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Prediction of annealed glass window response to blast loading

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ABSTRACT

Several software packages that are capable of predicting the response of annealed glass windows to blast loads are evaluated, by comparison to experimental data that has been obtained from full-scale arena blast tests in the field. A total of 34 instrumented, monolithic, glass window panes were subjected to explosive blast waves of varying intensity. A series of small-scale material tests and full-scale pane tests was also performed in the laboratory to obtain mechanical properties for use in the predictive models. The utility of various software tools, based either on single degree of freedom analysis or explicit finite element analysis, is hence assessed, for use in the analysis or design of glazing under blast loading.

1. Introduction

Recent world events have led to an increase in the perception of the danger that the public faces from malicious events such as intentional attacks. In response, protective structures are becoming an increasingly common design requirement for stakeholders that perceive themselves to be at heightened risk. Typically, the major consideration in the protective design of buildings is the response of a building's facade to the nearby detonation of an explosive device, as the facade is generally partially or fully constructed from glass.

The analysis and design of glazing subject to blast loading is an involved process, requiring the combination of a method for predicting the loads generated from a blast, a way to calculate the dynamic response of the glass pane to the calculated loads, and an appropriate way to estimate the time of failure of the glass. At present, several software packages are available for the express purpose of aiding the design of architectural glazing elements under blast loads. Each of these programs offers several load input methods and employs one of several well-established methods for the analysis of glazing panes while incorporating various unique initial assumptions. Due to differences in analysis method and assumptions, the output of each program is different to the others for the same input. Currently, there is little to no indication of which program, and its corresponding methodology, most accurately reflects the true behaviour of glazing subject to blast loads. There is, therefore, a need for a review of these software programs and the methods they employ, evaluated against reliable large-scale test data, in order to determine the validity and utility of their predictive capability.

2. Background

2.1. Effect of blast loading on glass

This paper focusses on the response of the glass components of glazing to blast loads, specifically the basic case of dry-glazed, annealed, monolithic, new glass panes. Due to its brittle nature and lack of energy-absorption capability, window glass is considered one of the weakest components of a structure and has been known to fail under relatively low blast pressures [1]. When annealed glass fails under blast loading, it both breaks into hazardous fragments, which are then thrust into the enclosed space, and it allows the blast wave to propagate into the structure [2].

The response of glazing panels to blast loads may also be influenced by the negative phase of a blast wave. In general, the response of any element is dependent upon the ratio of the blast wave duration to the element's natural period [3]. For glass panes, testing has shown that, for various scaled distances, this ratio is such that they can experience significant deflections during the negative phase of the blast load and may be susceptible to failure during rebound, even if the initial positive pressure was resisted [4].

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Nomenclature

σ	stress [MPa]
A	area of glass pane [mm^2]
B	risk function in Weibull statistics
c	bi-axial stress correction factor
E	Young's modulus of elasticity [MPa]
I_s	positive impulse of side-on overpressure [kPa-ms]
I_s^-	negative impulse of side-on overpressure [kPa-ms]
k	Weibull surface flaw parameter [m^{-2}-Pa^{-m}]
m	Weibull surface flaw parameter
P_f	probability of failure
Z	scaled distance [$m/kg^{1/3}$]
CWBlast	Curtian Wall Blast
FEM	Finite Element Method
GFPM	Glass Failure Prediction Model
GSA	General Services Administration
MPS	Maximum Principal Stress
SBEDS	Single degree of freedom Blast Effects Design Spreadsheet
SLS	Soda Lime Silica
WINGARD	Window Glazing Analysis Response and Design

2.2. Blast testing specifications

In order to reliably assess the performance of a glazing system for blast loads, full-scale field blast tests should be performed. Field testing of glazing involves mounting the specimen to be tested in a reaction structure, frequently called a "cubicle" or "target". An explosive charge of set weight is then placed at a specific standoff distance away from the target such that a blast load of desired intensity will be produced on the test specimen upon detonation. Several standards (ASTM F1642 [5], GSA TS01 [6], ISO 16933 [7] and BS EN 13123-2 [8]) are available which specify the charge size and standoff to be used as well as any requirements for the specimen being tested, the method of mounting the specimen and any requirements of the testing cubicle in the case of an arena test.

The ultimate goal of these test methods is to provide a quantitative evaluation of the ability of the glazing arrangement being tested to resist specific blasts. However, even the most stringently controlled blast tests on glazing will be highly variable in both the loading pattern and response of the target, making it very difficult to directly compare test results of the glazing itself. Therefore, how far fragments of broken glass are projected into a standard-sized test cubicle, as a result of the blast, is generally used as a benchmark to assess the protective ability of the glazing. The performance specification laid out by the General Services Administration (GSA) in TS01 [6] is the most prevalent standard for assessing this result. Essentially, a standard cubicle, as shown in Fig. 1, is divided into various regions, each of which is assigned a "hazard rating" which refers to the post-test state of the glazing (i.e. how far the glass flies) and the relative danger posed to building occupants [6].

2.3. Properties and behaviour of annealed glass

At ambient temperatures, glass behaves as an almost perfectly elastic isotropic material. On average, soda lime silica (SLS) glass has a density of 2500 kg/m^3, Young's modulus of elasticity (E) of 74,000 MPa and Poisson's ratio of 0.22 [9]. Due to its irregular non-crystalline nature, glass does not exhibit plastic deformation prior to failing in a notably brittle fashion [10]. The strength of glass, as

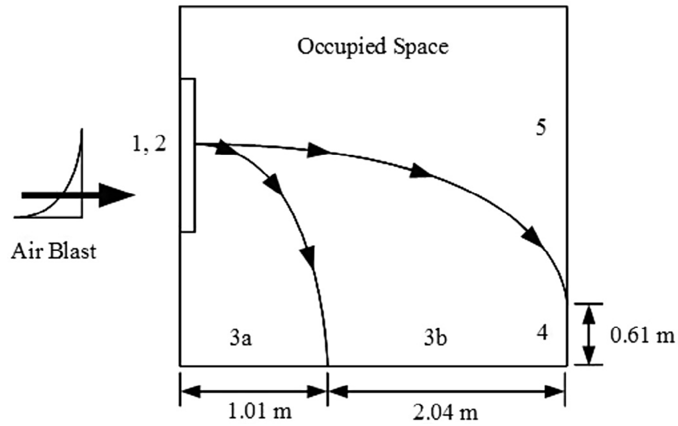

Fig. 1. GSA standard test cubicle (adapted from Ref. 8).

it relates to engineering applications, has been shown to be several orders of magnitude lower than its theoretical strength (between 1 and 100 GPa [11,12]). This discrepancy is explained by the presence of minute flaws, typically invisible to the naked eye, on the surface and interior of glass elements caused by manufacturing and weathering.

The effect of these surface flaws on glass strength can be described using fracture mechanics. When a tensile stress is applied to glass, the surface flaws amplify the stress. The stress at the flaw tip increases until a critical load is reached, at which point rupture of the material is initiated and the flaw begins to rapidly expand, cracking the glass element and resulting in a brittle failure. Relationships between the crack size and the applied tensile stress to cause rupture have been previously established by Griffith [13] and Irwin [14].

For the case of applied stresses too low to cause immediate failure, cracks may still grow at very low rates through the phenomenon of "sub-critical crack growth" or "static fatigue". Based in part upon the phenomenon of sub-critical crack growth, the strength of glass is a function of the duration of an applied load. It is known that glass panes may fail prematurely when exposed to low but long-duration loads and may also be able to resist much higher loads if applied at a high strain rate [15].

Following from fracture mechanics, it is noteworthy that failure of a glass element almost always initiates due to a tensile stress, as this is the mechanism which causes crack growth. Correspondingly, the strength of glass in compression is in the order of ten times its strength in tension. Further, since only a single flaw, often called the critical or Griffith flaw, is required to initiate failure there is a known size effect in glass strength such that the average strength of glass decreases with area placed under tensile load, since a larger area will more likely contain a flaw of a critical size [9]. Finally, the stress-raising ability of a given flaw is dependent upon its location and orientation within the tensile stress field, and therefore the critical crack is not necessarily located at the point of maximum tensile stress, and panes of glass which have directional flaws may exhibit very different strength values when exposed to tensile stresses in orthogonal directions [15].

2.4. Glass failure criteria

One of the most difficult aspects in assessing the response of glass under loading is predicting the failure load. One of two methods is generally employed to determine glass strength: the deterministic method or a probabilistic approach.

The oldest failure criterion for glass is the deterministic approach, also referred to as the maximum principal stress (MPS)