The Institution of Structural Engineers

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The Structural Engineer's response to explosion damage

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Foreword

This report arose from a suggestion that members of the Northern Ireland Branch of the Institution should record their experience of dealing with explosion damage to buildings for the wider benefit of members.

There are undoubtedly some unique aspects to that experience but it was important also to embrace a broad spectrum of knowledge of events of a similar nature, such as those witnessed on a massive scale in London. Accordingly, this report is the result of extensive consultation and written comment.

I write this note in an atmosphere of peace and freedom from terrorism, a state greatly to be desired and much appreciated by those who have experienced the obverse. It is to be hoped that few readers will find it necessary to act upon the guidance contained in the report in a terrorist context or as the result of some dreadful accident. Perhaps more readers will find it instructive in a contingency sense as a record of, and preparation for, what might be required of them in such circumstances.

My grateful thanks go out to all who have contributed to our deliberations over the past 24 months or so, to Professor Adrian Long and Mr Frank Robinson, Chairmen of the Northern Ireland Branch during the period, Mr Colin Maxwell, its Honorary Secretary, and to Mr Andy Lorans and Dr Susan Doran of the Institution who assisted us and saw the draft through to publication.

John A. Hill
Chairman of the Task Group
November 1995

1 Introduction

1.1 General

If one reluctantly faces the fact that acts of destruction by terrorists are a characteristic of modern society, then it is clear that some guidance should be available to Structural Engineers who may have to assess the damage and make recommendations for reinstatement. Most Structural Engineers have experience of assessing the condition of building structures in normal circumstances. Damage caused by explosion introduces new dimensions to assessment and repair which will be unfamiliar to many. This report is primarily intended for those who fall within this category. The general procedures set out in other Institution guides, in particular references 1 and 2, should also be noted. The appropriate Health & Safety legislation should be borne in mind at all stages.

This report deals primarily with the effects of the detonation of explosives external to buildings. The effects of accidental gas or chemical explosions are not considered, though there may be similarities. Some guidance is also provided for Structural Engineers who may be required to advise on the incorporation of measures beyond those required by the Building Regulations to enhance the robustness of a building structure.

The damage caused by explosive devices (bombs) placed by terrorists varies very widely in nature and extent. The particular circumstances surrounding different events can result in significantly different effects. Some explosive devices produce intense fires while others result primarily in blast damage. The guidance which follows is concerned with the effects of blast from an explosive device on ordinary buildings where the risk of explosion was not a factor considered in the original design.

1.2 Status of the report

The Institution of Structural Engineers has produced this report as a guide and, as such, it is only intended for use as a guide. It is not intended to provide the definitive approach in any situation, as in all circumstances the party best placed to decide on the appropriate course of action will be the Structural Engineer undertaking the particular project.

2 Inspection of damaged buildings

2.1 General

This chapter addresses what is often the Structural Engineer's first experience of bomb damage - inspection of the damage on site.

The inspection of bomb damaged buildings may involve the co-ordinated effort of Structural Engineers, Architects, Building Services Engineers and Quantity Surveyors. Others concerned with the financial aspects of the incident, such as Loss Adjusters, will also be involved.

When the damage is severe the Structural Engineer will be one of the first team members to enter the building to carry out an initial inspection and to ascertain if it is safe for others to follow. Personal safety must be the prime concern at this, as at any other time. All reasonable steps should be taken to avoid exposure to unnecessary or avoidable risk. Appendix A includes a checklist of personal safety and other equipment that the engineer should consider carrying when inspecting bomb damaged buildings.

The inspection of the building will normally fall into two distinct phases:

- an initial inspection to identify damage requiring demolition or other immediate attention and to formulate a policy for the next phase
- a second more detailed inspection to assess fully the damage in order to allow development of proposals for the reinstatement of the building.

In both phases the Structural Engineer will be expected to advise on damage to non-structural fabric, such as that to external cladding and internal partitions, in addition to the condition of the primary loadbearing elements of the building.

It is difficult to make generalisations about the possible effects of explosions on buildings and the damage to be expected as there are many variables involved such as:

- the nature of the bomb used
- the location of the bomb
- the general topography of the neighbourhood
- the form of construction of buildings
- the previous condition of buildings.

Quite unexpected effects are frequently found and often the explanations for them will remain uncertain. The Structural Engineer must be prepared to keep an open mind when inspecting a bomb damaged building in view of the apparently random nature of the damage, much of which may be hidden from casual inspection. Institution guides[1, 2] provide useful reading on many aspects of structural inspection which are beyond the scope of this report.

2.2 Safety

The inspection of bomb damaged property can be dangerous. In the interests of safety, a two person inspection team is to be preferred. Forethought and preparation are advised and sensible precautions must be taken despite the urgency of the situation. Emergency services personnel are trained and equipped to deal with hazardous and traumatic situations. Others have generally not been trained in this way and must accept direction from the emergency services, particularly in the early stages when access to the affected area or to a building may be prevented.

Plans of the building should be consulted if possible before carrying out an inspection. Not only will this help to identify the structurally relevant parts of the building, but it may also serve as a map of the building and facilitate safe access and egress.

A range of hazards may be present at the scene of the incident. If the explosion was recent, the first thing to be done is to report to the police at the scene as there may be other suspect devices in the area. Even with clearance from the police, it is important to be on the lookout for suspicious objects. If found, these should not be disturbed and the alarm should be raised.

The scene is likely to be littered with debris. The safest path to take to the building may be along the centre of the street to minimise the possibility of being struck by falling glass or masonry en route. Hard hats should always be worn.

On arriving at the building to be inspected, an external examination from a distance is advised to determine if is safe to go further. Even if there are no signs of imminent structural collapse , the engineer should look for damaged cladding, coping stones, glass, slates and any other external features which might have been dislodged and are at risk of falling. If such hazards are above the entrance to the building and there is no alternative route, the hazards should be removed to allow safe access.

Fig 1. Chamber of Shipping, St. Mary Axe, London, April 1992

Fig 2. Kansallis House, Bishopsgate, London, 1993

At this early stage, a close quarters examination of the external elevations may be necessary. Under no circumstance should the use of unorthodox or unsafe practices be contemplated. Appropriate and safe access equipment must be used. Until such equipment is available, it must remain sufficient to inspect from ground level, perhaps using binoculars, or from inside after a safe entrance to the building has been established.

Office staff and contractors may already be inside the building salvaging files and other valuables and clearing up. This can hinder a proper inspection of the building and greatly increase the risk of personal injury. In such circumstances it may be necessary to advise that staff and others leave the premises until an initial inspection can be carried out and the building declared or made safe.

Immediate danger to the public should be dealt with under the direction of the statutory authorities or other authorized bodies.

Once inside the building, hazards may present themselves and one must constantly evaluate if it is safe to proceed further. Common hazards include:

- broken and shattered glass
- unstable partitions
- damaged and collapsed ceilings
- debris under foot
- glass shards partly embedded in furniture and walls.

Less common is the presence of hazardous materials such as asbestos disturbed by the blast, or corrosive or toxic chemicals that may have been spilled.

Further hazards can arise from live main services which have not been disconnected. This disconnection is advised, at least temporarily, to reduce the risk of electric shock or gas explosion. The personal precautions to be taken include:

- not smoking or lighting matches
- avoiding standing water
- not grasping any metal parts that could be live.

Structural hazards vary greatly with the type of structure. Loadbearing masonry buildings are in general more unpredictable and hazardous than framed buildings. Signs of gross and local damage are important indicators of imminent collapse, for example:

- loss of critical members
- loss of bearing
- excessive deflection
- severely cracked, bowed or out-of-plumb loadbearing walls.

Following an explosion which has caused damage to a building there will usually be a considerable amount of general disruption in the area and many of the lighter portions of the building will have collapsed or been seriously displaced. Such chaos is often the basis for assuming that there must inevitably be appreciable damage to loadbearing structure. This assumption may not be well founded, except relatively close to the source of the explosion.

2.3 Initial inspection and preliminary report

The purpose of the initial inspection is to:

- ascertain the general extent of damage
- advise on any immediate measures needed to protect the safety of those in and around the building
- prepare a strategy for further and more detailed examination.

The Structural Engineer may be asked to make statements at this stage concerning the repairability of the building and the likely cost and timescale of reinstatement. Any such statements should be made with caution since early prognosis may prove misleading in the light of the more extensive investigation which will follow.

As stated previously, the Structural Engineer may have a wider interest than merely damage to loadbearing structure. In many cases of buildings affected by terrorist explosions there will be no damage to primary structure at all, but the stability of the external envelope and possibly the internal partitions may require detailed consideration.

Where damage occurs to the primary structure in a modern framed building, it is likely to be confined to a zone, vertically or on plan, relatively close to the seat of the explosion. Even when elements of a frame are damaged or destroyed, gross collapse and actual or potential instability is usually confined to this immediate vicinity. Such areas should be cordoned off from the rest of the building and adjoining public spaces. Demolition or propping may be needed to prevent further sudden collapse around the perimeter of the affected area. Vigilance is needed to identify novel or unusual structural arrangements and structures which later may need specialised investigation.

Unframed or partially framed buildings are likely to suffer more severe and extensive structural damage from a nearby explosion and should be approached more cautiously. The elements of such a building may not be positively or effectively tied together. The building may have been altered over the years by, for example, the removal of loadbearing walls at ground storey level and the insertion of beams. Such work can reduce the capacity of the building as a whole in tolerating damage to individual elements.

Ties in cavity walls are prone to failure by slippage on rebound leaving the outer leaf of the wall potentially unstable. This may not be readily detected after an explosion, but should be borne in mind in any subsequent investigation.

It would be wrong to assume that unframed buildings will inevitably collapse like ‘a house of cards’ in the event of an explosion, although an internal explosion is more likely to have this effect. Many older buildings have substantial walls, both internally and externally, and in general they have less fenestration than their modern counterparts. Because of these features, they may suffer less damage from a distant explosion than a building having curtain walling and lightweight partitions.

Many buildings in the unframed and partially framed categories are of historic interest. While it might not make economic sense to preserve them, there may be other compelling reasons so to do. When faced with such a building, the Structural Engineer will be expected to reduce demolition to an absolute minimum and be concerned to secure the damaged fabric for subsequent restoration.

When giving instructions for urgent temporary measures to be taken, the Structural Engineer should talk directly to the contractor who will carry out the work and not rely on others. The contractor should, whenever possible, be given clear and specific instructions and warned of the hazards which have been encountered during the inspection or are suspected.

As rubble and debris are cleared from the building, the Structural Engineer must be prepared to examine further damage uncovered by the contractor and to give new instructions or amend those given earlier. Work being carried out should be inspected to deterrmine that it is executed in a satisfactory manner.

An initial report is prepared when the initial inspection has been completed, and the instructions for immediate measures have been given. Except in extreme cases where demolition is clearly the only practical option, the report should be cautious in its conclusions and should refer to the possible existence of as yet unascertained damage and the need for a more detailed inspection.

2.4 Detailed inspection and full report

A comprehensive examination can only be undertaken effectively after the building has been cleared of debris and made safe. If possible, a full set of plans should be consulted to locate critical elements and member connections for detailed inspection, bearing in mind that the building may have been altered since the drawings were produced. In any event, a comprehensive examination cannot be achieved without a full understanding of the construction of the building.

The following indications should be studied:

- movement and overloading
- cracks in structural elements
- buckled members
- gaps between abutting construction
- any other signs of possible damage.

Due to rebound, apparent structural displacement may be much less than the peak displacement which occurred at the time of the explosion and may not give a true indication of the severity of the damage. Furthermore, large movements can be associated with slip in connections which still have a loadbearing capacity, whereas the failure of brittle connections may be accompanied by very little movement at all. This may apply not only to primary structural connections, but to fixings of cladding and to wall ties. A degree of opening up will be required to establish in detail what level of damage has actually occurred. The need for opening up will normally be indicated by some visible damage.

Window frames should be examined for permanent set or twist as this can overstress the glazing and lead to subsequent and unexpected failure. Watertightness and serviceability may also be impaired.

A theoretically computed assessment of the blast loading on the building may provide a general guide to the degree of damage that might be expected. However, it can be no more than a guide and, in some circumstances, may be misleading. It should not be allowed to override the actual evidence found in the building. Similarly, a dynamic analysis may suggest a level of damage which has not actually occurred. Firm recommendations cannot be based on such uncorroborated 'evidence'.

Computer simulations of the large explosions in the City of London in 1992 and 1993 recorded very high pressures on buildings and elements of buildings, yet only one building, a 14th century church, suffered complete collapse. Many buildings suffered damage to cladding and internal fixtures and finishes but only four buildings which were immediately adjacent to the explosions suffered severe local structural damage and one new structural steel framed building was taken down.

During the detailed inspection, the Structural Engineer may uncover defects in the building which have arisen from causes other than the explosion. Experience and judgement must be exercised in deciding if such defects existed prior to the explosion. A simple question may yield the correct answer: 'Is the defect consistent with damage other than bomb damage?'

Having decided what damage has been caused by the explosion, its significance is assessed next in relation to the strength and long-term durability of the structure. Where doubt exists, the significance of bomb damage can be evaluated by load testing.[3] It may be that a cosmetic repair will be sufficient, as an alternative to the replacement of damaged elements. At this stage, the Structural Engineer can often be subjected to pressure to condemn adequate members which only exhibit damage of no structural significance. There are many examples from general experience where total replacement is not undertaken in the event of damage.

The Structural Engineer's report is likely to form part of an overall report on the reinstatement of the building. It should identify and evaluate the various degrees of blast damage found in the building together with any other defects, and recommend suitable repairs, giving options where appropriate. The cost estimates, which will form part of the overall report, should include the cost of any temporary structural works required.

Fig 3. Exchequer Court, St. Mary Axe, London, April 1992

Fig 4. Hongkong & Shanghai Bank, Bishopsgate, London, April 1993

The Structural Engineer should bear in mind that claims for costs arising from bomb damage are frequently contentious and that reports may be subject to scrutiny and cross-examination in the Courts. Provided recommendations have been based on the evidence as found or 'could have reasonably been deduced', an equitable settlement of financial compensation should be secured.

3 Characteristics of an explosion

3.1 General

This Chapter presents an introduction to an essentially qualitative appreciation of the propagation of blast waves. The reader should consult the references for quantitative assessment.

An explosion occurs when a quantity of gaseous, liquid or solid material undergoes a rapid chemical reaction. When the explosion occurs, gaseous products of the reaction are formed at a very high temperature and pressure at the source. These high pressure gasses expand rapidly into the surrounding medium which, as a result, becomes pressurised and a shock wave is formed. Because the gases are moving, they cause the surrounding air to move as well. The damage caused by explosions is produced by the passage of the compressed air in the shock wave and the associated movement of the air molecules creating a dynamic pressure, sometimes referred to as 'blast wind'.

Blast waves propagate at supersonic speeds and will be reflected and diffracted as they meet objects in the vicinity of the explosion. As the blast wave continues to expand away from the source of the explosion its intensity diminishes and its effect on objects is also reduced. However, within tunnels or enclosed passages, the shock wave will travel with very little diminution or attenuation. Pressures experienced at a reflecting surface may be greatly magnified locally beyond the fundamental overpressures of the shock wave.

It should be noted that a complex environment exists in the region very close to the source of the explosion. Here the blast wave is in the process of being formed and the very hot, violently expanding gases will themselves exert intense loads which are difficult to quantify precisely. Once the blast wave has formed and is propagating away from the source it is sometimes convenient to separate out the different types of loading experienced by surrounding objects. Three effects have been identified:

- the effects of rapidly compressing the surrounding air (here termed 'Air shock wave')
- the air pressure and air movement effects due to the accumulation of gases from the explosive chemical reaction (here termed 'Dynamic pressure')
- the effects of rapidly compressing the ground (here termed 'Ground shock wave').

3.2 Air shock wave

The air shock wave produces an almost instantaneous increase in pressure over and above ambient atmospheric pressure at a point some distance from the source. This is commonly referred to as overpressure. The initial peak in overpressure falls rapidly and is followed by a phase when the pressure is below atmospheric, i.e. the negative phase. The negative phase is of longer duration and of lower intensity than the positive phase. (Fig 5).

The study of the durations of the various phases of the shock waves and the rate of propagation from the source for a range of sizes and types of explosive source is outside the scope of this report. However, except in the case of very large explosions such as those produced by a nuclear device, it is important in the context of structural damage to understand that the time scale for the positive and negative phases of most explosive shock waves is extremely short. As a result, although the pressures which are involved can be very large, the time of application to an element of a structure may be so short that the element has barely time to respond before the negative phase begins.[4]

It has been found that the effect is greatly influenced by the ratio of the positive phase duration and the natural period of vibration of the element of the structure under consideration. Where this ratio is less than about 0.2, the effect is considered to be 'impulsive'. Where it is much higher than, say 10, the effect is 'quasi-static' and the range between is said to be 'dynamic'. Biggs[5] discusses the behaviour of structures subjected to these types of loading. Fig. 6 illustrates the time related nature of the effects resulting from the positive phase.

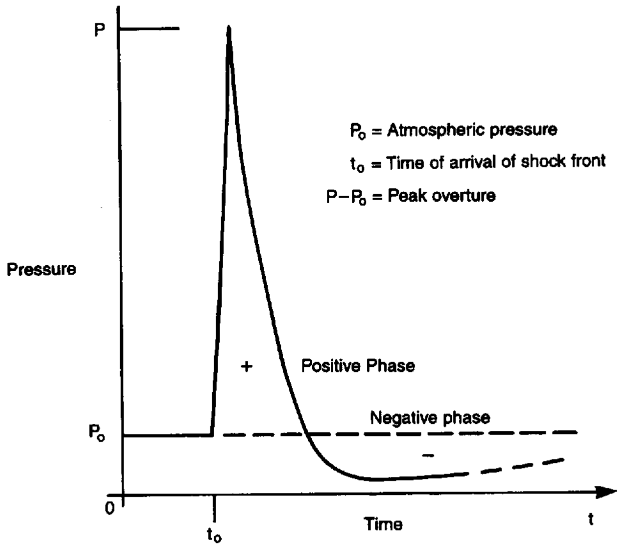

Fig 5. Blast wave pressures plotted against time

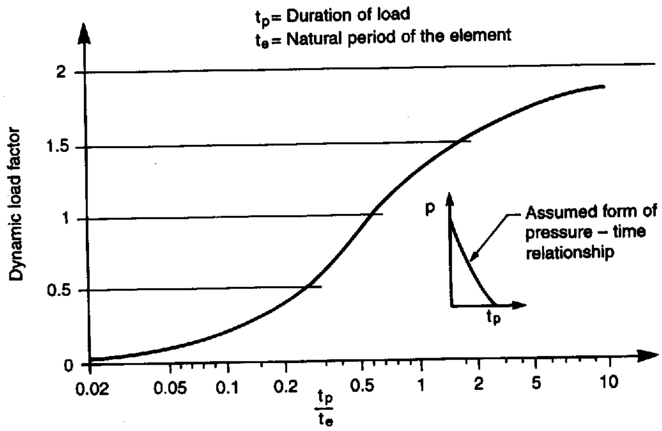

Fig 6. Elastic response to short term loading

The magnitude and the time scales of the various phases may be altered by the type of explosive and effects of reflection and diffraction, but the effects will almost always diminish with distance from the seat of the explosion. However, so many indeterminate conditions relate to any particular event that it is difficult to predict with any degree of accuracy what the effects of an explosion may be at a particular distance.

3.3 Dynamic pressure

As a rough approximation, 1kg of explosive produces about $1m^3$ of gas. As this gas expands, it acts on the air surrounding the source of the explosion causing it to move and/or increase in pressure. The movement of the displaced air may affect nearby objects and cause characteristic damage. Except where confinement or funneling may apply, the effects of the dynamic pressure diminish rapidly with distance from the source.

3.4 Ground shock wave

The ground shock leaving the site of an explosion consists of three principal components:

- a compression/rarefaction wave which travels radially from the source
- a shear wave which travels radially and comprises particle movements in a plane normal to the radial direction where the ground shock wave intersects with the surface
- a surface or Raleigh wave.

These waves propagate at different velocities and alternate at different frequencies. The actual movement of a particle of soil is the resultant of all three effects and the Peak Particle Velocity (PPV) is the maximum instantaneous velocity of a particle at a point during a given time interval.[6]

The ground waves diminish in magnitude with distance from the source and will have specific effects on structures, very largely depending on the magnitude and on the orientation of the elements of the structure relative to the line of the propagating waves.

When assessing the effects of the ground shock wave at a structure, it is usual to measure the ground movement in terms of three mutually perpendicular components, usually vertical, transverse and longitudinal or radial. The component PPV is accepted as the best guide to the likelihood of causing damage. Some national Codes have tabulated values below which damage is unlikely to occur for various types of structure and ranges of frequency.

Such guidelines are inherently conservative, being derived from measurements where damage has not occurred. It does not follow that damage must inevitably occur if measurements of vibration above the guideline values are recorded at a structure.

For many years the United States Bureau of Mines 'safe' limit of 50mm/s PPV was an accepted design standard. Recently lower values have been recommended in relation to elements of a structure with natural frequencies lower than 40Hz. Other national standards, such as the British Standard BS 7385 and the German DIN Standard 4150, suggest lower values in respect of different types of buildings. Some data suggests that the probability of damage tends towards zero at 12.5mm/s peak component particle velocity.

It may be helpful to indicate the order of magnitude of the movement which may result. The amplitude (A) of the particle movement may be estimated in relation to the dominant frequency (F) of the shock wave and to the harmonic motion: $V = 2 \pi F A$. Thus, for a vibration with a PPV of 25mm/s and a frequency of 40Hz, the amplitude of movement is 0.1mm, or the thickness of a piece of paper.

Such ground movements may be sensed by people but are often assumed to be much larger, partly because of the accompanying noise. It is not possible to evaluate these with any degree of accuracy by the 'feel' of the ground movement.

Damage to foundations much beyond the crater of the explosion is very unusual.

4 Structural response to an explosion

4.1 General

This Chapter discusses the response of structures to an explosion and the assessment of that response.

4.2 Structural resistance

When a shock wave impinges on a structure or on an element of a structure, the pressure will tend to cause the element to deflect, or to fail, or to be projected away from inadequate connections. The extent of the movement will depend on a number of factors:

- the mass of the element
- its fixity to surrounding parts of the structure, their response to the pressure and to the loads transferred from other parts
- the period of application of the pressure and the rate at which this may diminish
- the ability of the element to withstand deflection and to continue to provide a reaction to the pressure.

Some materials are capable of developing a significant reaction by elastic and plastic deformations. Thus, materials such as steel and reinforced concrete may be able to withstand the effects of such pressures up to some limit. Brittle building materials, such as plaster, light masonry or loosely fixed materials such as tiles, slates and lightweight ceilings, do not exhibit sufficient elastic or plastic behaviour of this kind. Timber members tend to split. Heavy elements, and those with long periods of natural vibration, will be less affected. Walley[7] discusses the availability of extensive 2nd World War data on damage to buildings.

As larger and more complex portions of a structure are considered in relation to a specific explosion, rather than isolated elements of the structure, it is usually the case that the period of natural vibration of the portion under consideration will be increased and the overall effect of the blast pressure on the structure will be diminished. The blast wave and reflected and diffracted waves travel at a finite speed and all parts of the structure will not necessarily be affected at the same time.

Where the supporting structure of a particular element is able to yield slightly under load without actually failing, some energy from the blast wave is absorbed. For this reason glazing which is mounted in resilient gaskets, or a building with a non-rigid structural form, should be affected less than would similar glazing in brittle fixings or a brittle type of structure.

Loadbearing masonry often presents a considerable surface area to a blast wave, much more than a framework of structural steel or reinforced concrete. Since loadbearing masonry is often associated with other elements of flooring or roofing which largely rely on gravity for interconnection, the destructive effects of a blast on masonry buildings is often extensive, yet the extent of damage may suggest the absence of overall residual stability which is seldom the case. Damage may involve extensive localised collapse, but the disparate nature of the structural form involved often leaves much of the masonry building relatively intact.

In general, reinforced concrete and steel framed buildings with well detailed connections are frequently able to withstand the pressures and vibrations generated by explosions without sustaining any extensive permanent damage. In the case of substantial masonry buildings, because the mass of the structure enhances its resistance to displacement under the short period effects of the blast wave, the masonry may not be affected to any extent which would effectively reduce its capacity to perform quite satisfactorily, even though minor damage may be done to brittle materials, e.g. plaster finishes.

4.3 Building defects generally

As mentioned previously, there is a tendency for it to be assumed, without further thought, that building defects which are noted for the first time following an explosion have been caused by the explosion.[8]

In the normal life of a building, some elements may exhibit defects. Causes may be natural processes such as:

- shrinkage
- thermal forces
- weathering
- ageing of the materials
- rust and localised decay
- the effects of abuse and localised impact
- damage due to overloading
- inadequate design or quality of construction.

Usually when such defects occur there will be little reduction in the serviceability of the structure.

Thus, observed defects may predate the event and may not have been caused by the explosion. They may have been disregarded previously, or not considered to be sufficiently significant as to require any remedial action. Perhaps the necessary remedial action had not been implemented. Where it can reasonably be ascertained that the explosion did in fact produce a defect, there should be no different approach to dealing with it than would be the case under normal circumstances.

It is not logical, therefore, in the case where minor structural damage has been caused by an explosion, to consider that other more drastic or extensive measures must be implemented to restore the structure to a useable and safe condition. In addition, most structures are considerably redundant with composite actions adding to the overall strength beyond those assumed by the designer.

Some of the wider professional issues surrounding the nature and extent of reinstatement are discussed in Chapter 7.

Techniques which may be relevant in the reinstatement of older building structures are discussed in reference 9.

4.4 Structural steelwork

Steelwork, acting on its own or compositely with reinforced concrete floor slabs, may have built-in reserve capacity because the size or shape of section provided had been selected not strictly to meet stress requirements, but to satisfy deflection limits, ease of fabrication or the economics of repetition. The continuity between members is often ignored in design but can be effective at large deflections. In these circumstances, minor damage such as localised distortion, particularly close to a connection where buckling may be unlikely to occur, or slight misalignment of the tension flange of a beam, may not require repair.

In considering the remedial measures which need to be taken, it is reasonable to assess whether any residual deflection of steelwork has reduced the loadbearing capacity of the structure below the safe level which the structure requires. If this is the

Fig 7(a). After explosion, 1992

Fig 7(b). After renovation, 1995

Fig 7. Lurgan town centre after explosion and renovation

case, a localised repair or strengthening would be better than replacement. The addition of suitable welded or bolted steelwork may be more satisfactory than the replacement of a damaged member, since this, in itself, may require extensive additional disruptive work.

4.5 Reinforced concrete

The theory of reinforced concrete assumes that the concrete will crack and deflect, and many concrete structures exhibit numerous shrinkage cracks, construction joint cracks and the like which do not in most cases detract from the useability of the structure. It makes little sense, following an explosion, to consider that such defects must, of necessity, require attention or are sufficient reason to contemplate total demolition of the structure. It may be arguable whether the defects have, in fact been caused by the explosion.

Even if they have, it is pertinent to consider whether they are of structural significance under the strength requirements, degree of exposure and other serviceability circumstances of the structure.

Where there are good grounds for considering that the slightly damaged concrete of the structure will still be adequate to perform its structural function with a reasonable factor of safety, it may be quite sufficient to deal with the defect by way of localised repair or cosmetic treatment. The prime purpose of those charged with dealing with the event ought to be to restore the structure to a useful, safe, functional condition as quickly and as economically as possible even if this means retaining slight non-significant blemishes.

4.6 Brickwork and masonry

Brickwork and masonry often exhibit minor defects due to localised differential settlement, expansion and contraction or other cause, and is still retained as satisfactory for its overall purpose, with or without minor cosmetic treatment. Loadbearing masonry is usually considerably redundant and capable of distributing stresses through areas which, under other circumstances, could be omitted entirely from the structure. Often the precise location of a section of masonry or brickwork is relatively unimportant. There is little logic in replacing a substantial section of wall which may have been slightly displaced by the effects of an explosion if it is still capable of performing its prime function in the new location.

Slight evidence of damage to finishes around the edges of the masonry, where two different elements of a structure have responded differently to the blast, is sometimes taken as sufficient grounds for demolishing a wall and rebuilding it. Such drastic measures are generally unnecessary except in the case of obvious and massive displacement of the walling. Masonry is remarkably tolerant of vibrations and often absorbs considerable repetitive vibration in industrial conditions for many years without exhibiting any significant damage. Too often it is assumed that some fundamental damage may have been caused to the bonding or to the integrity of the masonry in general by an explosion, when there is no evidence to support such a view.

4.7 Foundations and other substructure

Foundations are sometimes considered to be suspect as a result of ground vibration caused by an explosion. From an above surface explosion, ground vibration will usually have been much less than may have been 'sensed' by observers, and, in any case, the effect on foundations will usually have been minimal.

If the foundations can reasonably be considered to be capable of performing their prime function - distributing the loads of the structure to the ground at acceptable stresses - any disturbances due to having suffered some vibration in the process may be irrelevant and may not lead to a need to undertake expensive remedial measures. Most ground is not sensitive to the effects of the short-term vibrations produced by an explosion, and, while localised effects within the crater zone may require treatment, beyond this close range zone, it would be unusual to find any appreciable damage to the substructure or soil.

Underground services may need to be tested if damage is suspected. For example, fractured water mains or drain pipes could lead to loss of support in some cases.

4.8 Loss of value

It should be borne in mind that while structural adequacy is essential, perfection of reinstatement may not always be achievable or in the best interests of the parties to the damage. Where it is assessed at the completion of reinstatement that there has been a loss of value, this can be dealt with by means of alternative compensation which will usually be of much lower cost than that of extensive replacement and the consequent delay and extended disruption. In the converse, where a building has been improved on completion of reinstatement, a deduction for betterment may be sought by the compensating agency or insurance company. The advice given by the Structural Engineer should clearly indicate any engineering options which may be available to facilitate a decision by the client and agreement of the financial arrangements.

4.9 Secondary damage

As discussed previously, where an element of a building has a natural period comparable with or less than the duration of the positive phase of an explosion, the equivalent static loading resulting from the pressure wave will have been relatively high. This is the case with many non-loadbearing, thin-sheet elements of a building.

Glazing falls within this category. In addition to having little ductility, it is usually damage to windows which occurs at the greatest distance from an explosion. Where the glass itself is relatively robust, the framing may also suffer appreciable damage, while if this is also robust, the force absorbed by the glazing may be transferred to the surrounding structure. This will usually be localised damage unless the structure is close enough to the source to have absorbed considerable damage itself.

The blast effects close to the source can project the shards of glass with considerable force, but at greater distances the glass usually falls straight down from the window.

Other common building materials with large areas and comparatively small mass also respond to blast. Loosely fixed roofing, such as tiles or slating may be shaken loose or, where fixings are adequate, roofing timbers may be broken or split. Internally ceilings and partitions, doors and similar features may suffer appreciable damage and, since these elements are of importance with regard to the appearance of a building, total replacement will usually be necessary.

One aspect of plaster board finishes which is often noted following an explosion is the appearance of 'pop' defects where fixing nails have been drawn slightly into the plaster board as a result a slight forward movement of the board. It is clear that the different elements of plaster and substrate may respond differently and that the fixing bond may be disturbed, particularly where old and sensitive plasterwork may be involved. Old lath and plaster ceilings, where age may have destroyed much of the original integrity of the plaster key, will be particularly subject to such damage. Care should be taken to identify the extent of necessary repair in this type of damage.

Fixings for units of cladding which are relatively heavy, such as precast concrete panels, may be fractured, strained or disturbed if the response of the panels is significantly different from that of the base to which the panels are anchored. To some extent the degree of glass damage in the same area and signs of any disturbance of the filling in the joints between the panels may be a guide to the likelihood of damage to the fixings. As a test, it may be necessary to remove some panels to ascertain the condition of the fixings more accurately. Lighter facings, such as tiles or mosaics which are fixed with adhesive, are unlikely to have separated from the substrate because of the explosion unless the adhesion was already faulty, in which case it is probable that the damage will be obvious.

Sheet panels on roofs and facades, if damaged, are usually quite obviously distorted or have clear failure at fixing points. It is usually necessary to replace such units if damaged, even where the panels are not severely distorted. In response to the pressures, particularly in areas close to the source and where damage would be expected to be worst, they may have been a breakdown of the joint seals which could need to be re-sealed to restore weather-tightness to the structure.

5 Enhanced design of new buildings

5.1 General

Whether or not a new building is to be designed to take account of a general or specific terrorist threat is a matter for the building owner to decide. Once it has been concluded that protective measures should be built into the design, the Structural Engineer should establish what level of protection the building is expected to achieve against the potential threat and agree it with the building owner.

It is generally not possible to design a building to be 'bomb proof', which will survive an explosion completely undamaged, and with a guarantee of no injuries to its occupants. The best that can be achieved is to design so that damage is limited to an acceptable level and injuries to personnel are minimised. Such an approach, if a substantial threat is defined, will result in a very costly design which will probably be unacceptable from a normal architectural standpoint. Such circumstances require specialist expertise which is beyond the scope of this publication.[10]

However, it is possible to build in to a normal building measures which will enhance its performance in the event of a nearby explosion. Such an approach is the subject of this chapter. The measures to be discussed can be expected to reduce the extent of damage but may not eliminate it. It should be assumed that any explosion close to a building will cause damage to that building. Enhanced construction in a building remote from the explosion will reduce the radius from the explosion within which significant or any damage may be expected to occur. Guidance on safe areas within office buildings liable to bomb threats is provided in reference 11.

5.2 Planning

Much can be done at the planning stage of a new building to reduce potential threats and the associated risks of injury and damage. Although the measures which could be considered are not strictly speaking the Structural Engineer's responsibility, the engineer is often the person best qualified to highlight or comment on their advantages, even though it may be up to others to decide if they are to be implemented.

In relation to an external threat, the priority should be to create as much stand-off distance between an external bomb and the building as is practicable. On congested city centre sites there may be little or no scope for repositioning the building, but what small stand-off there is should be secured where possible. This can be achieved by the strategic location of obstructions such as bollards, trees and street furniture. An underpass or drive-through beneath a building, or carparking within or below the building, should be avoided unless access to and from it can be effectively controlled.

The shape of a building has a significant influence on the magnitude of the blast load it is likely to experience. Complex shapes that cause multiple reflections of the blast wave or features that contain the blast should be discouraged. Projecting roofs and floors, and buildings that are U-shaped on plan are undesirable for this reason.

Entrance to the building should be controlled. Precautions should be taken to prevent an explosive device being taken into a building where such an attack is considered likely to be a risk. The internal arrangement of the building, both physical and functional, should be analysed to see if there is scope for improvement. For example, if the reception area and other public spaces are free from columns and other obstructions, they can be more easily monitored and this acts as a deterrent to anyone planting a bomb inside the building. The entrance and reception areas should be separated from other parts of the building by robust construction for greater physical protection.

Extensive damage often occurs within modern buildings as the result of an explosion because of the absence of substantial partitions and internal walls. Some such sub-division is highly desirable and should be introduced on each floor if possible.

5.3 Structure

Practical experience over many years has shown that both cast-insitu reinforced concrete structures and steel framed structures with cast-insitu floors possess the required degree of robustness in buildings that are required to have a measure of blast resistance. Among the reasons why this should be so are that:

- interaction effects which are normally ignored in the analysis and membrane or arching actions which are generally discounted in design
- such structures possess considerable ductility and are capable of absorbing large amounts of energy through plastic deformation before they fail
- even when individual members do fail or are removed, significant collapse does not occur because of the development of alternative load paths or modes of structural behaviour
- the structures are relatively heavy and therefore less sensitive to impulsive loads
- most parts of the structure are interconnected
- many taller buildings are designed for the robustness requirements of the Building Regulations.

Any measures which build on these characteristics should enhance the ability of the building to resist blast loads. On the other hand, the pursuit of optimal economy in design and the increased use of lightweight materials and forms of construction will tend to have the opposite effect.

Framed buildings designed only to resist gravity and wind loads in the normal way have frequently been found to be deficient in two respects when subjected to blast loading, i.e.:

- the failure of beam-to-column connections, and
- the inability of the structure to tolerate load reversal.

Enhancements are required to address these weaknesses and to produce a more tolerant design.[12]

Beam-to-column connections, particularly those on the perimeter of a building, can be subjected to very high forces as the result of an explosion. These forces will have a horizontal component arising from loading on the walls of the building and a vertical component from differential loading on the upper and lower surfaces of floors. Providing additional robustness to these connections can be a significant enhancement.

With the dynamic nature of the substantial forces generated in the connection, it is hardly surprising that the normal details for static loading have been found to be inadequate. Improved details with enhanced blast resistance are shown in Figs. 8, 9 and 10 for reinforced concrete and structural steelwork. The main features to note in the reinforced concrete connection are the use of extra links and the location of the starter bars in the reinforced concrete connection. It is important not to rely on anchorage for

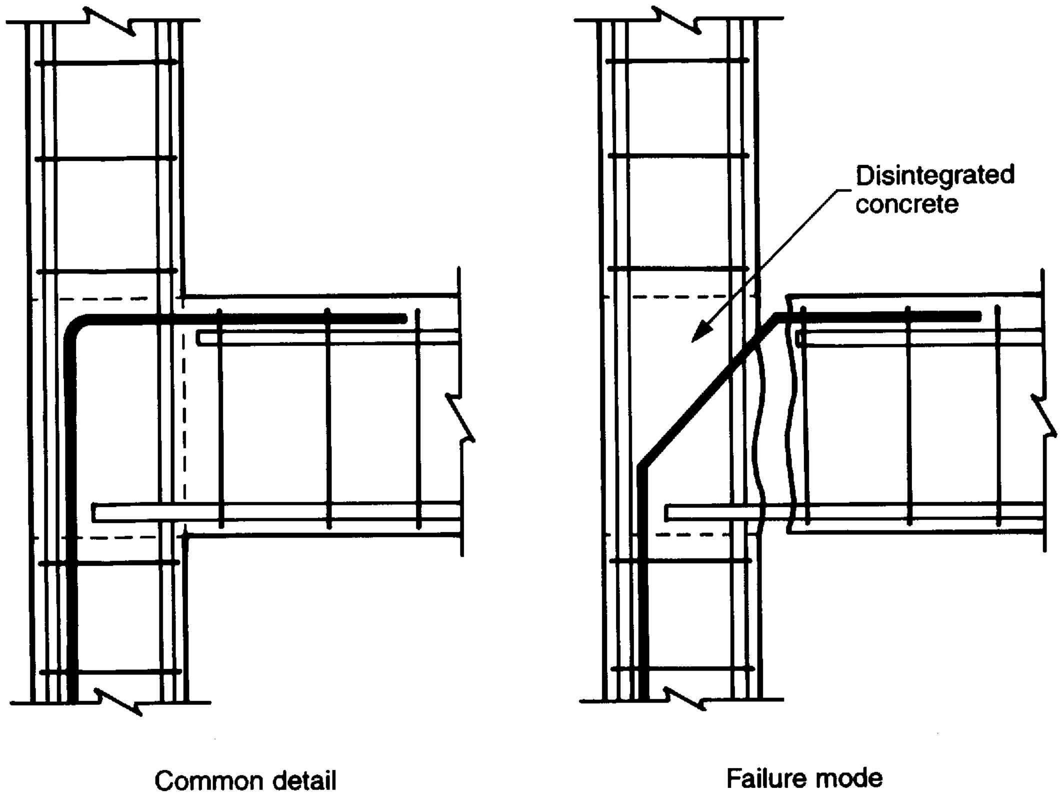

Fig 8. Common reinforced concrete beam/column connection

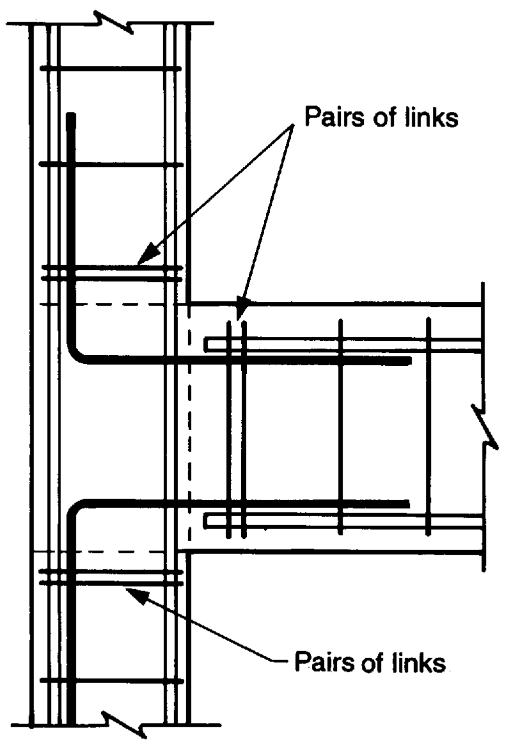

Fig 9. Enhanced reinforced concrete beam/column connection

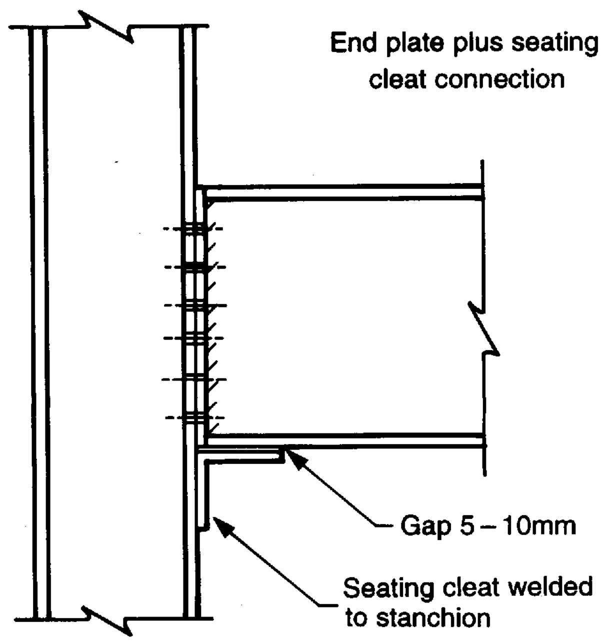

Fig 10. Bolted stanchion to beam connection with welded seating

reinforcement in the zone common to both beam and column. The additional cleat in the simple steelwork connection should be sized to carry the main beam under full load. These enhancements are intended to reduce the risk of collapse should the connection be damaged, possibly as a result of load reversal on the beam. Load reversal can come about in one of two ways:

- by blast loads being applied in the opposite direction to gravity or wind loads, or
- by elastic rebound.

All types of structural element can be affected and the provision of the following enhancements should be considered:

- continuous top steel in reinforced concrete slabs
- effective connections between beams and slabs
- lateral restraint to the bottom flange of steel beams
- additional ties or bolts between beams and perimeter columns
- moment resisting connections betweeen beams and columns.

The casing of perimeter steel beams and stanchions should be considered. The concrete casing facilitates the more solid building in of infill masonry, thus increasing its arching potential, and provides fire resistance which is unlikely to be disturbed in an explosion. With adequate reinforcement, the casing greatly increases the strength and stability of the perimeter steelwork and enhances continuity at connections, all of which can be mobilized in the event of an explosion.

Current Codes of Practice recognise the critical importance of key elements as being those elements whose removal would in effect lead to disproportionate collapse of the structure and the Codes require these to be designed accordingly. However, the Code requirements are not an adequate safeguard against a nearby explosion and, where possible, it is better to avoid reliance on such key elements, the removal of which could lead to extensive collapse.

Cast-insitu reinforced concrete floor slabs are the preferred option for blast resistant buildings, but it may be necessary to consider the use of precast floors in some circumstances. There is no doubt that precast concrete floors are not as effective in resisting blast, but provided that measures such as the following are taken they could be considered for the upper floors above first floor level:

- the units should be securely tied to their supporting beams
- a dense concrete screed with mesh reinforcement should be specified
- longitudinal ties should be built in.

Precast floor units are not recommended for use at first floor where the risk from an internal explosion is greatest, e.g. above the reception area.

In composite construction, the fixing of floor slabs to beams by shear connectors helps resist uplift. However, in the case of composite slabs on profiled sheeting, consideration should be given to thickening the concrete element. This increases the mass of the floor and facilitates the introduction of top steel to resist uplift - both measures enhancing resistance to explosion damage.

Lightweight roofs and, more particularly, glass roofs should be avoided. A reinforced or precast concrete slab is to be preferred, with a pitched roof above it if required for architectural reasons.

Some additional notes on simple enhanced methods of construction are set out in Appendix B.

5.4 Windows and cladding

Glass from broken and shattered windows could be responsible for a large number of injuries caused by an explosion in a town or city centre. The fact that windows with plain annealed glass fail at relatively low blast loads also means that extensive internal damage can be caused in buildings even when there is no other external or structural damage present. A reasonable priority when designing a building to have more than its inherent blast resistance is to enhance the design of the windows.

Fig 11. Europa Hotel, Belfast - laminated glass remaining intact

The choice of a more suitable glazing material is critical and it has been found that laminated glass is the most effective in this context. It is helpful to understand why this is so, since an appreciation of how the glass behaves when subjected to a blast load is needed in order that the window frame can be designed so as to exploit the full potential of the glazing material.

A pane of laminated glass will crack under a smaller load, static or dynamic, than a similar pane with the same thickness of plain glass, but when plain glass cracks it has in effect failed totally. Laminated glass, on the other hand, will resist an applied load long after it has cracked and its actual failure load is many times greater than the load which caused it to crack initially. This is due to the development of membrane action in the polyvinyl butyral (pvb) interlayer of the laminated glass. Total failure generally occurs at large deformations only when the glass disengages from the surrounding window frame. A strong and deeply rebated window frame is therefore needed to guard against premature failure of the glass.

A further advantage of laminated glass is that when it does fail as the result of an explosion it is normally still in one piece and may not travel any great distance before falling to the floor. It presents less of a hazard than plain glass whose shards can be projected at high speed into a room to cause serious or fatal injuries to the occupants.

The minimum recommended thickness of laminated glass for this purpose is 7.5mm. This has a 1.5mm thick pvb interlayer sandwiched between two sheets of 3mm glass. Laminated glass with a thinner interlayer should be avoided since it is the pvb that is primarily responsible for the blast resistant properties of the composite pane. If the windows are double glazed, it is the inner pane that should be laminated. The outer pane may be ordinary float glass, but toughened glass is to be preferred for improved performance and greater safety.

It is recommended that the rebates in the frames of enhanced windows should be 30mm deep and the glazing beads should be designed to resist both the inward and outward movement of the glass. Opening lights should have robust hinges and multi-point locking so that they are securely held in the closed position. The fixings of the frames and the strength of support to them should be capable of resisting the loading from the enhanced glazing system if it is to perform as intended.

An alternative to using laminated glass in special frames is to provide conventional windows, apply anti-shatter film to the inside of the glazing and install net curtains to 'catch' the glazing when it fails.

However, this strategy has a number of drawbacks:

- it is less effective than installing laminated glass in special frames
- the curtains are inconvenient and unattractive
- the film can be easily damaged
- the film has a limited life expectancy.

In view of these considerations, the strategy is not recommended for new work, although it could be considered for the enhancement of existing buildings. Further information on the design and performance of glazing systems can be found in reference 13.

After the windows, it is the cladding of a building that is most likely to suffer damage from an external explosion. Lightweight cladding systems in particular offer little protection and are easily damaged by blast. Masonry walls, on the other hand, can be quite effective, especially if arching can develop between floors and columns.

Precast concrete panels are a satisfactory form of cladding from a protection and damage standpoint provided they are reinforced and have adequate fixings to resist rebound forces. Panel fixings which can yield or 'give' in some way are worth considering. Flexible cleats are preferable to cleats with stiffeners and resilient 'washers' can be used to achieve a similar effect. Whatever fixing system is used, it should be accessible for inspection after an explosion so that any failure or movement can be detected.

6 Professional issues

6.1 The commercial context

A professional engineer is required to give advice to clients based on technical skill, experience and expertise and the knowledge and understanding of the client's needs. In exercising these skills, the engineer must be sympathetic to these needs because what affects the client's business or life will influence what the client asks of the engineer and what the client tells the engineer.

In the context of an explosion, the client can be anyone who wishes to employ an engineer to give advice on the response of a building, e.g.:

- the building occupier
- the building owner
- the insurer's loss adjuster
- a funding institution.

The general public and the civic authorities also have expectations of engineers though they are less likely to be employing them.

6.2 Contingency advice

Prior to an explosion affecting a building, the engineer's most probable client will be the building occupier, or tenant, who will be concerned for the continued well being of the staff and business in the event of an explosion. The client's needs may cover a wide range of subjects, e.g. :

- contingency plans in the event of a warning (which may include designation of safer areas within the building or evacuation plans for staff)
- communication links
- relocation plans
- alternative record stores
- alternative computer hardware and software facilities and records.

In this context the potential behaviour of a structure in an explosion will have different implications for tenant and building owner.

A building tenant will have an interest in the likely response of a building to an explosion at the time the lease is established. Explosion damage is an insured risk under many commercial leases and therefore repair and rectification is the responsibility of the building owner. The tenant is likely to have a repair and maintenance responsibility, so the ease and quality with which the building can be repaired so that future maintenance costs are not increased is important. The lease may have a clause giving only a limited time of rent cessation which will give trouble if the building cannot be repaired within that time, including any necessary investigations, negotiations, design and construction.

On the other hand, a building owner, or prospective building owner, who is contemplating the future letting and valuation of a building may wish to have the building or its design assessed for structural response to an explosion so a statement may be made that the building has been assessed for response to an explosion and found satisfactory, although there is no generally agreed definition of what 'satisfactory' means in these circumstances.

6.3 After an explosion

Following an explosion affecting a building and the immediate task of rendering the area and building not dangerous, different people have different involvements. The parties with the major involvement will be the building owner and the insurer's loss adjuster.

The building owner will need to repair and reinstate their building. Investment in the building by the owner or by any funding institution will need to be protected. The concerns of tenants will need to be satisfied. The owner will probably have to negotiate a repair and replacement funding procedure with the insurer's loss adjuster.

The procurement of many large modern commercial buildings has been arranged with a complex set of overlapping guarantees and warranties conceived to protect the building owner's investment. One of the effects of an explosion is to enable the providers of such insurance to claim, in the event of any defect subsequently found or occurring, that such defect was the result of the explosion and/or subsequent remedial works and thus avoid liability. The guarantees, therefore, are largely rendered worthless. The building's insurance will, however, provide recompense only for the reinstatement of the building as it was immediately prior to the explosion, (though that state is not usually known and can be debated) and not any betterment. It is unlikely that the buildings insurance will pay for the work necessary to reinstitute guarantees. If the building has been rendered structurally unrepairable this problem of guarantees does not arise as the building can be demolished and rebuilt.

The loss adjuster needs to establish a fair and equitable agreement between the insurer and the building owner for the repair and reinstatement of the damaged building. It will be necessary to understand the limit of destruction, the extent of damage and the cost of the repair work, together with an appreciation of the extent of uncertainty that will inevitably be present at each stage of investigation and assessment.

There may be tensions and conflicts between the different bodies employing engineers, which can lead to various pressures on the engineers. There is also an expectation that engineers can provide fixed, definite and correct opinions which will be relied upon, whereas, in reality, the effects of a explosion on a building can be assessed theoretically only within margins. A true and proper assessment must be related to site observation and testing with appropriate weight given to each contribution to the assessment.

7 Postscript

Explosions could be a continuing feature of life in cities and towns. Engineers may therefore continue to be asked to assess explosion-affected structures and buildings. There is a large body of knowledge on explosions and their effects but there are difficulties even for experienced engineers in matching this knowledge to an urban scene with buildings from many different eras and with different characteristics, and in conveying the engineering implications to a diversity of interested parties.

It is possible to build in measures to a new building which will enhance its response in the event of a nearby explosion. This can be achieved at very modest addition to the overall cost of a project.

Reports on the structural response of buildings subject to a explosion:

- should be carefully and expertly compiled and be capable of being supported by another similarly expert and experienced engineer working from the same facts.
- should be cognisant of the needs of the client. The technical conclusions of the reports should not be influenced by these needs but should be clearly based on all available theoretical and physical evidence.
- need to consider components such as fixtures and finishes as well as the more traditionally recognised structural elements.
- need to make clear at all stages any limitations of knowledge on which they are based and any limitation of confidence with which they should be viewed.

8 References

1. *Appraisal of existing structures*, The Institution of Structural Engineers, July 1980 (under revision)

2. *Guide to surveys and inspections of buildings and similar structures*, The Institution of Structural Engineers, November 1991

3. BRE Digest 402, February 1995: *Static load testing: concrete floor and roof structures within buildings*

4. Kinney, G. F. & Graham, K. J.: *Explosive shocks in air*. 2nd Edition. Berlin: Springer-Verlag, 1985

5. Biggs, J. M.: *Introduction to structural dynamics*. London: McGraw-Hill, 1964

6. BS 7385, Part 2, 1993: *Guide to damage levels from ground borne vibration.*

7. Walley, F.: *The effect of explosions on structures*, Proceedings of the Institution of Civil Engineers, Structures and Buildings, August 1994

8. McCaughey, J. D.: *Damage from explosions - real or imaginary?*, The Structural Engineer, **62A**, May 1984, pp 151-158

9. *Structural renovation of traditional buildings*, Report 111, CIRIA, 1994.

10. Mays, G. C. and Smith, P. D., Editors: *Blast effects on buildings - design of buildings to optimise resistance to blast loading*, The Institution of Civil Engineers, Thomas Telford, 1995

11. Home Office *Guide on safe areas in office buildings liable to bomb threats* (unpublished - available from the IStructE library)

12. Rhodes, P. S.: *The structural assessment of buildings subjected to bomb damage*, The Structural Engineer, **52**, No. 9, September 1974, pp 329-339

13. Anon: *Frame and fixing design parameters for laminated glass*, 1993. (unpublished, available from the IStructE library or ICE library)

Appendix A Personal safety and equipment checklist

Some or all of the following items of protective clothing and equipment should be considered for use during an inspection of structural damage caused by an explosion:

- hard hat
- reinforced boots
- overalls
- protective glasses or goggles
- heavy gloves
- torch
- tape recorder
- cameras
- binoculars
- personal identification.

Appendix B Additional notes on protective design

The following measures might be considered as part of a design philosophy where these is some perceived risk.

B1 Structural steelwork frame

In simple conventional construction, steel beams should be connected to stanchions using end plates to support total loads. Seating cleats, capable of supporting total loads, should be provided as an additional measure but connected to stanchions only (Fig. 10).

All stanchions up to the underside of the first floor level and first floor beams should be encased in reinforced concrete. Above first floor level, reinforced concrete casing should be applied to all stanchions and beams which impinge on the internal or external leaves of external walls.

Cast-insitu concrete should be used in ground and first floor slabs.

Top reinforcement should be provided over the complete area of first floor slabs and ground floors which have been designed as suspended. First floor slabs should be tied down to structural supports. Precast concrete floors above first floor level should:

- be securely tied to their supporting beams
- have a dense concrete screed with mesh reinforcement
- have longitudinal ties built in.

B2 Reinforced concrete frames

Beams should be connected to columns using top and bottom L-bars with full tension anchorages (Fig. 9).

All splices in vertical reinforcement to columns should be designed to achieve tension anchorage.

Top reinforcement should be provided over the complete area of first floor slabs and ground floors which have been designed as suspended.

Supporting beams at ground or first floor level should have top reinforcement over their complete length.

First floor slabs should be tied down to structural supports.

B3 Stairs

If precast concrete stairs are used they should be adequately tied to their supports.

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