Zeitschrift: IABSE reports of the working commissions = Rapports des commissions de travail AIPC = IVBH Berichte der Arbeitskommissionen

Band: 4 (1969)

Artikel: Safety in large panel construction

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DOI: https://doi.org/10.5169/seals-5909

II

DISCUSSION PRÉPARÉE / VORBEREITETE DISKUSSION / PREPARED DISCUSSION

Safety in Large Panel Construction

La sécurité dans la construction par grands panneaux

Sicherheit in der Großtafelbauweise

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Modern Engineering and the Safety Concept.

It has long been recognised by the engineering profession that absolute safety against all possible conditions and hazards can never be achieved. The problem is one of reducing risk, rarely, if ever, its total elimination. Indeed, one fundamental responsibility of the engineer is to achieve acceptable safety at acceptable cost.

Safety is related to both the risk and structural consequence of particular events relevant to the satisfactory behaviour of the structure. In general, past experience has shown that this combination has been adequately dealt with since few serious failures have occurred. To a large extent this has been fortuitous since the older forms of construction had an inherent strength which could cope with conditions not allowed for in design.

Modern developments in design, analysis, building material and techniques have resulted in the refinement of our structures to suit more precisely the loading and environmental conditions assumed in design. The accuracy and adequacy of these design assumptions have therefore assumed much greater importance since a precisely designed structure may be sensitive to a greater or different loading condition and the reserve strength previously available may be absent. At the same time the size of buildings has increased considerably, particularly with regard to height.

The statistical risk of any particular event occurring has probably changed but little: the structural consequences, however, may have changed radically. It is clearly no longer sufficient to assume that a structure designed for normal conditions will react satisfactorily for the abnormal or accidental condition. If we are to design our structures with both precision and safety we must make a conscious assessment of all conditions and hazards that might arise, however remote a possibility they may represent.

This does not mean that we must design against all hazards. It simply means that we should consider the combination of risk and consequence of the hazard so that appropriate action, if any, can be determined to achieve an acceptable and uniform standard of safety.

Definition of a Required Standard of Safety.

In defining a required standard of safety, two main aspects need to be considered: cost and risk to life.

Cost

Given the statistical risk of a particular cause of failure and how this risk may be varied with added or reduced cost, the cost consequence of the failure, the prevailing rate of interest and the proposed building life, it is possible to arrive at a design which represents minimum overall cost. Providing the relevant data are available this could be applied to any important building or structure. It could also be beneficially applied to less important or parts of structures.

Risk to Life.

This aspect is more difficult since emotional and political issues are raised, particularly in relation to housing, since people understandably expect to be 100% safe in their own homes. However, some comparison can be made with those risks which already exist as part of our modern way of life.

For example the risk of a person being killed on the roads is approximately 0.7%: the risk for a person flying 10 hours each year over a period of 70 years is also appreximately 0.7%, while the risk for a person doing, say, 300 railway journeys for each of his 70 years life is about 0.2%.

It is not for engineers to decide what risk to life is acceptable as a basis for structural design. This is a matter for the politicians and other representatives of the community at large. The engineer, however, can and should advise on the cost and other implications associated with any desired standard of safety. Above all, the engineer should ensure that any given expenditure is used to greatest advantage.

Design Against Progressive Collapse.

Progressive collapse is defined as collapse originating and spreading from an area of local failure. Such collapse may be above, below or to the sides of the area of initial damage.

There are three ways of designing against progressive collapse: -

(a) eliminate the hazards which may lead to local failure, or reduce the risk to an acceptable value.

(b) design so that the hazard, if it occurs, does not cause any local failure.

(c) allow the local failure to take place, but design the structure so that progressive collapse does not occur.

Methods (b) and (c) above involve a quantitative assessment of the hazard, part of which is to be allowed for in design. Anything in excess of this must then represent an acceptable risk.

Possible sources of hazards in Buildings.

The first step is to consider, in terms of both the statistical risk of their occurrence and their structural consequence, the possible hazards which might lead to local failure. Many such hazards exist. In the first instance, all should be considered, however remote a possibility they may represent, as follows:-

(i) Explosions - internal and external.
(ii) Fire.
(iii) Faulty design, materials or workmanship.
(iv) Differential settlement or local foundation failure.
(v) Wind.
(vi) External impact.
(vii) Local overload.

There may be other hazards depending upon the location of the building and its intended use. For example, in some areas of the world even sabotage may need to be considered and, at the very least, the saboteur's job should not be made too easy.

In this paper, only internal explosions will be considered in depth to illustrate the intended design philosophy. Similar reasoning could be readily applied to other hazards.

Internal Explosions

The explosion risk itself falls into three parts:-

(i) the risk of any explosion occurring.
(ii) the intensity of pressure which may be reached and the period over which it will act.
(iii) the area upon which the explosion pressure will be effective.

Taking all domestic explosions into account, a total of 1889 occurred in the United Kingdom during the period 1957-1966, and very approximately, the risk of an explosion occurring from any source including domestic town gas is 12 per million dwellings in any one year. This risk is less in flats where some sources of explosion do not exist.

With regard to the intensity of pressure reached in these explosions, very little information indeed is available but some guidance can be obtained from the extent of damage which occurred. For example it is known that the damage resulting from 50% of these explosions was confined to windows or doors and of the remainder only 40% caused cracking or movement of the walls, floors or ceiling joists. Only in very few cases indeed did severe explosion damage extend into the neighbouring dwellings.

Bearing in mind that most of the dwellings involved must have been simple brick terraced housing with timber floors, the equivalent static pressure (for brick walls but not necessarily for other types of construction) would appear to be, conservatively, as follows:-

0 - 1 p. s. i.		-	50%
1 - $2\frac{1}{2}$ p. s. i.		-	30%
$2\frac{1}{2}$ - 5 p. s. i.		-	15%
5 - 25 p. s. i.	<	-	5%

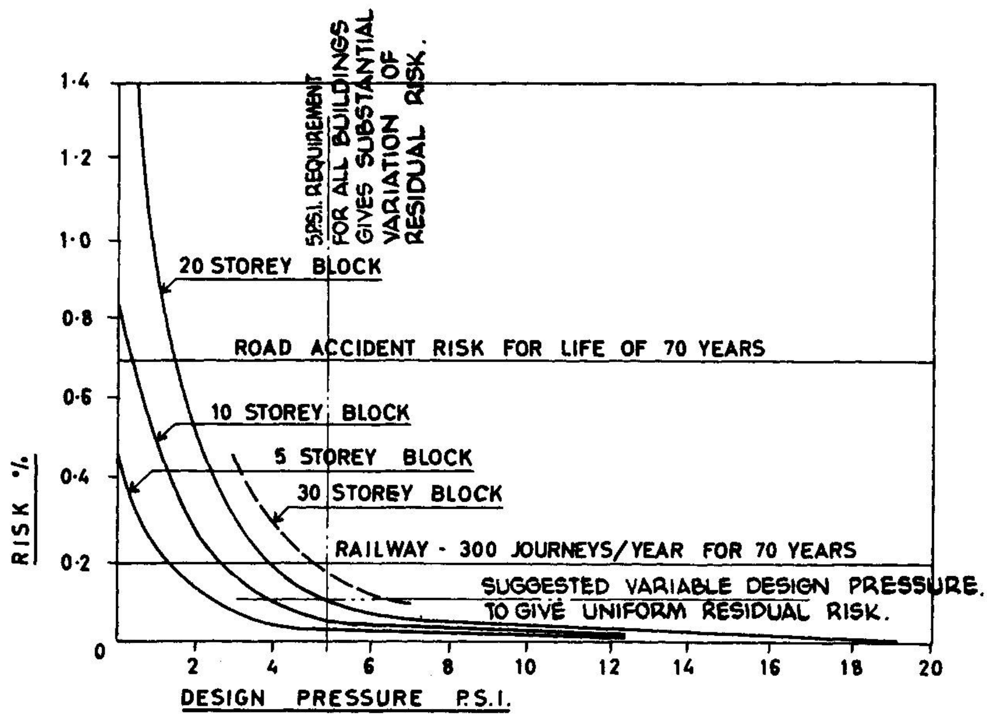
These figures are only the roughest of guides and are included here to illustrate principle only. An extreme pressure of 25 p. s. i. for town gas seems a reasonable extrapolation from information and test results related to propane explosions allowing for the venting likely to occur in domestic dwellings. A variation in explosion pressure is most likely since the probability is remote that ignition would occur precisely at the moment of worst concentration and volume of explosive mixture. Obviously these figures would need to be checked by research which should include the more careful recording and assessment, by a structural engineer, of the damage actually incurred during a number of domestic explosions.

The period of the explosion has an important bearing on the reaction of any structural component resisting the pressure, since the loading is of very short duration. The inertia of the structural member and the deflection it can sustain before failure will have an important influence on its resistance. For example a long span prestressed beam would be heavy and would also deflect a considerable distance before it failed. The time required to produce this movement may be much greater than the period of the explosion, particularly if venting can occur. In this case, a comparison between the explosion period and the period of vibration in the elastic range only would be, in the authors' opinion, erroneous and misleading. On the other hand, some structural elements can suffer only very small movement before failure and the effective pressure would then be near the peak. Load bearing brickwork would be in this category and therefore the pressure frequency referred to above probably represents an even more conservative assumption for most other types of structural elements of equivalent mass.

The area over which the explosion pressure acts is another variable about which little is known. Considering domestic dwellings supplied with town gas, the extreme case would be an explosion occurring in the whole dwelling. At the other end of the scale, the explosion would be confined to the room containing the gas appliance. In the absence of any suitable information, an arbitrary assumption regarding this has to be made taking into account that all explosions must involve at least one room and that very few, if any, involve a complete dwelling. A gradation from 1 in 1 to say 1 in 10 may be reasonable to allow for the proportion of the dwelling affected by the explosion.

Using the above reasoning and assumed pressure frequency figures, it would be possible to relate a chosen design pressure with the remaining risk of an explosion occurring giving a greater pressure. The design pressure is the basis for determining the extent of local failure for bridging purposes, or for designing to prevent local failure and if it is exceeded progressive collapse may occur.

If, in the event of progressive collapse one life is lost for each storey that collapses, it is possible to estimate the remaining risk to the inhabitants for any given design pressure. It will be seen from the accompanying diagram, that there is a very substantial reduction of risk as the design pressure is increased. If all the above assumptions are correct, and they will need to be proved by tests or other evidence, then for a 20 storey block designed to resist a pressure of 5 p. s. i. or designed to bridge over the damage resulting from a 5 p. s. i. pressure, the risk is reduced to something less, and probably much less, than 0.1%. If the risk is to be maintained at a constant figure, so that people are equally safe wherever they live, then the design pressure should be varied with the height of the building. For example, in a 5 storey building, the design pressure could be reduced to $2^1/2$ p. s. i. while in a 30 storey building the pressure should be increased to 7 p. s. i. to maintain the same level of risk.



VARIATION OF RESIDUAL RISK WITH ADOPTED DESIGN PRESSURE

BASED ON :-

1. BUILDINGS DESIGNED TO PREVENT OR TO BRIDGE OVER THE LOCAL DAMAGE RESULTING FROM THE DESIGN PRESSURE.

2. ASSUMED EXPLOSION PEAK PRESSURE FREQUENCY OF :-

0 - 1 P.S.I. = 50% : 1 - 2½ P.S.I. = 30% : 2½-5 P.S.I. = 15% : 5-25 P.S.I. = 5%

THIS DISTRIBUTION IS PROBABLY CONSERVATIVE BUT REQUIRES VERIFICATION.

THIS DIAGRAM IS TO ILLUSTRATE PRINCIPLE ONLY AND PARTICULARLY THAT, IF, THE RESIDUAL RISK IS TO BE KEPT AT A CONSTANT LEVEL THE DESIGN PRESSURE SHOULD VARY WITH THE NUMBER OF STOREYS.

Having, on the above basis, decided the design pressure, we must also decide the area over which it acts. The same diagram can be used for determining the pressure/area relationship to maintain a constant level of acceptable risk. For the purposes of illustration, let us assume that the probability of the explosion occurring in a combination of rooms in a four roomed flat, is as follows:-

1 room affected	100%	)	rooms would be defined as
2 roomsaffected	70%	)	bounded by substantial walls
3 rooms affected	30%	)	or floors, having a certain
4 rooms affected	10%	)	minimum mass.

If we consider a 20 storey block, a constant level of risk would be obtained if pressures are adopted as follows:-

1 room affected	5 p. s. i.
2 rooms affected	4 p. s. i.
3 rooms affected	2. 5 p. s. i.
4 rooms affected	1 p. s. i.

All the above relates to domestic dwellings containing town gas. The incidence of explosions in other types of building, the resulting pressures and their structural effects will all vary with the type of building, itsuse, and the size of rooms or spaces in which the explosion might occur. Other influencing factors will be the venting which might occur through the light and weak elements bounding the space and whether or not forced ventilation is provided. With adequate research and other investigations, it should be possible to allow for all these factors so that explosion ratings could be provided for use in design, as they are for fire. Such ratings should be based upon a statistical assessment of both the risk and consequence, with the objective of achieving a uniform and acceptable level of safety.

Reverting to the three ways of reducing the risk of progressive collapse to an acceptable value, as described earlier, (a) could be dealt with by consideration of venting, ventilation, or the removal of some of the sources of explosion, or a combination of the three, so that the hazard itself becomes an acceptable risk. Methods (b) and (c) could be dealt with by choosing an appropriate design pressure as already discussed.

Other Hazards.

In principle these could all be dealt with statistically using a design philosophy similar to that described above. Of greatest importance is the assessment of the sensitivity of any particular structure or part of the structure to the particular hazard being considered. This needs to be done not only for the accidental conditions but also for what would be considered as a normal loading condition.

In some cases, consideration of the hazard will involve a bridging ability, or alternative path, for the loss of a single structural element. In other cases, a combination of such elements may have to be allowed for.

Application of the Philosophy to Large Panel Structures.

Large panel structures are sensitive to the explosion hazard because the vertical load bearing elements present large areas on which the explosion pressure may act. On the other hand large panel structures can be designed and built to give massive overall strength so that overall stability is retained in spite of even severe local damage.

Before the application of the philosophy of design described, it is preferable to adopt a plan form which will realise the potential strength of this form of construction so that the structure is not sensitive to the loss of an individual structural member or a combination of such members.

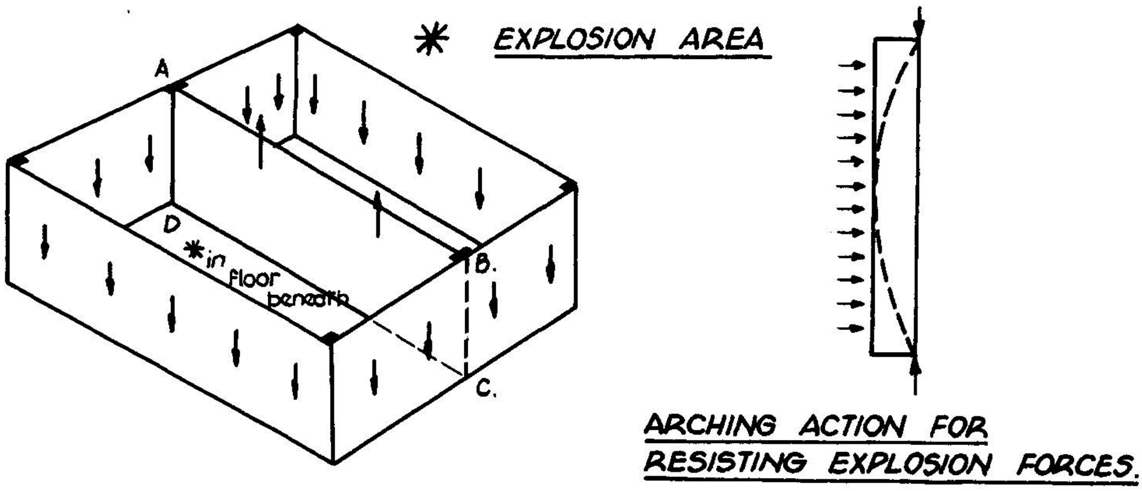
Having chosen a suitable plan, the described design philosophy can be applied to determine which elements or combination of elements are damaged by the particular hazard.

Three particular points are worth noting:-

1. Local Damage.

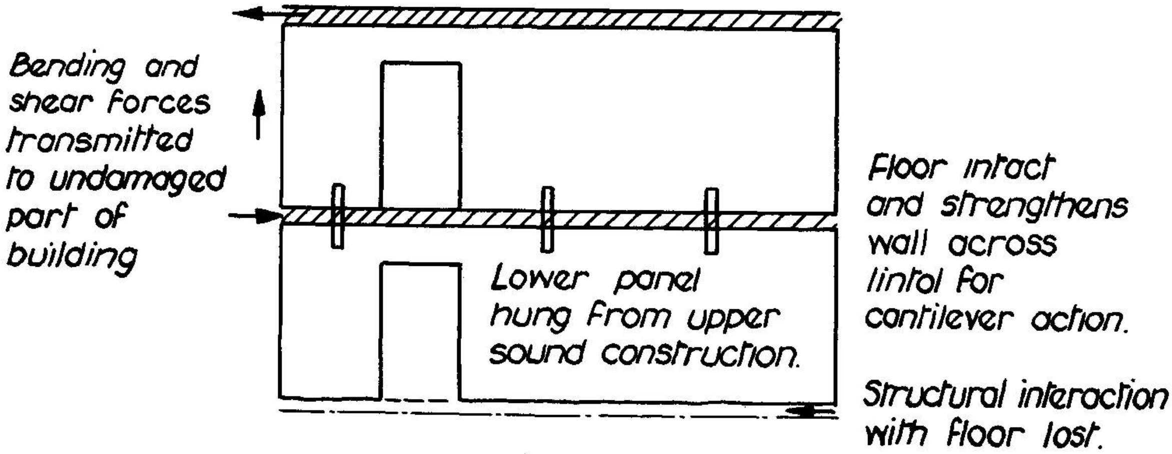
The resistance of the wall elements is increased by a vertical arching action, which can be considerable if the load of a large portion of the structure can be gathered over the wall subjected to the pressure.

IMPORTANCE OF SOME VERTICAL TENSILE CONTINUITY

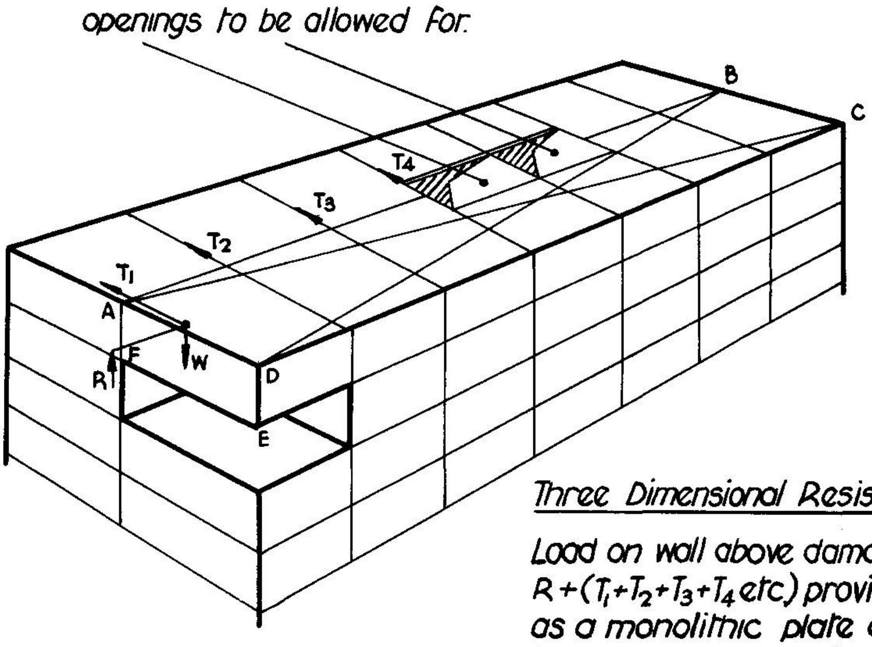


2. Bridging Action.

If the floors and walls are properly interconnected then beams of at least one storey in height can be obtained. Where openings exist, interaction between the wall and the floors at top and bottom is required. Cantilever or beam action can be developed by these composite structures. Since the floor at the level of the explosion may be damaged, it may be necessary to make provision for each wall to hang from the structure above.



It is also very helpful in assessing the building strength to take into account the three dimensional characteristics of the structure:-



Three Dimensional Resistance to Collapse.

Load on wall above damage can be resisted by $R+(T_1+T_2+T_3+T_4 \text{ etc})$ providing ABCD can act as a monolithic plate and is adequately jointed to wall ADEF. Openings in floor must be allowed for and all joints checked for required continuity.

3. Prevention of Progressive Collapse Downwards.

If local failure is permitted as in method (c) and progressive collapse downwards is to be prevented, the building must be able to withstand the impact loads from debris and other disturbances arising from the explosion area. Of primary importance is, first, the prevention of shear or bearing failure due to impact load, so that a maximum amount of the kinetic energy of the falling parts is absorbed in bending, and second, the structural interaction of components to limit the number of falling parts.

A building designed and constructed on the basis already described would almost certainly cater for any of the other hazards. Many buildings would require little or no special action. Others may require very special attention and extra cost to achieve the required level of safety. Nonetheless, in our opinion, an assessment of the hazards and their structural consequence should be made.

SUMMARY

The paper presents a design philosophy based on the assessment of the hazards and their consequential effects on the behaviour of structures. Internal explosions in buildings are taken as an example to illustrate the principles which can also be applied to other exceptional loads.

As a particular case, progressive collapse in large panel construction is treated in terms of the philosophy.

RESUME

Une philosophie de conception basée sur les probabilités de charges exceptionnelles et de leurs effets sur le comportement des structures est présentée. Le problème des explosions à l'intérieur des bâtiments est pris comme exemple pour illustrer les principes de base.

L'article traite en particulier, le cas de l'effondrement progressif dans les structures à grands panneaux préfabriqués.

ZUSAMMENFASSUNG

Dieser Beitrag zeigt ein Entwurfsverfahren unter Einschätzung des Zufalles und dessen Folgewirkung auf das Verhalten der Bauten. Um das Verfahren zu veranschaulichen, wurde als Beispiel eine innere Explosion angenommen; es können aber auch andere Ausnahmelasten berücksichtigt werden.

Als ein besonderer Fall wurde der fortschreitende Einsturz von Grosstafelbauten behandelt.