Blast Hazard Mitigation Through the Use of Performance-Specified Laminated Glazing Systems

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Abstract

Blast resistance is becoming a more common requirement for glazing in buildings. The technical aspects were addressed in the first author's GPD 2001 paper (reference 1), in which the benefits of laminated glass were emphasised. However, the incorporation of blast-resisting requirements into a building project have been found from experience to often give rise to convoluted contractual arguments about the meaning of the specification, about where responsibilities lie and whether the specification is being met. This paper attempts to clarify these issues and makes a recommendation on how to establish a clear working structure to deal with the problem.

Introduction

The requirement that new and existing buildings should have glazing with a designated blast resistance is increasingly common but can introduce protracted arguments between the parties involved. The reasons for this usually arise from a lack of understanding of the technical issues relating to blast. This paper draws attention to these issues, in an attempt to establish better understanding from the outset of a project.

Background

The problem stems from the fact that blast loading on a given building is a relatively rare event of uncertain magnitude, and outside the experience of most structural and façade engineers. However its consequences can be devastating to life and property, and many building owners and occupiers now perceive it to be prudent to make provision for a certain level of resistance. In the UK it is law that employers have a duty of care towards their employees, although how far that duty extends in respect of glazing provision has yet to be established by case precedents.

Laminated glass is found to give the best protection, and prediction methods for the degree of protection available from different layer make-ups and pane sizes have been established by various organisations. The chosen reference data base must be understood and correctly applied.

All window systems, whether blast resistance has been specified or not, will possess a degree of blast resistance, but the needs of a client extend to being aware in quantitative terms of what that resistance is.

Data on the performance under blast of a wide range of glass pane types, when rigidly supported on all four sides in single frames have been obtained by testing and analysis over a number of years, mainly by government agencies in the UK and USA. In the U.K. this data is classified Restricted in its circulation for security reasons, although it is made available to bona-fide organisations for legitimate use. Mandatory clauses in codes of practice and building regulations for blast-resistant glazing are unlikely to appear as it is difficult to make general rules which are relevant for different buildings in different locations with different users with different levels of perceived threats. Scenarios other than terrorist bombings may exist for some buildings where accidents at neighbouring industrial or military facilities may occur. These can be more specifically foreseen and provided for.

The existing glazing data correlate the values of blast parameters in tests with resulting observed hazards, and it is usually in the interpretation and handling of this blast data in the context of a particular project specification that contractual misunderstandings and conflicts arise

Client Needs

The decision on whether to make provisions for blast must come from the owner or user of the building. Usually he will have limited understanding of how much protection he wants or needs, of what is possible, of costs and physical implications, or how to specify his needs in contractual terms. The advice and guidance of a knowledgeable advisor are essential, but after considering the advice, the decision on the protection level to adopt must be the client's. It would be possible, given sufficient funding and freedom from other constraints, to provide glazing to protect against virtually any blast threat, up to the level where the building itself collapses, but it soon becomes apparent that blast protection requirements for glazing must be balanced against costs. However, the extra cost for blast protection (which arises from enhancements to both the glass and the frame or façade system) should be seen as an investment in preserving life and in preserving a working environment and the ability to carry on a business with a minimum of disruption after an event. Conditions as in photograph 1 will disrupt a business for many months whereas recovery from conditions as in photograph 2 can be almost immediate,.

The saving of life must be the primary objective in a civilised society, but the complete loss of a company's records may spell commercial disaster. Computer and IT installations are likely to be foremost among the most vulnerable assets.

Photograph 1- severe disruption

Photograph 2 – superficial disruption

Specification

Procurement of facades using contractor design to specific performance criteria is now commonplace and perceived to give benefits in cost and definition of responsibilities for performance. Methods of analysis for wind loading, handling and environmental effects are generally well established, but a specification and procedure for blast design is not widely established. The contractual implications of this are referred to later.

One of the following six methods is likely to be the basis on which a required level of blast resistance for a new glazing system is specified. Whichever method is adopted, it should be made clear in the specification what level of hazard is acceptable behind the various windows. (The actual definitions and measurement of Hazard Levels are outside the scope of this paper – see reference 1, para. "Comparison with Tests").

For example it may be accepted that on a large façade the most severely loaded window(s) closest to the seat of the explosion can be allowed to produce a certain level of hazard on grounds of economy, on the understanding that other windows, which are offset from the seat, remain more protective. In other cases, it may be required to fully protect specific room(s) at the closest range. It should also be specified whether it is required that the whole façade be glazed to the same details as required for the most heavily loaded point at ground level, or whether a graded approach to protection is to be adopted. The specification should state whether the façade system is expected to be reusable after the design event, or whether a level of permanent distortion is acceptable, necessitating replacement.

In outline, the six most likely bases for specifying are summarised as follows. Elaborations on each are added afterwards;

1. To state a bomb size and an idealised normal stand-off distance, to be used as the standard for all points on any of the façades, even though it may not be physically possible for this to occur at all points.
2. To specify a bomb of a given size at one or several specific locations in the building's vicinity, and to specify that blast loading is to diminish with distance and height from these points.
3. To specify the values of the peak reflected pressure and the reflected impulse. This differs from (4) only in the blast parameters being specified (i.e. incident or reflected).
4. To specify the design values of the peak incident pressure and the incident impulse. For both 3 and 4 it should be stated whether all the glazing should be designed for these values, or only the most vulnerable windows, a graded reduction in values being taken for the remainder.
5. To specify the glass to be provided, without any reference to bomb size, location(s), or values of blast parameters.
6. To specify the glass to be provided, and in addition, the bomb size, location(s) and stand-off, or the blast parameter values

A seventh method would be for the client-advisor team to carry out the complete design for glass, façade or frame in every detail and to invite quotations on this design from different contractors. This is an unusual course, in commercial projects, although it has its advantages where extreme sensitivity to security is an issue. It removes the option for façade contractors to offer their own chosen products and also removes all design responsibility from them.

Whichever of the six alternatives is adopted, elaboration in specification clauses will be necessary in order that misinterpretation, and therefore non-comparable tenders and arguments do not arise. Specification clauses should therefore be added to clarify the following points:

For Methods (1) and (2), it should be stated whether the stand-off is a notional distance for the purposes of achieving a glazing standard, regardless of whether it is physically possible for such a size of bomb to be placed at this distance from all points on the façade because of the geometry of the site. This will pre-empt any arguments about whether a stand-off distance can be physically possible at certain points on a façade.

The explosive type should be specified. If the bomb size refers to an explosive type other than TNT, this fact should be made clear. In the case of improvised explosives (as often used in terrorist vehicle bombs), the TNT equivalent weights for both pressure and impulse should be provided by the specifier, whether or not this data is realistic. It should not be left to tenderers to make their own differing assumptions on equivalent weights. Without this data, contention will arise if terms such as car bomb, lorry bomb etc are simply used in the specification. Real data on TNT equivalence may be unavailable, for security reasons, but notional values of equivalencies should still be given for the purposes of the tendering procedure.

For Method (2), it should be stated whether the specified bomb locations preclude consideration of any other possible locations. It should be made clear whether it is intended that complex analysis should be carried out of the propagation of the shock wave within the geometry of the surrounding buildings and streets. Such analysis is sophisticated, time-consuming and expensive and its results dependent on the analytical assumptions made. Particularly for a close range threat, it is doubtful whether such a course is justified. For more distant ranges, the analytical complexity increases, the reliability of results diminishes and any advantage of doing the work becomes questionable. It is a fact that real observations in many different buildings after real terrorist incidents have shown a whole variety of responses. Even within the same building with one type of window, responses vary in different areas of the building, raising the philosophical question of how much sophistication is desirable in predicting the hazards from glass breakage.

Method (3) is similar to Method (4) except that the conversion from incident to reflected values is done by the specifier. Again, it should be stated whether or not variation is to be taken over the face of the building.

For Method (4), incident (i.e. free air) pressure and impulse values need to be converted to reflected values, these being what are felt by a façade. Again, it should be stated at what point on the façade they should be taken to apply, or whether this is to indicate the standard for all the windows, or whether the diminution of loading with range and angle and blast clearing should be considered.

Methods (1) to (4) all place the obligation on the contractor to provide glazing to resist the blast threats, in whatever form the blast parameters are specified. The knowledge and information of how to do this is unlikely to be in the possession of most glazing contractors, and it is unreasonable at present to expect that they should have it. If they do have data (i.e. from a limited number of range or shock tube tests), it is possible that different conclusions may be obtained from data different sources. A client-advisor team which issues a specification in the format of Methods (1) to (4) inherently assumes that contractors have the knowledge and ability to make the glazing selection. The client-advisor team must therefore be competent itself to assess how far their selection meets that specification, and be empowered under the contract to rule whether an offered design is adequate, and to change it if they consider this necessary. The advantage however of methods 1 to 4, in the case of projects which include provision of both glass and flexible facades, is that the loading data is explicit, allowing tendering teams the opportunity to offer their own products and façade designs, even though it is likely that they will have to employ their own expert advisors to make use of the information.

Method (5), as an alternative approach, therefore has the advantage of removing the requirement of expertise in glass selection from contractors and transfers the glass selection requirements for blast directly to the client-advisor team. However, the requirements for other loading and environmental effects also need to be met by the contractor and there therefore needs to be interaction between the client team and the contractor on what these requirements are.

Adopting this method does however open another major problem area in specification, namely that of specifying the design method for frames or façade structures to hold the glass.

The interaction under blast loading of glass and its support structure (i.e. whether by discrete frames rigidly fixed to a stiff façade, or by flexible mullions and transoms spanning between structural floors) is a complex dynamic problem which cannot be investigated without a knowledge of the blast loading parameters. Different mullion systems have different flexibilities, and the fixing forces between glass and mullions, as well as between mullions and supports are dependent on these flexibilities. Flexible cladding may or may not be re-usable after a blast, depending on the deflections undergone. It is therefore necessary to specify what degree of distortion is acceptable, again requiring the specification of a blast load.

photograph 3 - flexible mullions

The adoption of Method (5) is therefore attractive in its simplicity for glass selection, but suffers from being deficient in specifying any basis for assessing support structure requirements. A façade contractor may therefore offer an existing frame or façade system in ignorance of its suitability, or he may proceed to make his own structural assessments on a misinformed basis. There is then the potential situation in which a contractor offers an economical, but inadequate system, and a client accepts it, when neither party is fully aware of its deficiencies in blast resistance. With this method, the client-advisor team is obliged to assess the dynamic response of the frame or the façade system after the tender is received, relieving the contractor of this responsibility.

Method 6 overcomes the difficulty with method 5, in that the glass selection responsibility is removed from the contractor, but at the same time the contractor is given the full blast criterion and responsibility for designing his façade or frame structure. The client-advisor team will need to specify a glass which is compatible with the blast loading, which an experienced advisor will be able to do. This is preferable when the knowledge of glass protective properties resides with the client's advisor, rather than with the contractor. This method therefore appears to be the most satisfactory. It does assume that the contractor's team will have the expertise to assess the suitability of their offered support system. It also leaves the contractor with the responsibility of ensuring adequacy of the glass for other loading and environmental requirements.

Equivalent Static Load

The concept of "equivalent static load" as a basis for specifying and designing the supporting frames, façade and fixings is appealing to the end-user because of its simplicity in use. However, the derivation of the value to be used is far from simple and begs the question of who is to derive it. The E.S.L. is simply an indirect expression of the calculated maximum dynamic deflection of a member during a dynamic response, the E.S.L. being that load which produces the same deflection as the dynamic deflection when applied statically. Its derivation requires dynamic analysis by a knowledgeable expert. For a flexible mullion system, there is little point in attempting this calculation before the proposed mullion properties are known. It therefore does not lend itself to ready quotation in a loading specification for flexible mullions. For rigidly supported frames it is more possible for the specifier to derive a realistic value for standard-sized windows in order to give indications of forces on frames and fixings, since notional values can be checked against previous observations in range trials. This process is an indirect way for the specifier to relieve contractors of the work of deriving forces for themselves.

Testing

Given the variations possible in pane size, thickness, glass type, framing, fixing and façade structure, and since the inadequacy of any one of these can lead to failure of the outer envelope of the building, it is often not possible at pre-contract stage for contractors or client's advisors to know categorically whether a proposed design will resist a prescribed threat, defined by methods 1-4 or 6. For specification method 5, while the glass requirements are explicit, doubts will remain on the matching requirements of the structural support details. The interaction of flexible, ductile panes with flexible mullions, connected by neoprene or sealant bonding and relatively stiff fixings presents a severe analytical problem, in which two of the key areas of uncertainty are 1) whether the edges of the pane are held in the frame rebates and 2) what are the dynamic resistance properties of laminated panes under high-speed loading, particularly in the rebound phase. The few blast tests which have been performed on complete glass-plus-flexible-mullion assemblies indicate that a flexible system is able to offer substantial economy over a system designed assuming rigid frame supports. Mathematical analysis depends on a reliable knowledge of the resistance function for high-speed loading and unloading of laminated glasses, which, as far as the authors are aware, has not yet been fully established.

Range testing can be the means of demonstrating the adequacy of a complete system, but if testing is decided upon, the following requirements need to be satisfied;

1. The tested prototype assembly should be the same in all respects as for the project proposal.
2. The prototype assembly should be tested in the front aperture of a closed cubicle in order to prevent rear-face blast pressures producing a false result.
3. If specification methods 1 to 4 have been adopted, a test charge and stand-off should be chosen to reproduce the blast parameters as specified, which are those for a large façade. The test charge and stand-off will therefore be more severe than the design event in order to compensate for blast clearing which will occur around the test cubicle.
4. If method 5 has been adopted, the test charge and stand-off will not have been specified.There is no single discrete set of blast parameters which defines the blast capability of the glass. For the purposes of a test, it is necessary that a set of blast parameters should be chosen so as to load the glass pane to produce a condition close to its point of failure, so that the corresponding ability of the support system to survive this load can be ascertained. Since there is a continuous range of different charge weights and stand offs which will bring a given glass pane to its limit of survival, and the interactions of the system components will vary with each, the test parameters to be adopted should be specified by the client-advisor team, their objective being to simulate the anticipated threat as closely as possible.
5. The specified bomb size may be too large for a test at the available ranges and a compromise size must therefore be adopted, with a compensating reduced stand-off distance.
6. The preparation for carrying out range testing is time-consuming

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and the cost of testing high. After tests, have been carried out, time is needed to analyse the pressure gauge readings and to properly assess the outcome. Allowance must be made for this in the project programme.

7. Because the outcome of a test is uncertain beforehand, more than one prototype assembly should be prepared and brought to the range for testing. Anticipation of the possible failure modes is necessary in order to prepare prototype assemblies on stand-by with alternative details. Experience from other testing programmes is invaluable in making judgements of what alternatives to prepare.
8. The full implications on design, cost and programme of carrying out design validation by blast trials should be recognised at the outset. These may include the need to develop in parallel an alternative façade design using proven blast-resistant elements, and require a willingness by the client and architect to adopt this alternative if the trials demonstrate that the preferred design is inadequate, whilst recognising that the programme may be jeopardised.

Concluding Remarks

Each of the specification methods 1 to 6 is self-sufficient and capable of achieving its aim, but the authors' preference is for method 6.

The key to the smooth running of a glazing contract with a blast resistance requirement is that all parties understand the requirements placed on them. On the client's side this entails having an awareness of his protection needs and how to specify them. On the contractor's side this entails an understanding of how to provide for those requirements. Both sides need access to experienced advisors, whether in-house or sub-contracted, who have a knowledge of the subject and have access to the necessary data base.

References

[1] Glazing for injury alleviation under blast loading – United Kingdom Practice. David C. Smith. Glass Processing Days 2001