THE ROLE OF THE ENGINEER BEFORE AND AFTER TERRORIST BOMBINGS - THE UK EXPERIENCE

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SYNOPSIS

The purpose of the paper is to present a collection of thoughts which have evolved in a Structural Engineer's mind over a period of time through visiting and observing the results of many terrorist bombings. The considerations, all aimed at alleviating human suffering, fall into three categories.

1) Predicting the outcome from a possible threat scenario.

2) Recommending procedures for personnel before an expected event.

3) Recommending details in building design to reduce hazards.

This paper is based on experiences of the United Kingdom's too many bombing incidents, and outlines in general terms its glazing studies.

THE INVOLVEMENT OF THE ENGINEER

The agencies involved in the aftermath of a terrorist bombing are manifold. In the first instance it is the emergency rescue services, the police investigators, and site security controllers. As time continues, progressively more parties become operative, such as

the public utilities
the local authority
the health and safety inspectors
the building occupiers, both companies and individuals
the demolition and repair contractors
the insurers
the lawyers
the legislators and politicians

The role of the professional engineer can relate to any of the above. His role of advising on the structural state of the buildings involved is immediate. However in the longer term a more fundamental role of formulating policy for making provisions for possible future events emerges. In the United Kingdom, Government has maintained a small group of engineers whose specialism is to understand and study building response effects and make recommendations on protection measures. In the early days of the present terrorist campaign, government and military buildings were usually targeted. More recently, the population at large and centres of commerce have also been targeted, resulting in the need for Government's acquired experience to be disseminated to those who need to know.

In the early days, in which relatively small hand-placed charges were used, it was apparent that

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the main hazard was that of projected glass fragments. The immediately obvious all-purpose protective measure was the application of glued-on polyester film and draped net curtains to the inside faces of glass, and this was generally recommended, without considerations of the size of threat.

Another strategy used by the bomber when using small charges was the exploitation of particularly sensitive parts of a structure whose removal by a small charge would cause disproportionate damage.

The more recent huge escalation of bomb sizes, driven in by van and lorry has grossly magnified the scale of the devastation, and raised further issues such as what sheltering procedures to adopt, and the survivability of facades or of whole structures.

In a free society the limitless choice for the terrorist of target, bomb position and moment of detonation create a theoretically limitless scenario for which protection measures are necessary. Therefore for those contemplating provision of protection measures it is necessary to form a judgement of general guiding principles as to how effort is best made in alleviating effects. It is the structural engineer, who has learnt by the experience of witnessing the aftermaths, and who has an understanding of blast and dynamic response on structures, who is probably best equipped to deal with the problem. The following collection of considerations have evolved from the experiences of one such engineer.

THE ENGINEER'S ROLES

In summary, the useful functions which the Structural Engineer can fulfil are:

1. To predict the order of magnitude of the devastation and hazards which would be produced by a certain threat in a certain location.

2. To recommend structural features for a building at design stage to alleviate hazards.

3. To recommend glazing specifications to survive given threats, and reduce hazards under other threats.

4. To recommend sheltering locations or escape procedures in the event of a bomb warning being given.

5. To recommend ranges at which cordons should be placed before the event.

6. After an event, to interpret the condition of surviving structures, and the excursions they might have undergone during the blast.

Expanding on the above

1. Awareness of the likely outcome in a possible scenario is a pre-requisite to taking measures of any type. However, since the geometry of every site is different and the specification of the threat is unknown, only very general predictions are possible, and these are best made on the bases of studies of previous incidents. The gathering of information on the performance of glass at more distant ranges is an essential part of this process. This involves relating, pane size, thickness and fragment throws with threat.

At closer ranges, broad classifications of internal damage levels are possible, ranging from occasional dislodgement of false ceiling tiles to complete destruction. All such records are always in terms of the bomb size, stand-offs and the building construction. The codifying and storage of these records, whether on computer, or in written reports, always has the problem of classifying different degrees of destruction in a way which is meaningful to a future user. Verbal or written descriptions are themselves extremely subjective, and comprehensive photography always provides the most conclusive information. A data-storage type programme must be able to effectively store this information.

The other programme type, which aims to predict by mathematical analysis the building responses of a blast in all its details needs to be extremely complex in order to deal with all the components in a building which produce the hazards, and it is questionable whether the result adequately describes the real-life situation.

2. In the normal run of civilian building (excepting embassies, which fall into a special category) the opportunities for designers to become involved in blast considerations in the standard requirements are usually few, because of the design brief. Unless Government makes such requirements legally mandatory through the building regulations, the motivation to act will remain influenced by financial, architectural and insurance considerations. This said, the adoption of the following principals may alleviate hazards ("may", since there will always be a threat level high enough to render any particular measure ineffective).

a. Skeletal-framed buildings with good continuity at connections and robust sections are least likely to suffer over-all collapse. Steel and reinforced-concrete frames perform equally well.

b. Stand-off is all-important. The loss of a vital column in a high-rise block would be catastrophic. The possibility and consequences of the removal of any column should be considered and guarded against. A contact charge against a column is a serious threat. Ability to survive collapse on removal of any one member can be designed in, as is required by the UK Building Regulations to guard against internal gas explosion effects.

c. The survival of the outer facade, including glazing will prevent devastation inside the building from an external blast. The interiors of modern buildings are full of light-weight, low strength components (partitions, false ceilings, ducts and trunking, services, furnishings) which easily become hazardous missiles once the outer facade is breached.

Total survival of a facade under one threat can change to the highly hazardous condition under another. Someone has to decide the "design" threat level for "design" purposes. However, acceptance of this onerous responsibility should not be grounds for accusation and incrimination of that person, should their threat predictions turn out to be inadequate.

d. The US experience of toxic explosion gases entering buildings from interior blasts and the destruction of the air-conditioning system in a sealed building raises numerous particular questions which the UK has not faced. The World Trade Centre experience has obviously highlighted this serious problem.

e. The basic minimum measure of adding anti shatter film and net curtains, if carried out in all buildings in an urban area, will reduce the glass fragment hazards at a certain radius where such a measure is effective. For a large bomb, this will be a sizeable area because of the large radius, but inside this radius, the measure will have little effect. The statistical overall reduction in hazards will be no consolation to those within this radius.

3. The ability to be able to predict the outcome of a particular blast on glazing ("glazing" includes glass and frames) provides an essential and invaluable function, particular in sensitive or vital rooms or buildings. This capability comes about through the mathematical correlation of data from trials, incidents and numerical analysis.

Armed with the resistance characteristics of different window systems, the glazing selection process can be placed on a rational basis. Trials on glazing form an essential part of this process. The setting up of glazing trials needs to be done with an awareness of the following problems.

i. Windows supported in free-standing frames, open at the back, will show a misleadingly high survival capacity due to the alleviating effect of the rear-face pulse. For this reason, tests are best performed using closed cubicles.

ii. Even when using a closed cubicle, there is likely to be clearing of pulse on the target face, which must be evaluated if the test result is to be meaningful.

iii. The explosive characteristics need to be known.

iv. Ideally, the reflected pulse history felt by the glass needs to be measured by gauges on the glass. This has not been attempted in the UK tests but it is becoming clear that this is necessary to overcome the problems arising from i), ii) and iii) above. Some experimental measurements have been made of pressure-time records on the face of a solid wall of the same dimensions as the cubicle, but these do not record inter-action effects on a flexible pane.

v. With a flexible member such as a glass pane, the negative phase may become significant in reducing inward motion or increasing rebound. It is a common observation that large quantities of glass fail outwards into the street.

THE FORMULATION OF POLICY - GENERAL THOUGHTS

It is the writer's experience that rules formulated for guidance can usually be demonstrated not to be applicable or relevant in certain scenarios, and may even be risk-enhancing in some. An example of this is the vexed question of sheltering procedures, which will be discussed later.

An intractable problem concerns the impracticability of protecting from lorry sized bombs at close range. Referring to the large UK incidents, the close-to buildings were always wrecked local to the seat of the explosion, to an extent that any occupants would not have survived. Fortunately these incidents have been timed to coincide with times of very low occupancy, or coded warnings have been given which have allowed evacuation. In the large London incidents, collapse of main members was of limited extent, but with the types of buildings involved, typically framed office buildings of 6 - 15 storeys with occasional tower blocks up to 36 storeys, the interior damage level of all interiors was so high that many serious injuries and deaths would have occurred had the buildings been normally occupied. The paths of the pulse propagation through the buildings were partly through interior routes from ground floor level, and partly through the exterior facade at each level causing complete devastation inside. Even though the nearest buildings usually remained standing, they were eventually removed and rebuilt because the overall damage was too severe for remedial work to be economical. The internal devastation levels at ranges of, say, less than 30m are so severe that major loss of life amongst occupants is inevitable, whether or not the structural frame collapses. The collapse of the structural frame will of course make recovery of victims even more difficult for the rescuers.

When the building is a high-rise tower and the internal destruction at higher levels is not catastrophic, it is clearly desirable that the whole tower should not collapse by a column destruction at ground level. This nightmare scenario has not arisen in the UK but was perhaps approached in New York. Parking controls appear to be the obvious measures to prevent this scenario. Even then, the suicide driver will be very difficult to foil, as evidenced at the US Beirut Embassy. The potential destruction from any lorry bomb means that stand offs of even 100m will cause serious damage.

Should the interior of the building have a hardened area affording good blast protection it is clearly necessary that the structure below should not collapse or that the structure above does not collapse into it.

UK testing experience on laminated glass has shown that at ranges of perhaps 50m or more, buildings subject to vehicle bombs could be given facades (including windows) which would keep the blast pulse or the major part of it, out without rupture. Such windows would be of thick laminated glass securely retained in purpose-designed substantial frames, and the facade framing would be designed to survive the deflections incurred, albeit with substantial residual deformations.

THE NEED TO DECIDE A THREAT

It is necessary for those responsible for any building, to clearly decide the degree of protection they wish to provide, whether at the design stage or retrospectively. Were mandatory anti-blast measures to be introduced into Building Regulations in response to terrorist actions, the implications would become a serious political consideration within the direction of the politicians. The Regulation writers would face an impossible task in identifying the threat level to be legislated against for any building, and the legal complexities introduced in the aftermath of an incident would magnify. Setting hardening standards legally would also give targets for the terrorist as well as the owners.

TESTING

Testing in the United Kingdom has focused mainly on hazards from glazing and has been carried out over many years. The objective has been to build up a data base of performances of a variety of window types under a variety of blast parameters albeit fairly limited because of the restrictions on UK ranges. Even though some 250 very useful results are now recorded, this is grossly inadequate to provide sufficient quantitive data on its own, given the number of variables in the problem whose effects need to be understood, eg.

Window size
Pane thickness
Glass type (annealed, toughened, laminated, polycarbonate)
Material in laminated inter-layers (pvb (grade ?), polyurethane, acrylic polycarbonate)
Single glazed, double glazed
Statistical variation of equivalent glass rupture stress
Pulse parameters
Fatigue effects of glass (ie rate of loading)
Condition of glass
Presence or absence of anti shatter film
Thickness of film
Presence or absence of bomb blast curtains
Severity of fragment throw
The failure prediction model used
Frame details

However, use of a simple theoretical model for failure and hazard prediction, based on an equivalent single-degree-of-freedom system with a resistance function to simulate the properties of the pane in question appears to give a consistent basis for comparing theory with practice. The procedure has been well presented in many places by Meyers (ref 1) for annealed and tempered glasses up to break point. A critical parameter in this procedure is the 'equivalent' tensile rupture stress of glass. As Beeson (ref 2) has pointed out, the fundamental failure mechanism of glass failure is by brittle fracture and is subject to the random distribution of flaws, as well as the rate of maximum stress increase (which is a function of the response, not the rate of loading). Failure does not necessarily initiate at the point of maximum stress. The "equivalent stress" concept (at the point of the pane where the maximum stress temporarily exists) becomes a convenience, but the equivalent stress values will assume a statistical spread to reflect the true behaviour. We have extended this procedure, admittedly with some uncertainties, into the realm of residual fragment velocities at break point (for plain glasses) and for calculating blast capacity up to rupture point of laminated glass, and the indications are that the procedure gives reasonable agreement with observed behaviours, probably good enough to give a broad idea of the degree of hazard. The advantage of having such an analytical tool is in being able to predict the outcome of the infinite number of threat scenarios and window parameters which have not been experimentally tested.

The treatment of laminated glass by this method requires knowledge of the pane resistance function in both the pre-crack and post-crack phases. Up to crack point, thin plate theory for a homogeneous plate of the same overall thickness provides this. We have adopted the view that under blast loading rates, inter-layer shears are insignificant in their resultant effect, particularly as most of the energy is absorbed in the post-crack phase. After cracking, the membrane resistance of the plastic interlayers becomes operative and has a large contribution to make in terms of energy absorbtion. The resistance function of the membrane under rapid loading has been back-calculated from trials observations on the assumption that it is of rising-triangle shape, and that the peak lateral deflection in a pane of 1250mm x 1550mm is of the order of 200mm under a certain blast on a certain thickness of laminated glass. From high speed films of trials it is established that such a deflection is, in round figures, the order of magnitude which p.v.b can undergo before tearing, or rebate pull-out commence (provided the rebates are deep and pane edges are bedded in silicone or polysulphide sealant). Slow-loading tests on p.v.b membranes using water bladder loading produce a resistance function of rising parabola shape, concave upwards, due to a large component of creep. If these slow loading p.v.b resistance functions are used directly in the SDOF analysis, the final membrane deflection calculated is much higher than observed to actually occur, and we conclude that this is because the absence of creep, at blast loading rates, means that p.v.b then presents itself as a much stiffer material.

The analytical model breaks down for filmed plain glass and resort then has to be made to visual observations related to the model predictions for unfilmed glass. The improvement in hazard level is thereby recorded empirically, and many trials have been devoted to this.

The object of this work is not that of scientific knowledge for its own sake, but for indicating, for those who wish to know, what window specification should be adopted for a given threat, and to limit hazards to given levels. In a climate of terrorism, reduction of human suffering is the prime consideration, not the complete survival of windows with no damage, and no insurance claims.

CASE OBSERVATIONS

Many practical illustrations of the effectiveness of precautionary glazing measures have been observed during the UK incidents for example:

1. Windows with film and curtains have stayed in place, or the fragments been contained in the curtains. In one incident, a baby slept in a cot beneath a window which cracked but remained held together by film.

2. Laminated panes have crazed but stayed in their frames, the occupants being unharmed. In one case, a child in a play-pen was unharmed behind a pane of laminated glass which crazed and bulged.

3. Laminated panes have pulled out of their frames and wrapped around occupants without causing injury or have travelled a only small distance into the room.

4. A filmed annealed pane has pulled out, stayed bonded together and wrapped itself around an occupant, with minimal ill effects. Loose shards would have caused him major lacerations.

5. Toughened panes have survived whereas annealed panes of the same size and thickness have blown in.

In these cases, one can of course always conclude that had the parameters of the scenario been different, the outcomes in these examples would have become unsafe. It is misleading to claim absolute protection from any measure.

THE QUESTION OF COMPUTER MODELLING

In the overall scene of devastation it is felt hardly justifiable to attempt to predict with great accuracy by dynamic response equations the exact response of all the building elements to a terrorist bomb, because

1. The bomb size and position is not known in advance, and is also difficult to ascertain after the event.

2. The detailed response of most individual building components is not important. A general awareness of the overall expectation of damage level is sufficient for a building owner or occupier to decide whether to make extra provisions.

3. It is the writer's view that in the scenarios where the structural survival of the frame is not in question the prime objective should be to keep all, or most of the blast pulse out of the building, thus preserving life and injuries, and allowing business hardware to remain functional or at least be retrievable. If the integrity of the facade and glazing is preserved, the internal environment would remain clean and safe.

4. Lastly, the amount of detail and effort needed to accurately model all the building components to reflect the true dynamic response behaviour is extremely expensive, labour and time consuming. The records of previous incidents in fact already do the job. Programmes based on iso-damage levels are in effect also simply referring to previous observations, and are as reliable as the data they are based on.

It has been the observation in the large UK incidents that for major framed buildings at ranges of 30m or more, the structural frames remain undamaged, yet the interiors are devastated as a result of complete failure of the cladding. This is understandable, as cladding is normally designed for wind and weather only. As stated earlier, the evidence is that laminated panes can be chosen to survive such blasts, provided the window frames also survive. The cost of such framing and cladding systems is clearly an increase to the total building cost, but it should be weighed against the loss of life, loss of the complete contents of the building and the consequential losses in the aftermath. Reactive forces from a surviving facade onto the structural frame obviously increase and should be considered at the design stage, but the expectation is that these will not be critical to the frame, due to the interaction behaviour between relatively flexible glazing and cladding, and a relatively stiff framework of high mass.

SHELTERING PROCEDURES

The role of advising building tenants on best sheltering procedures in the event of a warning being given presents the engineer with some daunting decisions, realising that lives are at stake. Because, on a global scale, the risk of an occupant being involved in a terrorist bombing is remote, there is a great temptation for building managers and occupants to not address the problem beforehand. However it is the case that if an alarm is raised, prior thought and mental rehearsal will drastically reduce the panic and hysteria which is likely to arise, and improve the chances of survival by following a pre-planned course of action.

The advising engineer needs to be able to predict the consequences in a building of various threats, which means a range of charge sizes and locations. Each threat scenario needs to be addressed separately. The building structure needs to be understood, and the location, if any, of particularly protective shelter areas identified. These should not be vulnerable to collapse, not be at risk from flying glass and other lightweight fittings, as shielded as possible and at as great a range as possible. The crucial decision which has to be made is whether there is greater risk in harbouring personnel in the best area offered (for a particular threat) which is seldom perfect in its characteristics, or of evacuation and retreat in the open. The latter course may involve large numbers of people being caught on vulnerable staircases, or outside at close range, subject to free air pressures and falling glass and debris. The thinking in the UK is that for such situations, if good internal shelter areas can be identified, occupants are better off staying in them. The pre-judgement of the adequacy of such areas, in relation to each given threat, remains an onerous task, which should be entrusted to an engineer with experience in the subject.

CORDONS

It is obviously necessary for the police to exclude people in the locality from the vulnerable area, in the event of a warning. The criterion of 'safe range' is difficult to define, since it is clearly desirable to be as far away as possible. For policing purposes, the recommended range is probably that of extreme window breakage, which for a vehicle bomb would be of the order of 500m or more. Nevertheless instances of people being thrown bodily inside a building at 700m range have been noted, in the same incident in which an office worker at 50m range survived and walked out of a devastated building.

CONCLUSIONS

This paper gives very little firm data because the nature of the problem is not firm. It has attempted to draw attention to the more practical aspects of the thinking behind anti-terrorist structural provisions, and to suggest useful areas of activity.

Reference 1: Structures to Resist the Effects of Accidental Explosions. Departments of the Army, Navy and Air Force 1990 Sections 6-27 to 31.

2: Glass Failure Prediction Model. W Lynn Beeson & J R Morgan. J Struct. E. AMSCE Vol 110 No 2 February 1984.