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Structural Glass Design Manual: A Design Guide and Voluntary Specification for the Use of Glass as a Structural Material in Buildings

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Abstract

Other than limited special cases, there is a lack of standards providing guidance on the design of structural glass in the United States and much of the world. This has resulted in an ad-hoc approach by cities (authorities having jurisdiction), architects, and engineers. This paper outlines the key aspects of designing with glass in a manner that has reliability and robustness consistent with other structural materials while recognizing the unique aspects of glass. This voluntary design manual is aimed at providing 4 consistent levels of risk in applications that allow Architects, Owners and Engineers to have an informed decision-making process for selecting levels of robustness, which may or may not be otherwise required by code. The document aims at developing consistent practices to facilitate confident design in glass while also addressing a number of technical challenges.

Keywords

glass performance, glass engineering, structural glass, laminated glass, glass interlayers, robustness, redundancy, retention glass, architectural glass, performance standards, codes-standards-rating systems

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1. Introduction

The Unites States, and indeed much of the world, is devoid of standardization on how to use glass as a structural material in buildings. After a decade of grappling with this challenge, there are multiple reasons that are apparent:

- glass is brittle;
- glass has been traditionally used in non-structural applications where breakage and fall out were accepted as the price for transparency;
- traditionally glass was smaller;
- the use of glass in buildings preceded the availability of suitable interlayers;
- glass is susceptible to damage from non-design loading events;
- applications of glass in one circumstance which is clearly acceptable in one application may be unacceptable in another and vice versa, making general rules difficult to formulate.

Without standardization for the use of glass as a structural material, Authorities Having Jurisdiction (AHJs) have had various responses, ranging from leaving it to the experts designing it, to ad-hoc regulations, to banning it as a structural material, and/or requiring expensive testing protocols.

In the absence of consensus standards, voluntary specifications and design guides can provide a vital role in forming standardized practices in the future that can help advance the use of glass as a structural material in buildings. The structural glass design manual provides a document which is able to be specified by architects who are not expert in the area of glass design, and used by engineers and AHJs as a reference point for items which they may need to consider on their projects. Of course, if the formulation of such a document was easy, it would have been done by now, but even an imperfect document forms a framework that can receive future input and development as a vital step towards standardization and widespread acceptance of glass as a structural building material.

Glass is one of the strongest materials known in compression, but is brittle and orders of magnitude weaker in tension. The combination of modern lamination technology and fabrication size capacity now available means glass has great potential for application as a structural material. The simple paradigm of "glass is used for non-structural windows" no longer represents the full extent of its usage. Heroic projects have proven the viability of glass as a structural material, but lack of standards and specifiable design manuals have limited its acceptance by AHJ's and hence its broad spread application on projects.

The Structural Glass Design Manual reflects the unique considerations of glass as a structural material and is a step towards glass achieving a broader acceptance for structural applications. For glass to achieve its full potential, it needs to be readily specifiable by architects, outline common practices and considerations for engineers, and make rational safety provisions for AHJs. The Structural Glass Design Manual aims to advance the available information in all of these areas.

This paper outlines the key aspects of the Structural Glass Design Manual as well as references other papers presented at this conference. Length of a conference paper precludes including all aspects of the Design Manual.

1.1. Structural vs Non-structural

For the purpose of this paper, 'structural glass' is considered to be applications involving an element or system that supports other element(s) or system(s) and/or has consequences of collapse, safety or function in the event of failure other than the cost of repair/replacement. 'Non-structural' describes an element or system that has little or no consequence in the event of failure (other than the cost of repair/replacement.)

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 considers 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 considering 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. A Structural Glass Design Manual has been created to act as a guide for philosophically different design methods, separating infill glass from structurally critical glass applications.

The Structural Glass Design Manual (SGDM) aims for reliability rather than statistically acceptable usage. It assumes that the critical flaw may be at the maximum stress location, thus it will be stress-based design. However, it also will assume that due to inclusions, surface damage, hard-body impact or for whatever other reason, there may be instances in which a glass component performs with capacity much less than anticipated. Much of the SGDM encompasses and encourages promoting good design practices that ensure robustness and safety, should one component of an element fail.

Whereas many other design guides focus on the capacity of the glass prior to fracture, and that is clearly an important part common to this design manual, prior monographs and standards, the degree of robustness that an element should have, and what loads are applicable in a damaged state, has far fewer precedent documents. CEN/TS 19100 incorporates design tests for unfractured state, fracture event and post-fractured state, but (until part 4 is published) lacks guidance on what is required when. It would be easy to simply say that all structural glass needs be fully functional in a cracked state, similar to reinforced concrete or masonry, but to do so would make many common glass assemblies significantly more expensive. It has been noted that glass failure is generally not due to exceedance of load capacity, but is more likely to be due to impact, inclusion or installation error. An extraordinary event is unlikely to coincide with a peak variable design load event, thus in many circumstances it is reasonable to design for less than full loads.

Where the principal causes of failure in glass structures are somewhat independent of design load distribution, the application of load and resistance factors in general cannot control the design of the system to prevent an initial failure. The challenge with applying either load factors based on occupancy alone, such as importance factors in ASCE 7 or reliability factors in EN1990 based on consequence classes, is that once a crack is initiated in monolithic glass, it potentially cleaves full depth of a section and the post-damage capacity can go to zero, irrespective of the probability of failure under design loads. ASCE 7 hints at the problem in table 1.3.1 stating that these are the target probabilities excluding earthquakes, tsunamis ***and extraordinary events***. In this context, glass fracture from causes other than (and often less than) design loads is an extraordinary event. ASCE 7 seismic provisions, ASCE 76 *Standard for Mitigation of Disproportionate Collapse Potential in Buildings and Other Structures* and

EN 1991-1-7 *Accidental Actions* all hint at the need for special detailing to control risk of disproportionate consequence and suggest reduced environmental loads associated with/following rare, extraordinary events.

What is required is a reasonable amount of load for a reasonable amount of time, with a reasonable level of damage with an acceptable outcome. While some cases are reasonably evident, the matrix of possibilities is complex and requires sound judgement as to when requirements or restrictions should apply. The Structural Glass Design Manual is intended expand on the principles of suitable risk through control of vulnerability suitable to the occupancy to provide guidance on robustness of the system using retention, redundancy and residual capacity in the context of glass design.

1.2. Design Manual Structure

Unlike countries and unions with centralized standards bodies with consistent formats, the United States have standards prepared by many industry organizations with many formats. As the material that glass most commonly interacts with -- aluminium, steel, stainless steel, and cold-formed steel -- have standards that use a common chapter format, it makes sense for the glass design guide to do the same.

Table 1: SGDM Chapter Structure.

Structural Glass Design Manual - Table of Contents	
Glossary	
A.	GENERAL PROVISIONS
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	A.3 Reference Specifications Codes and Standards
	A.4 Materials
	A.5 Professional Use and Limitations
B.	DESIGN REQUIREMENTS
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	B.2 Design Basis
	B.3 System Categorization
	B.4 Loads and Load Combinations
	B.5 Material Properties
	B.6 Design Strength of Glass
C.	DESIGN FOR STABILITY AND DIRECT ANALYSIS
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	C.2 Calculation of Required Strengths
	C.3 Calculation of Available Strengths
	C.4 Braces
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D.2 Principal Tensile Stress Capacity

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F.3 Moment Capacity of Imperfect Beams in Strong Axis Bending

F.4 Elastic Critical Buckling Moment

G. DESIGN OF MEMBERS FOR SHEAR

G.1 Shear Strength

G.2 Shear Stability

G.3 Torsional Shear

H. DESIGN OF MEMBERS FOR COMBINED AXIAL AND FLEXURAL FORCES

H.1 for $P/P_{cr} \leq 0.15$ and $M_x/M_{cr} \leq 0.4$, the following condition is adequate:

H.2 for $P/P_{cr} \leq 0.15$ and $M_x/M_{cr} > 0.4$, the following condition is adequate:

H.3 If $P / P_{cr} > 0.15$ or $M_x/M_{cr} > 0.4$

I. DESIGN OF COMPOSITE MEMBERS

I.1 Introduction

I.2 Extended Enhanced Effective Thickness (EEET)

J. CONNECTIONS

J.1 General

J.2 Methods of Analysis

J.3 Empirical/Proprietary Data

J.4 Justification by Testing

J.5 Justification by Rational Analysis

J.6 Countersunk Holes for Transfer of Out-of-Plane Loads

J.7 Isolation of In-Plane Loads

J.8 In-Plane Bearing Holes Through Glass

J.9 Friction Type Connections

J.10 Adhesives

K. Compatibility

K.1 Deformation compatibility

L. USE OF TEST DATA FOR DESIGN

L.1 GENERAL

L.2 PROOF TESTING – Validation of Strength

Each chapter is discussed in brief with highlights of the technical principles adopted.

2. A. SCOPE

The Structural Glass Design Manual is intended for glass as a structural material in buildings; it is not intended to replace other standards which have been developed for non-structural applications. In this context, structural means applications in which there is a consequence should the element fail; non-structural refers to elements where there is an acceptable risk should the element fail or fallout. Where the SGDM does not provide guidance within its scope, it provides references to other documents which may be useful for that aspect of application. So, while standards such as ASTM E1300 would continue to govern window glass via methods of statistically acceptable usage, this guide takes an approach more consistent with load and resistance factor design (LRFD) as used by other structural building materials to manage the overall risk, due to design loads and extraordinary events.

3. B. DESIGN REQUIREMENTS

3.1.1. Robustness and Glass Risk Category

One of the greatest challenges for designing with glass is determining what robustness requirements are appropriate in various circumstances. Currently there is a spectrum of design between ASTM E 1300, which has no requirement for post failure characteristics, and ASTM E 2751 for glass walkways, which requires retention, redundancy, and robustness with no further breakage after one critical ply is broken. The design requirements for the SGDM follows the principles of ASCE 76 Standard for Mitigation of Disproportionate Collapse Potential in Buildings and Other Structures, wherein:

$$\text{Risk} = \text{Hazard Likelihood} \times \text{Vulnerability} \times \text{Consequences} \quad (1)$$

In-service conditions follow the usual load demand and capacity approach, and in the post-damage condition the vulnerability is controlled by robustness requirements based on the Glass Risk Category (occupancy and consequence). Robustness requirements range from no requirement to one ply broken with reduced loading or 2 plies broken with reduced loading.

The Glass Risk Category (GRC) follows similar principles to the (Building) Risk Category in ASCE 7 and International Building Code (IBC), however whereas the highest occupancy governs for the whole building in those documents, the GRC applies only to the occupancy in the immediate proximity of the glass and occupancies using the proximity as an egress path. The Building Risk Category in the United States has parallels to the Consequence Classes in EN 1990 with the addition of a lowest category in which occupancy is so low that there is minimal chance of consequence; for example, green houses will not be occupied during peak storm events, thus a US Risk Category II correlates to an EN Consequence Class 1 (CC1); III corelates to CC2; and IV corelates to CC3.

Table B-1: Glass Risk Category Descriptions

Glass Risk Category	Description
G-I	• Glass usage that represents a low risk of injury in event of failure.
G-II	• Glazing and/or glass structures, the failure of which could pose a limited risk of injury because of low probability of proximity, such as residential and low occupancy lobbies. • *Limited detachment of damaged glass is possible in some circumstances.* • *Height of fall may be limited.*
G-III	• Glazing and/or glass structures, located where the failure and dislodgment of glass could pose a significant risk to human life or cause injury, and occupancy is likely in the proximity of the glass. • Glazing and/or glass structures, not included in Glass Risk Category IV, with potential to cause an economic impact and/or disruption of day-to-day civilian life in the event of failure. • Glass immediately adjacent to or part of the emergency egress path of Building Risk Class III or IV, unless otherwise specified as Glass Risk Category IV. • *Damaged glass is generally retained in position and may have reduced post-damage capacity where appropriate.*
G-IV	• Glazing and/or glass structures designated as essential to the performance or use of the facility. • Glass has post-damage capacity and shall continue to serve a specified level of function in a damaged state.

Note: To avoid confusion, the tables and figures are numbered as they are in the design manual.

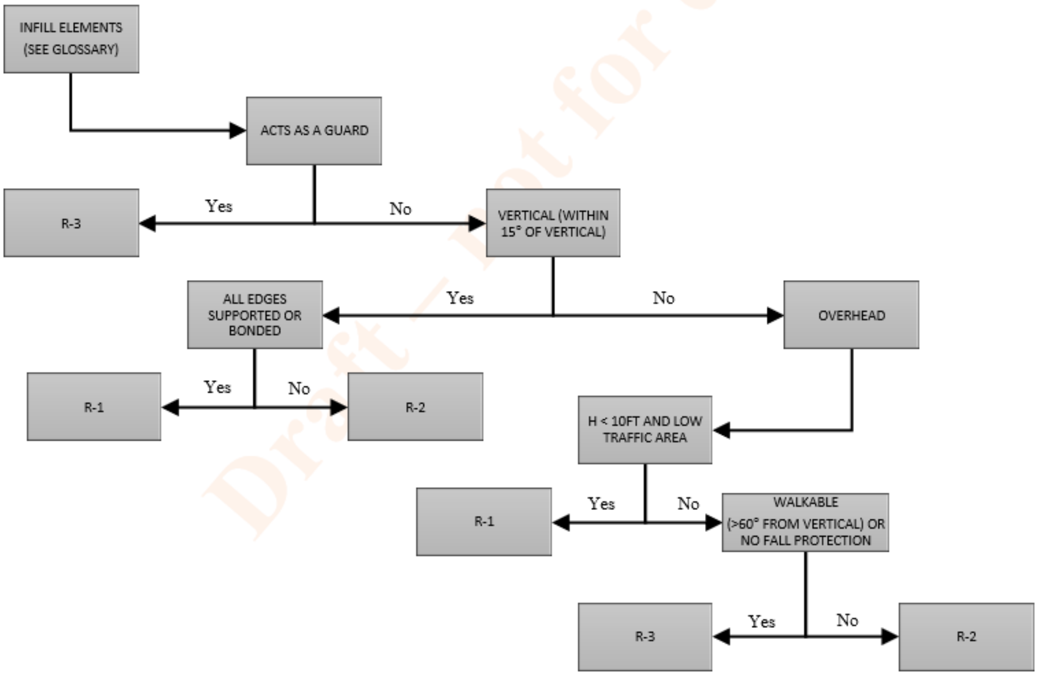
Robustness is determined from a combination of element type, application and Glass Risk Category.

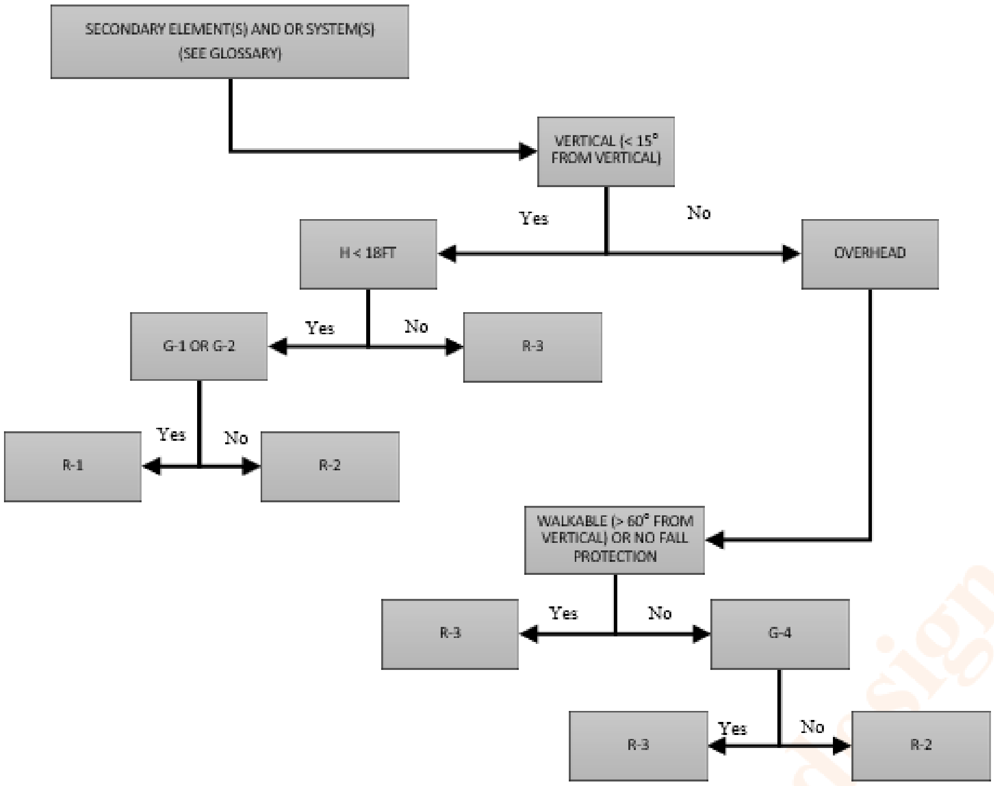
Some definitions:

- System – a group of structural and/or non-structural elements, assemblies, or both, interacting to serve a common purpose, which may include glass, interlayers, assemblies, structural adhesives, reinforcing elements, and connections providing a structural load path.
- infill, n – elements or assemblies that are only required to support themselves and applied loads.
- *Other than those that are part of the primary structural system.*
- secondary, n – a structural element, assembly, or system that is not considered a primary or infill system:
- primary, n – an element, assembly, or system that constitutes one of the following:
- Columns, including glass fins and glass walls which support trafficable roof and/or floor elements;
- Structural members having direct connections to the columns, including glass fins and walls, and are required for stability of the columns;
- Elements, assemblies or systems that support secondary systems and the failure of which would cause the collapse of the secondary system.
- Any Element, assembly, or system which is required to maintain the lateral stability of a structure.
- Bracing member(s) that are essential to the stability of the above elements.

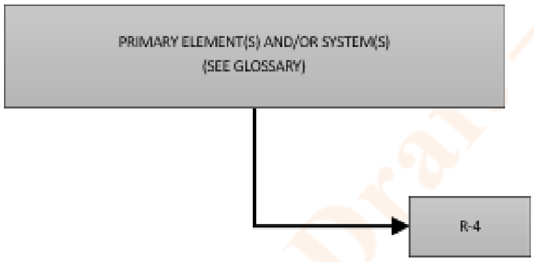
The minimum amount of robustness for each type of element can be determined from flow charts for each element type:

Figure B.1 Flowchart - Robustness Requirements





SECONDARY ELEMENT(S) AND OR SYSTEM(S)
(SEE GLOSSARY)
VERTICAL (< 15°
FROM VERTICAL)
Yes
No
H < 18FT
OVERHEAD
G-1 OR G-2
Yes
No
R-3
R-1
Yes
No
R-2
WALKABLE (> 60° FROM
VERTICAL) OR NO FALL
PROTECTION
R-3
Yes
No
G-4
R-3
Yes
No
R-2



PRIMARY ELEMENT(S) AND/OR SYSTEM(S)
(SEE GLOSSARY)
R-4

Table B-2: Robustness Requirements

	R-1	R-2	R-3	R-4
Design for unbroken condition				
ULS – Ultimate limit State (Strength)	×	×	×	×
SLS – Serviceability Limit State	×	×	×	×
Design for safe breakage (retention)		×	×	×
Design for post-damage (redundancy)			× (1 plies or lite)	× (2 plies)

Each element type has its own set of robustness requirements as a function of the Glass Risk Category, height, orientation, and application. Unlike the Building Risk Category, in which high risk in one area affects the entire building, the Glass Risk Category only affects glass in the proximity of the relevant occupancy or its egress path.

If we take the notion that where glass damage occurs, it is frequently not due to design loads, then risk can be considered in two separate conditions: an in-service condition where the glass is damaged and the risk is a function of the distributions of load and resistance calculated in the usual manner; and a damaged condition where per equation one, since the likelihood is not well defined, either the vulnerability to cause consequence must be low or the consequence must be inherently low due to low occupancy. The suitable outcomes can range from: limited fall height in limited occupancy has limited risk of injury (R-1); through retention in location is sufficient to prevent glass falling and causing injury (R-2); through residual capacity is appropriate to prevent progressive collapse or disruption (R-3); through the system needing to perform a vital function or to prevent structural collapse and consider the rarer event of 2 plies being damaged with residual capacity (R-4). The residual capacity requirements follow the principle of probability of consecutive rare events (and an assumption that damaged structural glass will be repaired) to consider the 'accidental' and 'extraordinary event' load cases for the damaged case.

There is a significant body of assembled work in the range of 12-20ft (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 10ft (3m) height is acceptable without retention and that glass greater than 26ft (8m) high requires retention. For the intermediate range, 10ft to 26ft (3m to 8m) possible compromises included that retention would be at the discretion of the designer if: an AN/HS fin element has continuous structural silicone to one long edge (such that the fragments would be bonded and not fall), or, a fully tempered (FT) glass fin that has been heat-soak tested and is protected from edge impact. For the purpose of simplicity, a nominal height of 18ft (6m) was selected as the transition from Robustness Category R-2 to R-3, which requires checks with one ply broken. A voluntary specification allows some discretion in which those who know the project specifics can set appropriate limits.

3.1.2. Limit States

In addition to the usual strength ultimate limit state (ULS) and serviceability limit state (SLS) the SGDM includes guidance for post-damage limit state and, where appropriate, damage-event limit state. Where possible, the SGDM follows ASCE 7 extraordinary event load combinations whist providing additional information suitable for structural glass design.

3.1.3. Strength Model

Structural glass is used to support a variety of different load types. In order to take advantage of the load distribution information developed for the LRFD loading codes, such as ASCE 7, the limit-state strength model is used. This is consistent with a requirement for reliability, as opposed to statistically acceptable usage, and assumes that there is a flaw at the critical location. ASCE 7 table 1.3.1 sets target reliability indices (β) for different modes of failure. Significantly, the typical probability of failure of 8:1000, which is typically applied to a 50 year mean recurrence interval wind ($8x10^{-3}$ / 50 = $1.6x10^{-4}$ annual probability) is still greater than the $1.25x10^{-4}$ probability target for systems in building risk category I that are not sudden. More importantly, these targets do not cover extraordinary events, and glass is susceptible to failure due to extraordinary events. As a consequence, structural glass must be designed with more conservative stress levels and develop strategies other than reduction of probability of breakage to deal with non-design event fracture. The SGDM uses a target reliability of β=3.5 and uses robustness indices to prevent widespread progression of damage. The strength model adopted is based on peak principal tensile stress and is consistent with similar formulas in EN16612 and CEN/TS 19100. Adjustment factors provided for the strength model are made to achieve other target reliability indices in accordance with the principles in ASCE7 equation C2.3-2, allowing for the different coefficients of variation for annealed (AN), heat-strengthened (HS) and fully Tempered (FT) glass. These are standardized to Glass Risk Category II (G-II), with the recognition that there is correlation between the glass risk category and building risk category and that target reliability adjustments are achieved by load adjustments between the risk categories.

3.1.4. Loads and Load Combinations

Load combinations for the undamaged state are essentially the same as ASCE 7 and International Building Code (IBC), with the addition of a load combination for cleaning snow off rooves with skylights, which was noted by NiOSH/OSHA as a condition that has led to multiple fatalities. Loads for the post-damage conditions are reduced, following the principle of conditional probability that extraordinary damage of a ply is a rare event and that replacement will occur prior to a design loading event, such as a 1 in 50-year wind. Exceptions are cases where the load will always be present (dead load) and where the damage causation event and loading may be synchronous or have critical implications such as live load. The probability of synchronous events is a function of occupancy and is dealt with by having the residual capacity be a function of the Glass Risk Category.

Glass is a time sensitive material and ASCE7 does not specify load durations. Precedent documents have a large range of possible values, for example ASTM E2751 has a 10 minute load duration for live load, but the National Design Standard (NDS) for wood (another time dependent material) considers live load to be 90% of the design load for 10 years. As such, ranges of load durations are suggested, with final selection by the design professional with knowledge of the project specifics. The time effects for load duration are consistent with ASTM E1300 and an added duration of 0.3 seconds for sudden load redistribution during damage events.

Post-Damage Loads are reduced from typical load combinations due to the principle that damage is a rare event and the damaged state has conditional probability. There is a presumption that damage to the glass will be repaired in reasonable time and prior to a peak event.

Post-Damage Residual Capacity Combinations

$$\alpha_D D + \alpha_W W + \alpha_S S + \alpha_{T.} T$$

$$\alpha_D D + \alpha_L L + \alpha_S S + \alpha_{T.} T$$

Table B-3 Post-Damage Load Factors

Load condition	Glass Risk Category			
	G-1	G-2	G-3	G-4
Dead Load: α_D	1.0	1.0	0.9 or 1.2	0.9 or 1.2
Wind Load*: α_W	0	0.2	0.32	0.60
Snow Load: α_S	0	0.25	0.50	1.00
Live Load: α_L				
UDL (vertical)	0.5	0.5	0.5	1.00
Point Load (vertical)	1.00	1.00	1.00	1.00
Guard Load (horizontal)	N/A	0.5	0.5	1.00
Self Straining: α_T	1.00	1.00	1.00	1.00

*Note that in the United States, wind load, W, is a factored limit state load; 0.6W approximately represents the wind load with a 50-year mean recurrence interval for a Risk Category II building.

4. C. DESIGN FOR STABILITY AND DIRECT ANALYSIS

Glass is elastic to the point of brittle fracture, but interlayers are visco-elastic with deflection as a function of time and temperature. Glass is also often used at slenderness ratios that are much greater than typical construction materials. Glass is much stronger in compression than in tension. The usual compression yield failure-based design principles are inadequate for structural glass design. The slenderness makes amplification of imperfections under load, with resulting tensile stress due to minor axis deflection important to design. The lack of ductile yield plateau makes those tensile stresses critical.

The Direct Analysis Method is applicable to glass design with care. As with other structural materials, imperfections can be accounted for by modelling the imperfection explicitly or applying notional loads. Models need to account for P-Δ non-linearity, while P-δ effects may be accounted for within the model or the relevant chapter for the load type.

5. D. DESIGN OF MEMBERS FOR TENSION

Due to the lack of ductility, analysis including local stress concentrations in tension members is critical to the success of this type of member. The strength model has a reduced stress capacity for edges under uniform tension. Guidance is provided for care around holes, re-entrant corners and connections.

6. E. DESIGN OF MEMBERS FOR COMPRESSION

Glass is one of the strongest materials know in compression, but the tensile capacity of a flawed surface is less than 1% of that; so, when looking at compression, the following considerations are important: how the load is applied – non-uniform support may cause deformation of the glass and tension adjacent to the point of application; slenderness and imperfections, compression forces applied to imperfections in slender members can result in significant minor axis deflection and tensile stress at less than the buckling loads. Formulas are provided for determining incremental displacements and associated tensile stresses due to compression forces. Formulas for incremental displacements and resultant stresses are based on the work of Luible (Haldimann et al. 2008).

7. F. DESIGN OF MEMBERS FOR FLEXURE

A separate paper at this conference by Green, Bedon and Galuppi is dedicated to the design of beams and cantilevers including: calculation of Saint Venant torsion stiffness and warping stiffness for both monolithic and laminated sections, effective thickness modelling, continuous elastic restraint from structural silicone, and the effect of imperfections. The use of Kala's equation relating (Euler) critical elastic buckling moment, section properties, elastic stress capacity, and imperfection magnitude allows an analytical process for various levels of imperfection and production/installation specification.

8. G. DESIGN OF MEMBERS FOR SHEAR

While it is extremely rare that shear controls design at a material strength level, significant amounts of commentary are provided regarding tension arising from applied shear loads and the potential for buckling, causing secondary bending and tension stress.

9. H. DESIGN OF MEMBERS FOR COMBINED AXIAL AND FLEXURAL FORCES

The interaction of axial and bending actions on glass members is particularly complex due to the high slenderness that is often used and the limiting being due to resulting tension, rather than the more usual compression yield or crushing.

For systems in which both the axial load and moment is low, simple superposition of stress is considered adequate.

Where axial stress is low and the moment is moderate, then the combined ratios of the amplified tensile stress due to axial load from Chapter E, divided by the tensile stress capacity and the applied moment divided by the moment capacity calculated in Chapter F, are added and compared to unity.

For high load combinations (at the time of writing this is still being validated) the following process is used:

- The design stress capacity for the type of glass is calculated
- The stress demand and amplified imperfections due to axial force are calculated
- The residual stress capacity (glass capacity less tensile stress due to axial actions), and a reduced buckling moment allowing for the axial compression are used as input to calculate the reduced moment capacity using a process similar to Chapter F.
- Where the reduced moment capacity, considering the axial load, is greater than moment demand, then the section is acceptable.

10. I. DESIGN OF COMPOSITE MEMBERS

The Extended Enhanced Effective Thickness Method is presented in detail in a separate paper at this conference by Green, Bedon and Galuppi, which expands on Green et al. 2023. It provides processes for generalizing the laminate sandwich which can be analysed, includes Saint Venant torsional stiffness for stability (as well as proposals being mathematically tested for warping stiffness).

11. J. CONNECTIONS

Connections are one of the most interesting and challenging aspects of glass structures. To attempt to provide prescriptive solutions would potentially limit future innovation in this critical area. One of the philosophies of the Design Manual is to provide multiple paths to problem solving without limiting designs to prescriptive approaches. Multiple paths are offered or suggested: first, empirical/proprietary capacity data; second, testing, and third, rational analysis -- including modelling or relevant formulas. Offering multiple paths promotes innovation and is a valuable resource for practitioners.

The empirical route allows design through past experience and testing, or data developed by proprietary suppliers; it also encourages a process of product certification.

Testing is outlined in Chapter L with options for validation of design by rational analysis (small sample) or design by testing, with requirements to achieve statistical significance (larger sample with variance and confidence intervals.)

Rational analysis is an available option with guiding commentary on areas to be cautious of, particularly when used by engineers who may be less experienced with glass.

Specific guidance is provided for:

- Modelling of laminated glass with out of plane loading at point fixings
  - Concentrated loads: 3-dimensional effects due to out of plane compression of interlayer
  - Contraflexure: local effects on effective thickness due to reverse curvature generating shear at the interlayer that is not fully developed or not favourable.
- Countersunk Holes for Transfer of Out-of-Plane Loads
- Isolation of In-Plane Loads
- In-Plane Bearing Holes Through Glass
  - Stress Concentrations; Fabrication Tolerances; Edge Strength; Bearing
- Friction Type Connections
- Adhesives

12. K. COMPATIBILITY

One of the few analysable design cases that has the potential to fracture multiple plies at once (other than extraordinary events such as vehicular impact or bomb blast, etc.) is a lack of compatibility between the glass structure and the surrounding structure with which it interacts. Glass is very stiff in plane and incompatibility to imposed displacements can generate large forces. The overall guiding principle is that there should be no damage/fracture at ASD (Allowable Stress Design = ~50 year mean recurrence interval) and no collapse or fall out at LRFD (Strength Limit State = 700~1500 year mean recurrence interval.) Maintaining engagement of connections is important, as is isolation of differential movements. Where the load path changes due to displacements, the capacity of the load path under displacement needs to be justified (unless isolated).

13. L. USE OF TEST DATA FOR DESIGN

The testing section is intended to provide general guidance for achieving statistical significance without providing specific test methods. The section follows similar principles to AS1170.0 Appendix B with general guidance and reporting requirements, validation testing for systems otherwise numerically analysed, and prototype testing for achieving statistical significance of adequacy by testing alone.

14. M. DESIGN FOR SERVICEABILITY (Non-Mandatory)

Design for Serviceability is the non-mandatory companion to the Compatibility chapter. In addition to providing guidance on some common displacement limitations, it also has sections on applicable loads, durability, temporary conditions, and ponding considerations.

15. N. OTHER CONSIDERATIONS (Non-Mandatory)

Materials such as steel have companion standards that deal with fabrication tolerances, installation, and quality control. The Design Manual does not attempt to create specifiable standards, rather it highlights the importance of coordination between the design assumptions and the specified fabrication and installation tolerance parameters.

Guidance is also provided regarding durability and maintenance, staining, mechanical abrasion, chemical attack, and moisture effects.

Long term success of all structures is dependent on correct maintenance; thus, sections are dedicated to maintenance manuals and repair and replacement strategy documentation.

16. APPENDICES

Appendix 1 provides non-mandatory guidance on selection of an appropriate Glass Risk Category. Those familiar with ASCE 7 will find the format familiar with similarities to the building risk category based on occupancy, however unlike the building risk category, in which high risk in one area affects the entire building, the Glass Risk Category only affects glass in the proximity of the relevant occupancy or its egress path.

Appendix 2 provides a discussion of why the Design Manual uses limit state design (LRFD) rather than allowable stress design, which is utilized for standards such as ASTM E1300, ASTM E2358, and ASTM E2751.

In short:

- The above standards are based on one predominant load type, whereas the Design Manual considers many load types;
- Standards such as E1300 only deal with load resistance to a probability of breakage for "non-structural" applications, providing statistically acceptable usage at levels of reliability less than other structural materials; the Design Manual targets structural reliability with suitable consideration of if/when damage occurs due to non-design loading in structural applications of consequence.

Appendix 3 is reserved for Advanced Methods of Determining Elastic Critical Buckling Loads of beams and cantilevers, for which there is a separate paper at this conference.

Appendix 4 provides a commentary on why the Design Manual adopts balustrade loadings from international standards such as EN1991, AS/NZS 1170.1, BS 6993, ABNT NBR 6120 etc. rather than ASCE 7. A separate paper is dedicated to this subject at this conference.

Appendix 5 is a list of other useful references and standards.

17. Conclusions

In areas where there is a lack of standards, it is still important to have a document that has a collection of useful criteria that is in a form that is specifiable on a project-by-project basis. The Structural Glass Design Manual is not intended to be a comprehensive standard, however it addresses a number of the challenges to designing structural glass on a voluntary basis by providing 4 consistent levels of risk suitable for different occupancies and risk objectives. It has identified and addressed a number of deficiencies in common practices and existing standards. For some of the more challenging aspects of glass design it has proposed technical solutions.

The Structural Glass Design Manual is a document aimed a promoting the use of glass as a structural material by providing simply specifiable Glass Risk Categories for Architects, design practices for Engineers and robustness categories to promote safe usage for consideration by AHJs as a supplement to the usual code requirements.

At the time of the conference it is anticipated that the Structural Glass Design Manual will be available in final draft format for public comment.

18. Citations and References

ANSI/AISC 360 Specification for Structural Steel Buildings. American Institute of Steel Construction

ASTM E1300–- Standard Practice for Determining Load Resistance of Glass in Buildings, ASTM International. West Conshohocken, PA

ASTM E2751 - Standard Practice for Design and Performance of Supported Laminated Glass Walkways, ASTM International. West Conshohocken, PA

Australian Standard AS1288 Glass in Buildings – Selection and Installation, Standards Australia GPO Box 476 Sydney, NSW 2001 Australia

Bedon, Chiara, Belis, Jan, and Amadio, Claudio (2015). Structural assessment and lateral-torsional buckling design of glass beams restrained by continuous sealant joints. Engineering Structures, 102 (11): 214-229.

Bedon, Chiara (2021). Lateral-torsional buckling (LTB) method for the design of glass fins with continuous lateral restraints at the tensioned edge. Composite Structures, 266: 113790.

CEN/TS 19100-1 Design of glass structures–- Part 1: Basis of design and materials

D'Ambrosio, Gianmaria, and Galuppi, Laura (2020). Enhanced effective thickness model for buckling of LG beams with different boundary conditions. Glass Structures & Engineering, 5(2): 205-210.

EN 16612: Glass in building. Determination of the lateral load resistance of glass panes by calculation

EN 1993-1-1: Eurocode 3: Design of steel structures–- Part 1-1: General rules and rules for buildings

Galuppi, Laura, and Royer-Carfagni, Gianni (2014). Enhanced Effective Thickness of multi-layered laminated glass, Composites: Part B, 64: 202–213.

Galuppi, Laura, and Royer-Carfagni, Gianni (2020). Enhanced Effective Thickness for laminated glass beams and plates under torsion. Engineering Structures, 206: 110077.

Galuppi, Laura, Manara, Giampiero, and Royer-Carfagni, Gianni (2013). Practical expressions for the design of laminated glass. Composites: Part B, 45: 1677–1688.

Green, R., Bedon, C., Galuppi, L.(2023): Design and stability of laminated glass fins with continuous lateral silicone restraint. Glass Structures and Engineering 8(3):1-20 http://dx.doi.org/10.1007/s40940-023-00224-1

Haldimann, M; Luible, A; Overend, M - *Structural Use of Glass* IABSE (2008)

Kala, Zdeněk (2013). Elastic Lateral-Torsional Buckling of Simply Supported Hot-Rolled Steel I-Beams with Random Imperfections. Procedia Engineering 57: 504-514.

NCCI SN-003-EN-EUNCCI: Elastic critical moment for lateral torsional buckling, by Access Steel. https://eurocodes.jrc.ec.europa.eu/doc/WS2008/SN003a-EN-EU.pdf

NCCI SN-006-EN-EUNCCI: Elastic critical moment of Cantilevers, by Access Steel.

Nizich, Adam J, La GReca, Andrea M and Galuppi, Laura. Advances in Effective Thickness For Laminated Glass Structural Design, Facade Tectonics Institute's biennial World Congress, 2022.

Simulia (2022), ABAQUS computer software, v.6.14, Providence, RI, USA.

Strand7 finite element software, R3.1.1, Sydney, NSW, Australia. https://www.strand7.com/

Challenging Glass Conference Proceedings – Volume 9 – June 2024 – Louter, Bos & Belis (Eds.)
International Conference on the Architectural and Structural Application of Glass
Challenging Glass Conference 9 – 19 & 20 June 2024 – TU Delft – The Netherlands

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