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The Challenges of Writing a Structural Standard for Glass

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Glass has been used as a prized construction material for centuries. Typically it has been used as a window infill, initially designed empirically where thickness available was adequate for the sizes available. As technology has proceeded, the size of glass available has increased by orders of magnitudes and standards have been written to guide the design in windows. Glass remains unique amongst the construction materials, that failure and replacement is considered an acceptable price to pay for the transparency of glass. The same logic has, however, limited the use of glass as a 'structural' material, despite the numerous built examples of it performing adequately. If it is acceptable for glass to break and collapse in some circumstances and not others, how does a standard define that boundary? The challenges for standardization are both numerical and philosophical. The means of forcing glass to behave with a robust manner with failure mechanisms that incorporate redundancy and retention generally comes through lamination. But the question is what to require when? Additionally, the performance of the glass in the composite is stress-time dependent and the stress itself is load-time-temperature dependent. This paper describes the philosophical and numerical challenges to writing a structural glass standard, the concepts of glass importance factor, post-failure loads and durations and progress that has been made in the drafting of an ASTM Guide to the Design of Structural Glass..

Keywords: Structural Glass, Standards, Robustness, Retention, Redundancy

1. Introduction

{The opinions expressed herein include those of the author and should not be considered as having been agreed at a committee level. They should not be regarded as indicative of any future ASTM standards. The author wishes to thank all the members of the committee for their valuable input; it is greatly appreciated.}

Glass is unique amongst building materials as being both transparent and brittle. Unlike the other common brittle materials, concrete and masonry, cracking of any kind is regarded as a failure. Due to the technology initially available, breakage and fall out were considered to be a necessary risk for the transparency glass offered. However, the same assumption of sudden failure also reduced the acceptance of glass from structural applications. As technology has advanced, so has the potential for robustness through redundancy and retention. Specialist designers have successfully constructed many glass structures. However, many poor practices are perpetuated because of the lack of code mandated standards. To make glass as a structural material available to the wider design community, and as a reference to the building authorities that review and monitor them, a new structural glass standard is required. While many of the technical considerations will be common to the other material standards, the nature of glass and its design has many unique aspects that also require philosophical consideration. This paper makes proposals for the consideration of circumstance and consequence to add to the usual criteria of strength, stability and serviceability to develop a design standard that promotes good design of structural glass.

2. What is required in a guide/standard?

There are many good books on the strength of glass and how to calculate the strength to first fracture, but very few that provide guidance beyond that. There are several ASTM standards concerning glass: ASTM E1300 provides a probabilistic approach to acceptable loads for window glass in buildings, ASTM 997 for statistical methods of testing window glass, ASTM 2353 and 2358 for balustrades, and ASTM 2751 for glass walkways, to name a few. However, despite these numerous standards, specifications and test methods, there is not an overarching guide to the design and engineering of structural glass. Even simple glass assemblies, such as glass fin storefronts, do not have a standard by which their adequacy can be measured (in the United States). Traditional material design standards are entirely concerned about preventing failure of an item; in the case of glass design, the inevitable failures must also be considered and the consequences controlled.

The ASTM committee selected to initially publish the document as a guide, rather than a specification, for several reasons. Rather than specifying minimum standards, a guide can provide guidance for good practice with some discretion allowed to the designer. By providing 4 consistent glass risk levels, it also makes it possible for specifiers or regulators to require a particular performance level.

Glass differs from other building materials in that it is both brittle and cracks are considered unacceptable, as they impede the transparency. The other common brittle materials, concrete and masonry, are also strong in compression and brittle in tension, but utilize steel reinforcement to provide predictable tensile capacity following small but acceptable cracking of the material. Plastic extension of the tensile reinforcement allows ductility of the system and redistribution of loads to less critical areas. In this way, prediction of the initial formation of cracks is not critical to the overall structural performance of the material and stress-based design gives consistent lower-bound predictions of the capacity. For glass, with few exceptions, cracking is regarded as a form of failure, thus the demands on the material must also take into consideration aging and the flaw distribution of the surface, which initiates the cracks that control the capacity of the system.

Window glass design around the world has separated into two camps: ‘stress-based design’ and ‘probabilistic design.’ To treat glass as a generalized building material, one has to realize that all materials have statistical basis. For ductile homogeneous materials, such as steel, variability is small and failure modes can be predicted consistently on a stress capacity basis. For brittle materials, the addition of tension steel has allowed concrete and masonry to be treated in a similar manner, but adjusted with material safety factors to account for greater variability. The strength of glass is strongly dependent on the distribution of flaws on the surface, such that there can be wide variability of performance and cracks do not necessarily initiate from the point of greatest stress. The combination of variable overall flaw distributions, variable initiation location and variable wind loading to the individual panels has resulted in a history of statistically acceptable usage. Some countries have accounted for this by allowing higher stress for infill panels, but test for peak stress only; ASTM E1300 has adopted Beason’s Glass Failure Prediction Model, which evaluates the distribution of stress over the surface area to evaluate the probability of failure.

Glass design practice has the added complexity that, due to the technology available in the past, glass breakage and fall out was considered unavoidable and has become accepted in some circumstances. Glass is unique in this respect, and is regarded as an acceptable risk for the transparency gained. When applied to window glass, the formation of cracks usually has a commercial, rather than structural, risk associated with it, and risk to the public is only associated with glass falling to the ground. While some countries in the world now require laminated glass on the exterior, historic inertia makes it very difficult to change practices in countries such as the United States. With this in mind, the idea of this brittle material being used for structural purposes in primary or secondary structures has not been codified, nor have the philosophical questions of designing robust glass been addressed.

3. A structural glass standard

3.1. Why a New Standard?

ASTM E1300 is used for the statistically acceptable use of glass under uniform load with continuous support on one, two, three, or four edges. The glass failure prediction model on which it is based takes into account not just the maximum stress within the panel, but an integral of the stress and the area applied with a probability function to take into account the flaw distribution of weathered glass. This performs well to define acceptable usage in windows and allows efficient design taking into account that the critical flaw will probably not be at the point of highest stress, as is often observed in testing. This assumption, however, may not be appropriate for design of elements which serve other structural purposes and where failure could cause greater consequential damage. Design of these systems needs to meet the test of reliability rather than statistically acceptable usage. The new standard is to act as a guide for philosophically different design methods, separating infill glass from structurally critical glass applications.

The structural glass guide aims for reliability rather than statistically acceptable usage, so it will assume that the critical flaw may be at the maximum stress location, thus it will be stress-based design. It will also, however, assume that due to inclusions, surface damage, or for whatever other reason, there may be instances where a glass component performs with capacity much less than anticipated. Much of the standard will be about promoting good design practices that ensure robustness and safety, should one component of an element fail.

3.2. The 5 R’s of Glass Design

Glass in various circumstances will need to satisfy the 5 R’s of glass design: Resistance; Retention; Redundancy; Residual Capacity and Regulation.

Resistance is controlled by strength, stability and serviceability. That is to say, it must be able to resist the loads without breaking: for stability, it must not buckle, and the deformation of the glass structure must be both aesthetically acceptable and compatible with the structure around it; each with appropriate safety margins. The matters of strength are being well-researched, as are the stability behaviors of both monolithic and laminated glass. These technical aspects are common in all building material standards. While lower loads are often used when designing for aesthetic criteria, where deflection can initiate breakage, loads with appropriate factors for strength design need to be maintained. Glass, in part because of its historical usage as a monolithic infill material, now requires new standards to redefine acceptable behavior in both service and post-failure conditions.

Retention is preventing glass from falling immediately if broken. It does not have any specific post-failure capacity other than not to fall to a location of potential human injury during or immediately following the fracture event. Different classes of retention have been identified and will be discussed herein.

Redundancy is where there are alternate load paths in the event that one element or ply is fractured.

Residual capacity is where the element continues to perform a critical function with all plies broken.

Regulations are required to govern when each of these design attributes are required. This takes into consideration not only the size of the element and the load that it is required to resist, but also the location of the element, its circumstance, and the consequences of failure. As an example of how consequence can influence the design, consider a glass fin secondary element supporting 2.5m x1.5m sheets of glass on either side. If this element was in a ground level storefront, the consequences of failure could be considered to be minor. However, the same element supporting the same area of glass subjected to the same loads as part of a 30m high glass wall could cause significant injury should it fail.

3.3. Glass Design Characteristics

While the system of using glass design classes has been dropped, in favor of specifying behavior characteristics, it is still useful to review some typical groups and means in which characteristics may be satisfied.

Design Class A – Unrestricted

Design Class A is for glass that has no specific post-failure requirements. This is similar to the current window glass standards. In the U.S. regulatory environment (and countries using the International Building Code or ASTM's), this would be covered by ASTM E1300.

Design Class B – Safety Glass

Safety glass is defined as fully tempered (toughened) or laminated glass with a variety of requirements and exclusions in the existing building codes. This standard does not address "safety glass" requirements; rather it acknowledges the presence of requirements at a Code level. In particular it would govern design of elements where retention was not required but the use of fully tempered (toughened) glass was considered to reduce the risk of injury.

Design Class C – Retention

C1 – The fall area is limited to areas not trafficable by humans, thus fallen glass is retained within an area where it will not cause human injury. (This is included as a reference to current IBC practice for overhead glazing, but will be controlled by risk categories, retention requirements in the tabular format of the guide.)

C2 – A second glass unit or safety screen is placed below the glass to prevent broken glass from falling and causing injury.

C3 – Glass that is retained with an adequate organic coating (safety film) which is adequately anchored or contained within the glazing pocket to prevent fall out.

C4 – The glass is laminated, such that glass is not released when one or all components are broken.

Design Class D – Redundancy

D1 – Load can redistribute to a different element (via an alternate load path).

D2 – Multiple discreet elements in parallel. The load is shared between several elements in such a way that if one breaks, the remainder can resist: a.) a non-extreme event; or b.) a design event with reduced safety factor.

D3 – Multiple plies laminated as a composite. For example, a laminated stair tread with the load perpendicular to the plies; the loss of stiffness and strength may be less than (for interior plies) or much greater (for outer plies) than the number of plies broken divided by the total number of plies.

D4 – Multiple plies laminated in parallel. For example, a laminated fin with the load applied in the plane of the plies: the loss of stiffness and strength is notionally (ignoring the residual capacity of the broken ply) proportional to the number of plies broken / the total number of plies.

As sub-classifications:

D#(a) where the capacity of the system with one ply broken is not required to exceed the unfactored design load, but provides sufficient capacity to resist non-extreme loads and allow replacement;

D#(b) where the ultimate capacity of the system with one ply broken exceeds the unfactored design load.

Design Class E – Redundancy and Retention

The system has multiple load paths and fractured elements are prevented from falling.

Design Class F – Post-Failure Capacity Required

The system continues to have capacity to perform a critical function with all components of an element broken.

F1 – The system continues to have capacity for sufficient time to make safe evacuation or make the area safe.

F2 – Has the capacity to resist a reduced return period design load (say 1 to 5 years) to allow safe replacement.

F3 – It continues to resist design loads with all plies broken (deflection not considered).

3.4. Precedent Standards

With the glass characteristics identified, the design elements of occupancy, circumstance and consequence can be introduced and evaluated to formulate Glass Design Categories. One of the best examples regarding building materials that evaluates the effect of failure modes, circumstance, and consequence, are the seismic provisions of ASCE-SEI-7. This standard takes into consideration the occupancy, the seismic loading, the material ductility and failure modes of characteristic structural systems, including materials such as steel, concrete and timber to ensure progressive and proportional yielding without collapse. It indicates restrictions and limitations or permissibility of the systems and special detailing requirements for each of the categories. The Seismic Design Category takes into consideration the occupancy, seismic load and ground conditions to be placed in a seismic design category from A to F, where A is the least demanding, and F is in an area of high seismicity and/or adverse ground conditions. It also takes into consideration not just the capacity of an element but also the behavior of a system and introduces the concept of 'special detailing'. For example, ordinary steel concentrically braced frames are not limited in usage for Seismic Design Categories A to C, but are limited to a height of 35ft (10m) for Design Categories D and E and are not permitted in Design Category F; steel concentrically braced frames with special detailing is allowed in all design categories with height limitations of 50m for Categories D and E and 30m for category F The permissibility of any given system recognizes the failure characteristics of the system as a whole and not just the strength and stability of the building material or individual element. Extensive tables of standard systems are provided in the Standard.

3.5. Special Detailing

As an example of how special detailing can make a difference, consider a laminated glass skylight (single glazed) with support on 2 sides only. In the event that one ply is broken, then the load capacity is reduced and the deflection is increased, but both redundancy and retention is achieved. Should both plies break, then the capacity and the stiffness of the system is controlled by the strength and stiffness of the interlayer, the sizes of the glass fragments, temperature, bond and many other effects; but most importantly the edge detailing of the glass to the glazing bar needs to be considered, if the glass pulls out of the glazing pocket due to deflection and pull-in then the entire glass unit may dislodge, whereas a system with adequate structural silicone would be retained in the opening as a membrane. So the post-failure characteristics depend on the system detailing as well as the glass element itself.

The design of structural glass is not defined entirely by the strength and stability of the system, but also by its failure mode and suitability for circumstance. Hence, it makes sense for a new structural glass standard not only to include the technical aspects of strength and stability, but also guidelines and limitations on what constitutes good design practice for various situations. For many common cases, this can be relatively simply and easily defined, however given the specialty nature of high-end glass design, it should also express this in terms of design principles that govern in the general case, so as to continue to allow creative innovation.

While the technical aspects of strength, stability and probability of failure can be determined through scientific and academic testing, the questions of what constitutes 'good design practice,' 'acceptable failure modes,' and the amount of post-failure capacity required are somewhat more philosophical.

As examples of variation in accepted practice in window glass usage, some countries require external laminated lights in high rise structures while others require tempered 'safety glass' with the risk of spontaneous fracture and fall out. Some codes around the world, the United States included, have traditionally considered fully tempered glass as presenting a low risk, relying on it to break into 'small harmless dice' when it fractures. Monolithic fully tempered glass was allowed for glass balustrades up to and including the 2012 edition of the International Building Code (IBC) but has been prohibited in IBC 2015 (other than where glass would fall into a protected area.) However, the mechanical interlock of the dice, particularly in larger thicknesses, causes the fractured fully tempered glass to remain in 'clumps' until they are disturbed by impacting a surface. If that surface happens to be a person, there are many documented cases of severe and critical injuries. Unfortunately, when this occurs, and particularly when it makes front page news, it reinforces the public's opinion that glass is not a safe material for building construction. Conversely, while it would be easy to say "all glass should be laminated," this approach must be weighed against the economic costs and evaluation of the risks. Thus it is not practical to take such a simplistic approach. The question is, how much risk is reasonable?

3.6. Design Parameters and Risk

ASCE-SEI-7 provides risk categories for design of buildings for flood, wind, snow, ice and earthquake loads. In this format (paraphrased)

- Risk Category I Structures that represent low risk to human life
- Risk Category II Structures not in I, III or IV (the default)
- Risk Category III Structures whose failure could pose a substantial risk to human life due to the nature of the structure or high occupancy
- Risk Category IV Essential facilities, high risk facilities and structures required to maintain functionality of other category IV structures.

The risk category influences the loading applied to systems through: importance factors to increase/decrease the load; selecting return periods for extreme events and; influences the seismic design category and hence the special detailing requirements.

Similarly Risk Categories are used for glass design.

- Glass Risk Category I Glass that represent low risk to human life
- For example: a glass house; standard window glazing supported on 4 sides
- Glass Risk Category II Glass not in I, III or IV
- For example: a glass fin wall with limited height and/or limited occupancy
- Glass Risk Category III Glass whose failure could pose a substantial risk to human life due to the nature of the structure or proximity to high occupancy
- For example: high glass walls, skylights
- Glass Risk Category IV Glass elements providing an essential role and glazing required to maintain functionality of other category IV structures, glazing requiring a post-failure residual capacity.
- For example: glass flooring and staircases, hurricane glazing.

Each risk category has its own set of allowable circumstances and recommended height limitations. Currently the selection of the risk category allows for some discretion on the part of the specifier, however this may become more prescriptive as the document further develops or as the guide is adopted by regulatory bodies.

There is a significant body of assembled work in the range of 4-6m in vertical glass walls without redundancy or retention that have performed successfully with very few injuries. In common with all glass standardization documents, there are contradicting objectives of minimizing cost to community while maintaining an appropriate level of safety. For designs in risk category II in particular, there has been debate about what is an appropriate height to require retention of glass with a free edge. It is generally agreed that glass less than 3m height is acceptable without retention is acceptable and that glass greater 8m high requires retention. For the intermediate range, 5m to 8m possible compromises included that if fin elements have continuous structural silicone to one long edge and any Fully Tempered glass has been heat-soak tested retention would be at the discretion of the designer.

4. Some generalized rules and considerations

- Glass that lacks retention should either be supported in a system that promotes a stable fracture pattern or in a location where breakage has limited consequence. As examples; a monolithic glass fin in a storefront with the highest point less than 3m (10 ft) from the ground has a limited risk in the case of a fracture event whereas the same fin at 10m (30ft) presents a greater risk; glass that has structural silicone on all edges has less risk of dropping glass and having a stable fracture pattern than glass with a free edge. Designers may of course choose more conservative solutions and certainly design guides should recommend them, however building standards need to define minimum requirements for the mandatory sections and has a responsibility to society to provide cost-efficient design.
- Limited additional heights without retention may be appropriate, but only where there is an appropriate risk profile and the system has a track record of reliable performance.

- Monolithic glass that has free edges will generally not have a stable failure pattern. Thus it should have secondary retention when the highest point is greater than 3m from a trafficable surface, or as appropriate. Current provisions in the International Building Code require retention by screens or lamination for glass at an angle of greater than 15^o from vertical, however vertical elements with free edges are also unstable when fractured, so should have a similar provision. One of the challenges for the committee has been the legacy of using the largest available monolithic fully tempered (toughened) glass fins most of which have been without mishap, but as glass becomes taller how high is a reasonable risk before retention is required? The risk classes assist in this respect, since a showcase window with limited access would be a different risk class to the same system between a busy street and a highly populated lobby.
- 'Safety Glass' provisions can be complemented by the concepts of retention and redundancy requirements rather than treating laminated and fully tempered glass as similar.
- Existing code dictated safety glass provisions for unlaminated options would remain to control the nature of glass fragments.
- Testing of structural glass assemblies with custom connections should either be required or promoted through the use of load factors that penalize untested designs. (There is a potential for proprietary rated systems similar to the ICC-ER certificate scheme, where load capacities of proprietary products such as fasteners and concrete anchors are rated for capacity in accordance with IBC.)
- Load factors can be used to improve reliability (or reduce the probability of failure), however the possibility of random fracture, however so caused, cannot be excluded in any type of glass. Good design practice should ensure that systems continue to function (or fail in an appropriate manner) should one component have little or no capacity. The level of load factor required may be a function of the level of redundancy embodied in the system, such that a system with high redundancy has a commercial advantage over systems with little or no redundancy.
- The post-failure requirements are characterized separately by load types, with factors and durations for permanent loads, environmental loads and live loads.
- Glass design has traditionally recognized any fracture as a failure, however to fully evaluate the safety of the system, the structural capacity of the system in the non-fractured, partially fractured and fully fractured states need also be considered. Appropriate design loads to be considered for each of these states may vary with circumstance.
- The strength model is based on limit state principles. The strength model in prEN-16612 has been reviewed and found to be conservative relative to ASTM E1300 and forms a good basis for stress based analysis. Load factors in the United States would, however, be consistent with ASCE-7, much like a national annex in Europe.
- As well as determining appropriate reliability for the glass system in the undamaged state, suitable behavior is required in a damaged state. Separate post-failure load factors are required for permanent loads, environmental loads and live loads. For each of these a characteristic load duration is provided. Additionally, guidance for retention and redundancy requirements with acceptable post-failure performance are characterized.
- Post-failure performance criteria include:
- No requirement
- No further breakage with 1 ply broken (dislodgement due to increased deflection is unacceptable)
- No fall (dislodgement is acceptable, but must not swing through a populated area)
- Retained in opening, with all plies broken and some degree of post-failure capacity
- Not permitted, where a particular configuration is considered inappropriate for the circumstance and risk category.
- Is the glass element part of the overall stability system? If so, the full capacity of the system is required with the element fully fractured (all plies); element(s) must have residual capacity when fully fractured, or the system has alternate load paths with adequate factor of safety with one element missing.
- Where the element supports live load, the element must be adequate (ultimate) with a sacrificial ply broken (consistent with ASTM E2751 Design and Performance of Supported Glass Walkways). Test to (unfactored) design load with critical ply broken; no further breakage allowed.
- Similarly critical non-trafficable element, members designed for only 1 ply broken should sustain the ASD (unfactored 1:50yr) design load without further breakage.
  - For less critical elements the post-damage load may be reduced.
  - Loads in a broken condition: ASCE 7-05 damaged components, C2.5.2 extraordinary events require 20% design load (0.2 x 1.6 = 0.32 load factor).
  - Loads in a broken condition: 1 year return period for variable load: 50% design load (0.5 x 1.6 = 0.8 load factor), unmonitored and/or long lead time items.
- Where there people under the element, retention is required to prevent broken glass falling on people.
- If there are people under other parts of the system supported by the element then redundancy and retention is required such that the loss of one element in its entirety does not cause consequential collapse or risk to people.

- If there is immediate collapse without element and the highest point is greater than 3m* then redundancy and retention is required.
- Reduced capacity without element (i.e. system has capacity for 6 month return loads without element): If higher than 3m – retention; If less than 3m – no requirement.
- Will the fractured state be unstable?
    - No: design as window glass using probabilistic acceptability (per ASTM E1300),
    - Yes: If the element is above 3m, provide retention,
- Lamination with time/temperature sensitive materials shall not be relied upon for the support (strength and or stability) of permanent loads, but may be used to provide serviceability for the design life of the element.
- Overhead elements are designed for Pf= 1:1000, or use glass importance factor Ig = 1.6 for improved reliability.
- Fully Tempered (Toughened) glass is not recommended for elements that people are standing on; although it may be safe, the fracture event may be traumatic nonetheless.
- The retention period of the glass shall not be less than a reasonable period to replace or make safe the glass. Glass with long lead times shall have an appropriate retention time or make safe method statement.
- Elements with the 'no fall' criteria may dislodge from the support on 1 or more sides, but must be retained and must not swing through occupied space.
- Element between 30 to 60 degrees from vertical are assumed to require an additional access device (such as a ladder) and/or fall arrest system.
- The use of heat-soak testing may increase the height limits of use for some configurations and risk categories.
- New test methods will be required to determine: the stability of fractured state, post-failure capacity etc.
    - e.g. Hurricane missile impact testing, sand bag testing, etc.

5. Rules Format

To summarize the specific requirements a tabular format is used. While the tables are necessarily extensive at this time, their use by a practitioner is relatively simple: first, select the table for the relevant risk category; next, find the description that most closely resembles the desired design; then, read across for the design parameter options. For many circumstances there are multiple compliance options, but only one need be satisfied. This means, for instance, that if the performance with all plies broken is satisfied, then it is not necessary to satisfy that there is no further breakage with 1 ply broken and vice-versa (although a designer may choose to check multiple performance criteria.)

6. Additional Testing Methods

This concept of designing with all plies broken raises an area of glass design which is rarely considered in architectural building applications. The design of glass in the fractured state as a compression element with a secondary reinforcing tensile element, be it an interlayer or a high-tensile element, is somewhat akin to reinforced concrete design. Utilization of glass in the broken state is already considered in applications such as hurricane glazing and also in automotive windscreen applications where the bonded, laminated glass is utilized as a sheer diaphragm to prevent sway collapse of the roof in rollover accidents. Methods for analyzing glass in the fractured states still needs further investigative study before design calculation methods can be fully utilized. Until that time, some design requirements may continue to require destructive testing for justification. Many destructive test methods are already described in ASTM standards and elsewhere. Additional test methods may be required as part of a suite of standards relevant to structural glass design. A good structural glass design standard will, however, also provide guidance for numerically engineered solutions, where possible minimizing the amount of testing required.

Elements of a structural glass standard should include circumstance, consequence, strength, stability, serviceability considerations and post-failure behavior. A proposal of topics to be addressed is summarized in Figure 1. Some of these topics are well-known, while others require further research. In some areas, it will be necessary to take an 'engineered response' rather than a scientific one; where we do not know an exact answer, good conservative practices will have to suffice or be justified by testing.

7. Conclusions

Glass is a material that has been utilized for its transparency, but also has excellent capacity in compression and a limited capacity in tension. Specialist glass structures around the world have demonstrated its ability to be used as a structural element, not just as a cladding or infill element.

The widespread usage of glass as a structural element has been limited by the lack of design standards. This has prevented the adoption of the material by non-specialist engineers and designers and also limits the ability of building authorities to evaluate structures, even those by glass specialists. In some cases, the lack of a design standard has allowed the construction of inadequate 'copycat' installations.

The public perception of glass as a structural material has been greatly enhanced by high-profile projects such as the Apple staircases. Conversely, the public perception that glass is either unreliable or dangerous is reinforced by practices such as monolithic tempered glass balustrades falling off buildings.

It is the hope of the author that a new guide for structural glass can promote good design practices and preclude potentially dangerous ones. There are many aspects of glass design that remain unpredictable. However, taking this into consideration with the technologies that are now available to us, it is still possible to design systems and elements with appropriate robustness and reliability.

Many standards around the world have attempted to reconcile what is scientifically justifiable with what is known to be statistically acceptable usage in common applications such as windows. The proposal of the author to the ASTM committee is that these things should be treated as separate, with the probabilistic class failure prediction model continuing to be used for window glass design and stress-based reliability design for glass structures.

Good global structural system design will take into consideration circumstance, consequence, failure characteristics, and overall system performance to facilitate the design of advanced and exciting glass structures.

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Fig. 1 Section Map.

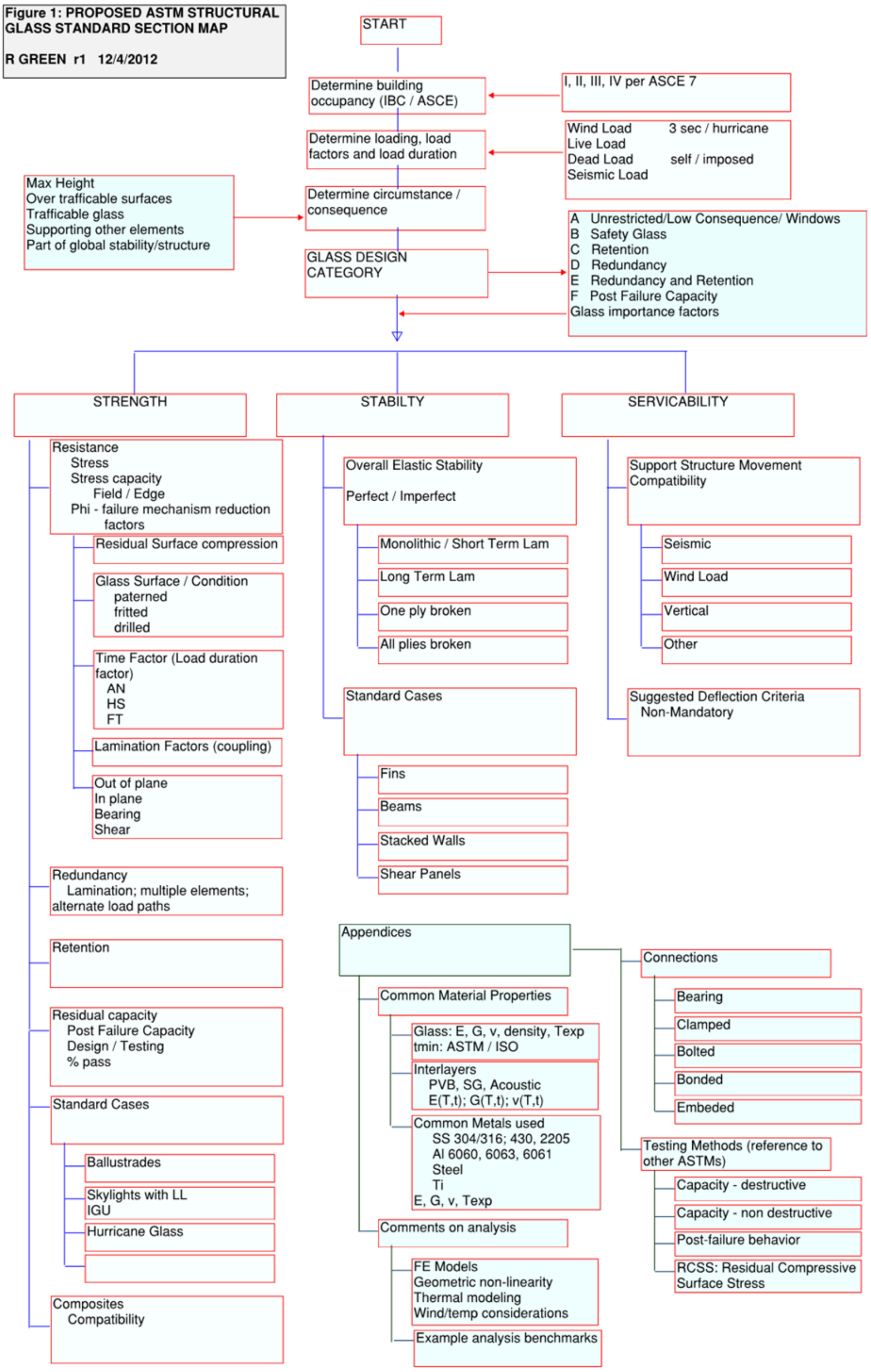

Figure 1: PROPOSED ASTM STRUCTURAL GLASS STANDARD SECTION MAP

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