of relief, which is possible when they are hinged on one side. The existence of five strong catches also acts against the easy removal of the windows by explosion. Thus, during an explosion either the glass panes would burst or the whole frame would be pushed out of the wall. If each pane of glass is 4 mm $\frac{1}{6}$ in. thick it may be estimated that the pressure at which most of the double glazed windows would burst would be of the order of 7×10^3 N/m^2 (1 lb/in.^{2}). However, the double thickness window in the kitchen would not burst until a pressure of about 21×10^3 N/m^2 (3 lb/in.^{2}) had been reached. It is not possible to judge the pressure at which the whole of the windows would be pushed out of their frames. The front door of the hall is also relatively heavy and butts up against the 25 mm (1 in.) jamb. For the purpose of this report it has been assumed that the windows of the kitchen, the living-room and the bedroom would blow out when the pressure reaches 7×10^3 N/m^2 (1 lb/in.^{2}).

Calculation of maximum pressure

7. The maximum pressure reached in a vented explosion depends markedly on the nature of the fuel gas, the shape of the compartment and particularly the extent to which the gases in the explosion are in turbulent motion. The existence of turbulence in the gas or the creation of turbulence by the explosion itself, increases the rate at which the flame travels and at which pressures increase; turbulence therefore tends to cause higher pressures.

Conditions of low turbulence

8. In general when a stationary fuel/air mixture is ignited inside a well vented compartment the explosion does not develop serious turbulence as long as there are not too many objects present in the compartment that obstruct the motion of the flame towards the explosion relief. Although no direct experiments have been carried out under conditions identical with a typical situation in a domestic room, some work has been done under conditions which are roughly similar in one or more respects to allow an estimate of the explosion pressures that may develop. This work leads for fuel such as L.P.G., petrol and flammable solvents, to the following expression for the maximum pressure developed for the most explosive mixtures of the gas and air:-

$$P_m = 10\ P_v + 3.5\ K\ (kN/m^2)\ \text{[illegible]}$$
$$P_m = 1.5\ P_v + 0.5\ K\ (lb/in.^2) \quad \ldots\ldots (1)$$

where P_m = maximum pressure reached in the explosion (kN/m^2 or $lb/in.^2$)

P_v = the pressure within the compartment at which the vent covering is removed (kN/m^2 or $lb/in.^2$)

K = is venting ratio A_c/A_v (dimensionless)

A_c = is the smallest cross-sectional area of the compartment

A_v = is the total area of the explosion reliefs

9. The second term on the right-hand side of equation 1 expresses the effect of the size of vent and is based on a collation of available information on experiments using propane, or other gas with similar burning properties, carried out with open vents or vents closed with very easily removed covers (2), (3). Most of this work is on a comparatively small-scale, but a useful scaling point is available, in experiments carried out in Sweden (4) in an approximately cubical chamber of volume 200 m^3 (7,000 ft^3) which supports the correlation. The coefficient of the second term makes an allowance for the presence of furniture in the room on the development of some turbulence in the explosion. The first term of the equation, which expresses the effect of the vent covering on the explosion, and the fact that the two terms are given as additive, are based almost entirely on experience at the Fire Research Station on a wide range of small-scale tests with propane air mixtures in which vent covers were held in place by magnets with a force up to 4 kN/m^2 (0.6 $lb/in.^2$) (3), (5), (6). A useful scaling point is again available in the Swedish Tests in which covers were held back by magnets and springs with a force of 1.0 kN/m^2 (0.14 $lb/in.^2$).

10. Taking all the above factors into account it is felt reasonable to apply equation 1 to rooms of the size and shape found in domestic premises as long as the following conditions are fulfilled:-

(1) maximum and minimum dimensions of the room have a ratio of less than 3 : 1;

(2) the vent area factor K is between 1 and 5;

(3) the weight of the covering on the vent which flies in the explosion does not exceed 24 Kg/m^2 (5 lb/ft^2) of vent area;

(4) the covering is held in place by a force which does not exceed 7 kN/m^2 (1 $lb/in.^2$) which force can be removed virtually completely after the vent cover has travelled a few millimetres. A glass window would come into this category or any door held by small springs or latches.

(11) On the basis of the information in paragraphs 5 and 8, it may be estimated that the explosion relief area in the kitchen, the living-room and the bedroom expressed as a value of K to the nearest whole number was 2, 2 and 5 respectively. On this basis, the maximum explosion pressure that would be expected in these rooms is the most flammable mixture of propane in air when ignited in the room would be 17.5, 17.5 and 28 kN/m^2 ($2\frac{1}{2}$, $2\frac{1}{2}$ and 4 $lb/in.^2$) respectively.

Conditions of high turbulence

12. When the explosive gases are either turbulent when ignited, or if they become turbulent during the course of the explosion, pressures considerably in excess of those given by equation 1 may be obtained. This may be prone to happen in domestic premises, since the action of pushing combustible gases through an internal door can ~~create turbulence on the other side of the door. The existence of strong windows~~ which do not burst until a pressure of 7 kN/m^2 (1 $lb/in.^2$) is reached tends to aggravate the situation, since until the window is open, all the expansion of gases takes place through the internal door. In fact, the way to avoid high pressures developing is to have available in a wall opposite the internal door some explosion relief which is either open all the time or opens at a very low pressure, and before the flame reaches the turbulent mass of gas on the other side of the internal door. This relief may be called "Back relief" as distinct from "General relief" covered by equation 1. There is no information available on a scale comparable to that of domestic premises to provide estimates to allow the explosion pressures to be calculated under these conditions. However, some small-scale laboratory experiments have been done, mainly with ducts, which give an indication of the extent to which pressures might be increased, and the requirements of back relief to mitigate this pressure rise [(3), (5), (7)]. This information suggests that the area of back relief should be approximately one-half to one whole of the area of the internal door and should open at a pressure less than 1.75 kN/m^2 (0.25 $lb/in.^2$). Application of this concept to the situation in domestic premises at Ronan Point is illustrated in the next three paragraphs.

13. The behaviour of an explosion which started in the hall would depend on the time when the front door of the hall is pushed out and acted as an explosion relief. Until this happened the gases from an explosion in the hall will relieve into the three main rooms, and if ignition took place of the turbulent pocket of gas in these three rooms prior to the front door being burst open, then pressures higher than those indicated in paragraph 8 would be obtained. Small-scale tests on cubical boxes carried out at the Joint Fire Research Organization suggest that under these conditions the pressure in the three rooms might rise to values of 30, 30 and 60 kN/m^2 (4 $lb/in.^2$, 4 $lb/in.^2$ and 8 $lb/in.^2$) respectively. However, if the front door gave way before a substantial pocket of gas in these rooms became ignited, then this would provide back relief and it would be unlikely that the maximum pressure in these rooms would be affected, and the maximum pressure in the hall would not exceed about 7 kN/m^2 (1 $lb/in.^2$).

14. Another possibility is an explosion starting in one of the main rooms of the flat and venting through the internal door to other rooms of the flat and starting a turbulent explosion there, before the main explosion relief becomes available in the room in which the explosion started. The presence of a veranda door in the living-room would form sufficient back relief and it is unlikely that an explosion starting in that room would cause turbulent explosions elsewhere in the building. A similar effect could be obtained in the kitchen if the double thickness pane were removed and converted into a swinging panel, or indeed, if a door leading onto the veranda similar to the living-room door could be inserted. The effect could not be obviated so easily, however, in explosions starting in the bedroom, although here if the front door of the building were a good explosion relief this would help reduce considerably the effect of any turbulence in the explosion passing into the living-room and the kitchen.

15. A difficult condition would occur if ignition took place in either the water heater cupboard, the bathroom or the cupboard in the hall. These spaces have no rearward explosion relief and the deflection of the flames as they entered the hall would cause turbulence, which on the basis of small-scale tests with ducts (7) is estimated to give rise to a pressure of about 30 - 35 kN/m^2 (4 - 5 $lb/in.^2$) in the hall. If the front door were to burst open before any substantial pocket of flame ignited in the kitchen, the living-room and the bedroom, then again it will be unlikely that pressures in these rooms would exceed the pressure reached in the corridor. However, if there is a delay in the front door opening, then the pressures reached in the three main rooms might exceed this value. No small-scale tests are available to the author which would allow an estimation of the extent to which the value would be exceeded.

Effect of change of conditions

16. Most of the tests on which the above estimates are based were carried out with propane. Available information suggests that for equation 1, P_m should be proportional to the fundamental burning velocity. There is also evidence that under other conditions particularly in long ducts the maximum pressure in a vented explosion is proportional to the square of the fundamental burning velocity (6). A list of fundamental burning velocities for different gases and vapours is given in Table 1. From this it can be inferred that if methane (natural gas) were the fuel, for given conditions of venting, maximum pressures would be somewhat lower, but if ethylene, town gas or acetylene were the fuel, maximum pressures would be substantially higher than those given above. For common solvents and liquid fuels the maximum pressure would be similar to propane.

17. The estimations given in paragraph 11 were based on the assumption that the explosion reliefs in the windows of the three main rooms do not operate until an internal pressure of 7 kN/m^2 (1 $lb/in.^2$) has been reached. If the windows are scored then they will burst at a lower pressure [8]. It is also possible to weaken the catches or the pivots holding the windows. If it is assumed that the explosion reliefs operate when the explosion pressure is 2 kN/m^2 (0.3 $lb/in.^2$), then according to equation 1 the maximum pressure reached in the explosions would be about 7 kN/m^2 (1 $lb/in.^2$) less.

18. The assumption has also been made that the fuel vapour is present in a mixture with air in the proportions that would give the most violent explosion (4 to 6 per cent for propane), and that the amount of fuel present is such that more than one-sixth of the volume of the compartment under consideration is filled with this mixture. If the volume of fuel/air mixture ignited is less than this, then the explosion pressures would be reduced. Again, if the concentration of the vapour were other than that indicated lower pressures would be produced. Propane can give explosive effects when its concentration in air lies between the flammable limits of 2.2 and 9.5 per cent. In general only a small part of the vapour zone above the liquid spillages will contain the most explosive mixture. There is also evidence that the extra violence caused by turbulence falls off markedly as the concentration approaches the flammable limits [7].

Damage caused by pressure rise

19. All the above estimates are for maximum pressures reached in explosions, but the interest here is the effect of this pressure on certain critical load-bearing walls. As a rule, on the basis of general principles of structural engineering, a static pressure may be defined for failure of these walls to occur. However, owing to the fact that the walls are heavy and have to be moved against elastic, frictional and deformation forces, a finite time of application of force is needed to bring them to collapse. Much practical and experimental data have been gained on this aspect of response of structures to explosions in high explosives acting externally on a building [9], [10], but practically none on internal slow moving explosions.

20. If the time of duration of the pressure pulse is substantially larger than the period of natural frequency of the item of structure being acted upon, then the equivalent static load is approximately equal to the peak pressure of the pulse; the ductility of the stressed material plays some but not a major part in determining the equivalent static load. If the duration of the pressure pulse is less than the natural frequency period, then the equivalent static pressure is substantially less than the peak pressure in the pulse and is significantly smaller for more ductile materials than less ductile materials [10].

21. The natural frequency of floors and slabs in rooms is of the order 20 - 30 cycle/seconds, i.e. a natural period of 40 m s [10], [11]. A completely unvented propane explosion in a volume of 30 m^3 (1,050 ft^3) would give high pressures for several seconds; about 0.75 seconds to build-up to the maximum pressure [12] and several seconds thereafter for the reduction in pressure by cooling. An explosion in the most explosive propane-air mixture in a room provided with sufficient explosion relief to keep pressures down to a few pounds per square inch under conditions of low turbulence would have a duration of about 300 m s - several times the natural period. An explosion in the most violent mixture of towns' gas air and an explosion in highly turbulent pockets of all common gases when ample explosion relief is present, will tend to give pressure rises which last 20 - 150 m s.. This is of the same order as the natural period and the equivalent static pressure would be somewhat lower than the peak pressure. If more were known on the pressure time curves in explosions in full size rooms or groups of rooms, and response of different types of loadbearing panels to internal pressures, then it should be possible to calculate the equivalent static pressure for explosion conditions in domestic premises.

Discussion

22. The above estimations indicate that it should be practicable with fuels such as liquefied petroleum gases (i.e. butane and propane), natural gas (methane) petrol vapour and common solvents to design domestic premises so that the maximum pressures reached in explosions do not exceed specified pressures between 17 and 35 kN/m^2 (2.5 and 5 $lb/in.^2$). The broad principles are that windows should be of reasonably generous proportions and be made to burst or fly open at the lowest practicable pressure to provide necessary resistance to wind suction forces, although it is not likely that this factor will be of critical sensitivity. However, a certain part of the explosion relief specified as back relief should open at rather lower pressures than that associated with suction forces of the worst winds. These could be conveniently placed in the form of doors leading to verandas or to large open corridors.

23. Where it is not possible to provide back relief in a room in which ignition of a flammable vapour is a possibility, then other means may be provided to prevent turbulent explosions being transmitted to the rest of the building. These may take the form of:-

(a) a self-closing door which can be relied upon to be shut and to withstand the maximum pressure of a low turbulence explosion in the room;

(b) sufficient mechanical ventilation to prevent the accumulation of a dangerous amount of flammable gas in the room [13];

(c) flammable gas detectors which can sound a warning or bring in mechanical ventilation. Except perhaps for a large spillage of petrol or solvents, it is unlikely that dangerous pockets of flammable gas/air mixtures would build-up in less than one hour.

24. In general, it is not possible to stop an explosion travelling from one room to another in a domestic flat. Major rooms without sufficient general explosion relief should thus have critical loadbearing walls bridged over in case a loadbearing wall is removed. However, if all rooms have sufficient general relief and back relief (or if some equivalent precaution is taken) it is unlikely that a loadbearing wall would be removed. Nevertheless, bridging over all loadbearing walls would be a useful precaution to take.

25. There has been extensive extrapolation from available data in providing the above estimates. Further information is very desirable on the following points to check the estimates given:-

(a) The pressures at which windows and doors in domestic premises blow out, i.e. the value of P_v;

(b) pressure-time curves for single and sets of rooms provided with "general" and "back" relief and containing furniture;

(c) the response of elements of structure to loads applied internally both under static and explosion conditions.

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Table 1

Fundamental burning velocities (maximum) of some gas-air mixtures under atmospheric conditions

Gas or (vapour)	Burning velocity ft/sec	m/sec
Methane (Natural gas)	1.2	0.37
Propane	1.5	0.46
Butane	1.3	0.40
Hexane*	1.3	0.40
Ethylene	2.3	0.70
Town gas ‡	4.0	1.2
Acetylene	5.8	1.8
Hydrogen	11.0	3.4

*Similar to petrol.

‡Approximate value for town gas depends on composition.

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