Basic structural design considerations and properties of glass and aluminum structures

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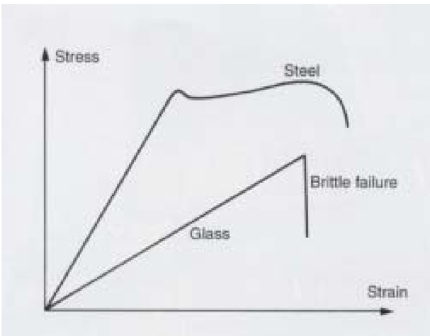
Synopsis

A short review for design consideration of two common materials used in facade and curtain walling is presented. The characteristics of light-weight facade enveloping a building are different from the conventional steel or concrete structures. Glass cannot crack like concrete and it is much more brittle than steel. Aluminum involves many buckling modes similar to but more common than steel. Owing to the low Young modulus of elasticity around 1/3 of steel, buckling and large deflection nonlinear effects are important consideration in their design. This note summaries the most fundamental features of structures made of these materials.

Keywords: glass, aluminum, buckling, structural design, nonlinear analysis, design codes, breakage.

Introduction

Glass is a brittle material that is weak in tension because of its non-crystalline molecular structure. When glass is stressed beyond its strength limit, breakage occurs immediately without warning, unlike steel and aluminum where plastic mechanism can be formed. Stress or moment re-distribution does not occur in glass and local and then consequential global failure is very common in glass. Testing has shown that glass strength is statistical in nature. High**l**y stressed and larger stressed area results in a higher probability of failure.

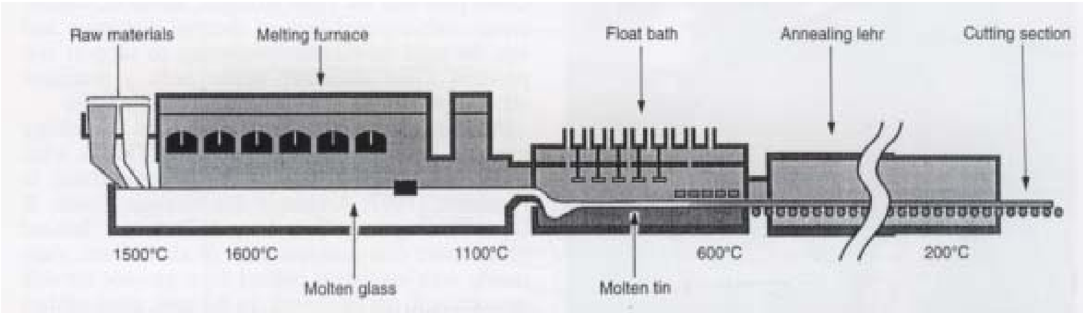


Stress vs strain curves for steel and glass

Damage of glass panels during typhoon

In spite of the structural shortcoming of glass, its use is unavoidable since they are transparent and aesthetic and can be tailor-made in shape and color to suit various architectural purposes. We can see that most award-winning projects overseas contain heavy glass ingredient.

Glass was developed 4000 years ago. In early this century, sheet glass was invented by drawing glass ribbon vertically out of the molten glass pool. It is distorted because of various viscosity of molten glass. In 1959, float glass was introduced. Glass ribbon is pulled through a tin bath and exit on rollers through an annealing lehr where it is cooled. Rolled glass is made by passing molten glass from a furnace through a series of rolls. It is used for wired glass and patterned glass. However, most common glass used to-day is float glass.



The float glass manufacturing process

For conventional glass panels under heat-treatment for strength improvement, structurally they can be classified into 3 groups as annealed, heat-strengthened and tempered glass. As glass is a brittle material that stress cannot be re-distributed and failure is assumed once crack occurs, the failure stress can only be referred as a probability of failure. The following permissible stress will contain a probability of failure of 0.8% for annealed glass. Also, as a brittle material, glass is failed theoretically by tension only and its compressive stress is extremely large. The quoted stress is 800 N/mm^2 (St. Gobain Glass Manufacturer).

MTR entrance in Japan

Damage of high-rise buildings in Hong Kong during visit of typhoon York

Stresses in glass used in various national design codes

Six national codes have been reviewed. They are the U.S.A., U.K., Australia, Canada, China and Japan. In Japan, they normally use the manufacturer data and the code does not provide stress value. In U.K., the Piklkington glass recommendation is used since BS does not provide this value. In Canada , they give detailed stress value. Whilst the charts in U.S.A. are similar to the Canadian one, they are based on the same stress. In Australian and Chinese codes, explicit stress is given. They are tabulated as follows.

Typical properties for glass
Weight = 2500 kg/m^3
Young's modulus of elasticity = 70 kN/mm^2
Shear modulus of elasticity (G) = 30 kN/mm^2
Poisson's ratio = 0.22
Coefficient of thermal expansion = 8.5x10^{-6}/C
Permissible deflection (from Australia standard) = structural span/60
Deflection is very important as complaints are always due
to excessive deflections.

Deflection of glass panels under Design pressure
(Note the reflection)

All units below are in N/mm^2 : t = thickness of glass plate

Glass Type	Canada[1]/ U.S.A[2]	Australian[3]	U.K.[4]	Chinese[5]
Load duration	60 seconds	3 seconds	3 seconds	60 seconds
Load factor	1.5	1.	1.	1.4
Annealed	20/25 (edge/center, following similar)	20	41 for t≤6 34.5 for t≤8 28 for t≤10	28 for 5<t<12 20 for 15<t<19
Heat-strengthened	40/50	32	-	-
Tempered	80/100	50	59	84 for 5<t<12 59 for 15<t<19

1. Canadian General Standards Board (1989), "Structural design of glass for buildings", CAN/CGSB-12.20-M89. The first one refers to centre stress and the second one to edge stress.

2. ASTM (1997), "Standard practice for determining minimum thickness and type of glass required to resist a specified load, E1300-97.

3. Standards Australia (1994), "Glass in buildings – selection and installation".

4. Pilkington Glass (see IStructE, Structural Use of glass in buildings, 1999)

5. "Technical Code for Glass Curtain Wall Engineering", JGJ 102-96, 1996, Beijing, China

NOTE:

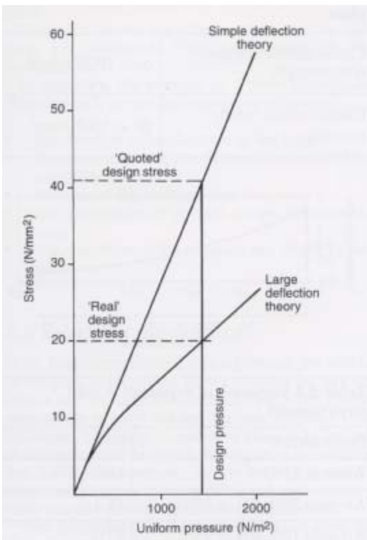
- For 0.8% probability of failure in annealed glass, a design factor of 2.5 is used against the averaged stress. For 0.1% of failure, the design factor is 5. For sloped glazing, the 0.1% failure probability of failure is commonly used.

- Glass strength is time dependent and these countries use different load duration.(e.g. for a 4-side simply supported glass plate, we have $R_t = R_{1\,\text{minute}} t^{-\frac{1}{15}}$ where R is the pressure and t is the load duration.)

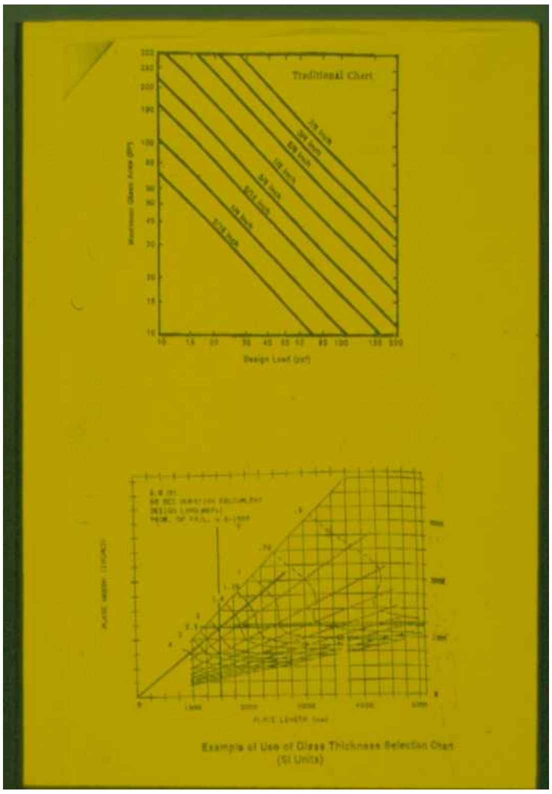
Design procedure for thickness of glass panes

1 Determine the shape and size of glass panes
2 Assume boundary conditions along each side of the glass pane (i.e. point-supports, 4-side, 3-side or 2 side support)
3 Check the supports for the pane are not deforming too much (i.e. they would not deform more than span/180). Otherwise strengthen the support or assume a more conservative boundary conditions.
4 Assess loads and load type. Magnitude and duration of loads are estimated.
5 Compute stress (σ) and deflection (δ) of glass pane by a Nonlinear Finite Element software and check against maximum stress for glass type and glass deflection (see stress for edge or center locations and for short or long term loads in Table above and glass pane deflection should generally be less than structural span/60). Non-linear large deflection theory reflects more accurately the actual behaviour of a glass pane which behaves nonlinearly.
For regular shaped glass panels, design charts are available.
6 Determine glass thickness
7 Detailing against stress concentration, fabrication, water leakage etc.
8 Check practicality and study safety

The reason why nonlinear theory predicts less deflection which is closer to experimental result is due to the membrane action. As the central point deflects, the material on the four sides with less deflection restrains the centre movement and thus the deflection is less. The detailed explanation can be found in the paper by So, Lai and Chan (2002).



Nonlinear Large Deflection and
Linear small deflection theory



The design charts by linear and non-linear analyses
in ASTM (Upper one is linear, lower one is non-linear)

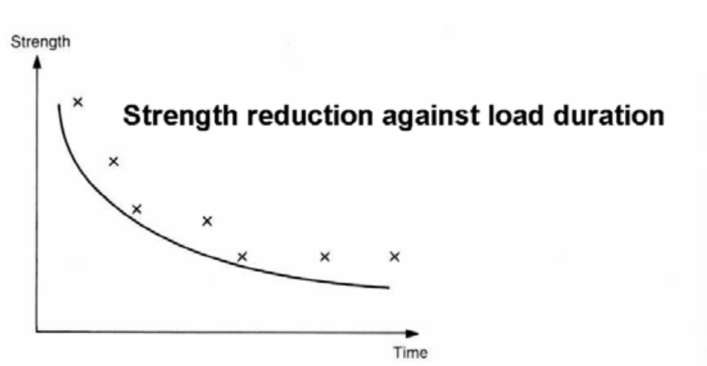
Linear vs. Non-linear analysis

Nonlinear analysis is not popular in Hong Kong, because of at least two main reasons as follows.

1. Nonlinear analysis for frames checks P-δ and P-Δ effects and therefore the related buckling modes will not be missed. Linear analysis produces prediction for higher load resistance as it does not consider all possible buckling modes. Unfortunately, many analysts said angrily" Why I have no problem in designing my structure by my old software and now the structure is detected by a new nonlinear analysis as "unsafe" ? Nonlinear analysis is no good to my project ……. until the following happens but it becomes too late".

2. The users are not familiar with nonlinear analysis at all.

Table 6.1 in Hong Kong Steel Code (similarly for Table5.1 in Eurocode-3) is required for a full and proper second-order analysis. Make sure software allows users to input imperfections to Table 6.1 otherwise its output is not to code safety requirements.



Time dependent nature of glass strength

Breakage

The causes of breakage for glass can be due to (NOT in order of importance):-

- Excessive stress from wind pressure or other loads or insufficient glass thickness
- Thermal stress due to differential temperature on different parts of the pane (For 33^0C, the thermal stress is 20.7 N/mm^2)
- Buckling due to large compression (e.g. glass rod and glass fins)
- Surface or edge damage
- Deep scratches or gouges
- Severe weld splatter
- Windborne missile (i.e. debris impact)
- Direct contact with metal (e.g. window aluminum frame) and
- Impurity inclusion like nickel sulfide – VERY COMMON IN H.K. Heat soak test is a QA procedure though not 100% eliminates the contaminated glass, it is believed to be capable of reducing the breakage by 95% for every hour of heat-soaking.

Excessive deflection

Deflection can be a major consideration in glass design for following reasons.

Aesthetic
Excessive deflection causes discomfort to the occupants and the outsiders who may feel discomfort, fainted or unsecured. This happens in a number of real cases.

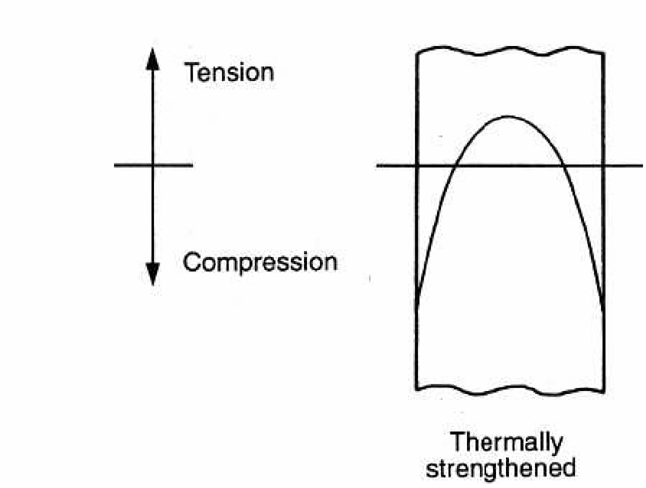
Structural safety
Glass deflection affects the gaskets and sealant and the supporting frame. If not properly considered, glass-to-metal contact may occur and dislodging of gasket takes place. Excessive deflection causes the sealant to stretch. Possible contact with other building material such as those in spandrel. This results in scratching on glass surface.

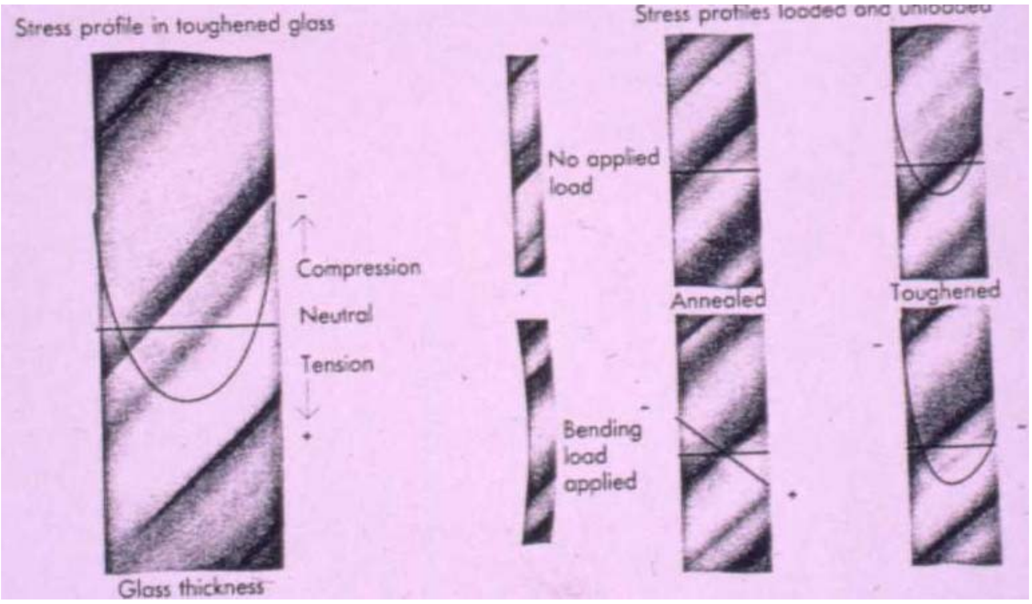
There can be sharp object behind a glass panel
Watch out !

A general requirement for typical glass panes is span/60 suggested in Australian standard.

Tempered glass

In order to provide a larger resistance against tension and to achieve the objective that breakage will not generate sharp pieces for hurting human, an annealed glass (without heat treatment) can be under a heat-treating process. The common process is to first cut the glass to the desired size and then put inside a furnace and heated uniformly to 621^0C. Upon leaving the furnace, the glass is cooled rapidly so that the outer surfaces are under compression and the inner parts are under tension since the formers cool faster. The thickness of the compression zone is about 0.2 of the total thickness and the inner tension zone is about 0.6 of the thickness. The permissible stress is increased 4 times to that of the annealed glass (3 times for some countries where the heat treatment temperature is not that high). The permissible stress is about 50 N/mm^2 under unfactored load.

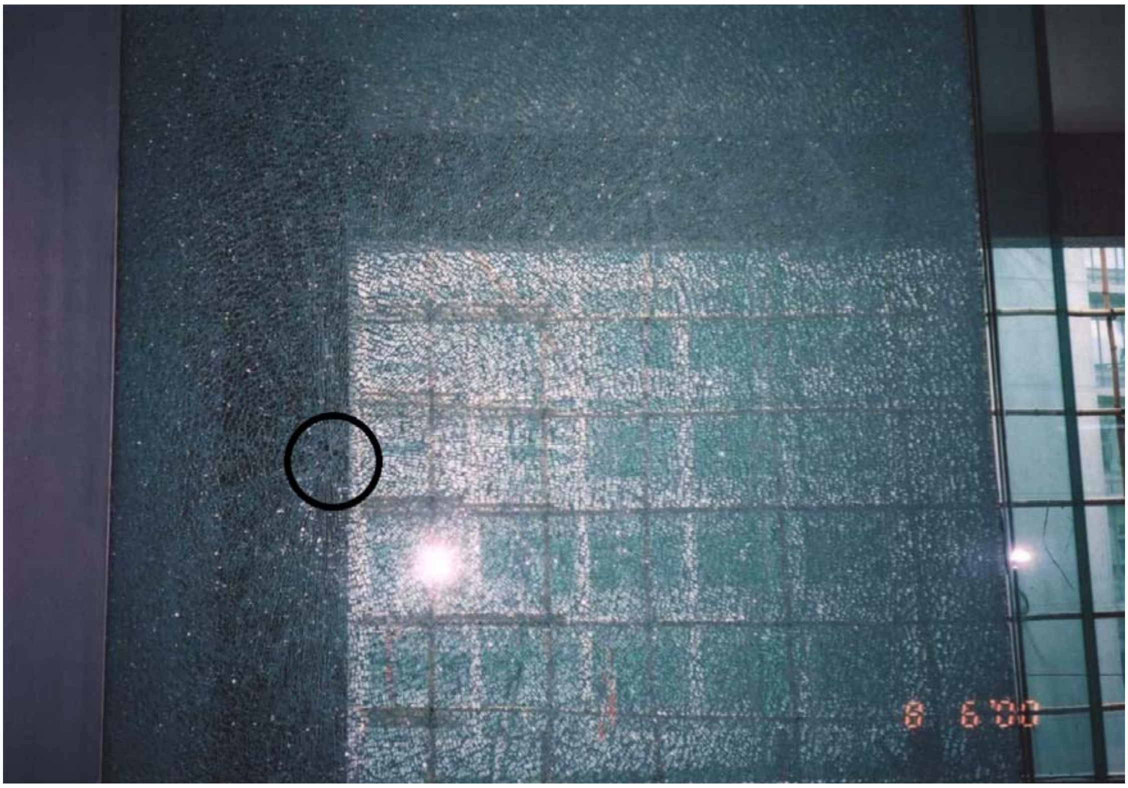




Stress inside glass and after load application

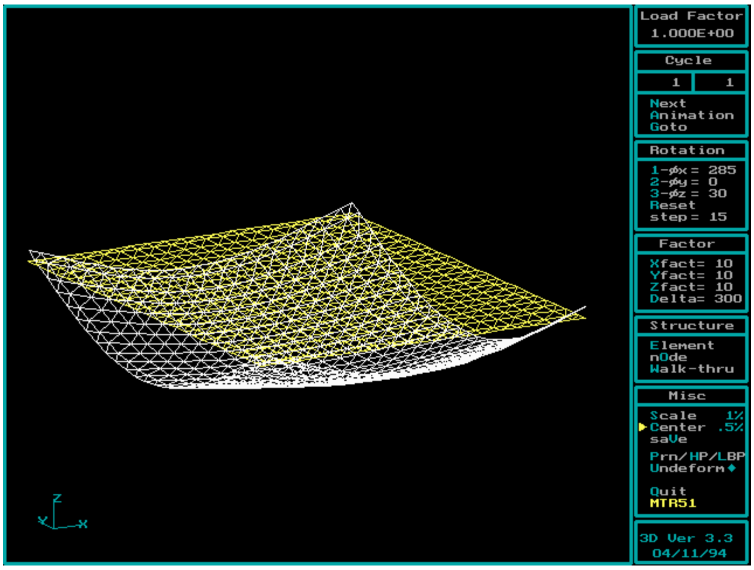
The checking of safety glass was suggested to be carried out by breaking the glass and counting the number of dices. This is an obstructive test and is not strictly applicable to the case for tempered glass which may not be a safety glass. A better test will be using the refractometer of measuring the surface stress. This is a better method since it is non-destructive, can be used to check installed samples and gives a more scientific measurement. The minimum surface stress should not be less than 69N/mm^2 (ASTM C1048-85). Tempered glass has no problem in resisting thermal stress due to sunlight.

One big disadvantage for using tempered glass is the problem of spontaneous breakage due to impurities nickel sulfide (NiS). NiS is formed when nichel-rich contaminants like nichrome wire and stainless steel, are unavoidably introduced into the glass melting furnace and when they are mixed with sulfur, nichel sulfide is formed. They are harmless in annealed glass since the induced stress cannot break the tensile failure stress of glass, but causes instantaneous breakage when they are located at the tension zone of tempered glass and expand with temperature and time. Heat-soak test is an effective procedure to break the glass panels containing NiS in factory rather than after installation. The time and temperature are important in heat-soaking and their requirement varies from one country to another. Buildings Department sets a requirement for the test and further improvement is proposed jointly by the facade group of HKISC and Facade Association which can be downloaded at www.hkisc.org .

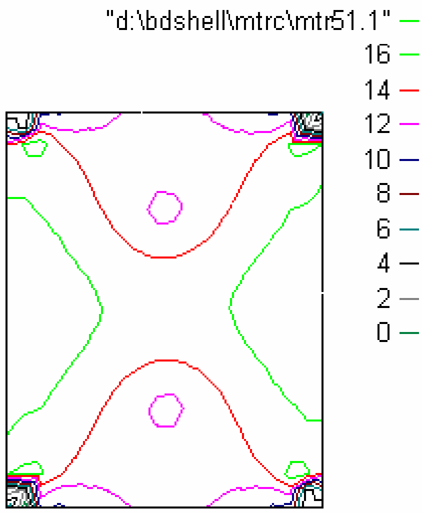


Spontaneous breakage of tempered glass due to NiS
Note the butterfly origin

Glass panels with opening for bolting are tempered glass in order to cater for stress concentration.



Deformed and undeformed shape of a four-point supported
Glass panel by NAF-SHELL



Stress Contour of the Four-point supported glass plate
By NAF-SHELL

Heat-strengthened glass

The surface compressive stress is less than tempered and its strength is normally half of tempered glass or twice of annealed glass (see specification in ASTM C1048). When broken, the break pattern is much larger and about the size of an ash-tray. Recently cases of nickel sulfide were also reported and heat-soak test is therefore required. Its cost is higher since thicker glass panel than tempered glass is needed for the same pressure. Its strength is strong enough to resist thermal stress due to sunlight.

Annealed glass

It refers to those glass panels without heat treatment. The permissible stress is taken approximately as $15N/mm^2$. Sometime we cannot avoid using annealed glass because of manufacturing difficult such as the size of glass panels being too large for heat treatment. Due to the small strength, annealed glass is weak in thermal resistance. Partial shading causes annealed glass to fail by thermal stress. Very often, glass fins are annealed. Try not to use anneal glass under direct partly shaded sunlight.

Broken glass panel due to thermal stress

Tinted glass

Tinted glass or heat-absorbing glass is made by adding colourant to normal clear glass. Light transmittance varies from 14% to 85%, depending on colour and thickness. Because of this nature, the tinted glass is hot and heat-strengthened glass is normally used in making tinted glass.

Coated glass

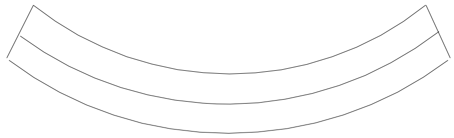
Coated glass is manufactured by placing layers of coating onto the glass surfaces. There are two types, the solar control (reflective) and the low emissivity (low-e) types. They are more related to energy absorption, light transmission and only indirectly affects the structural strength by changing the thermal stress. Because of this, for colored glass to prevent excessive thermal stress, at least heat-strengthened glass should be used.

Wired glass
Wired glass is made by introducing a steel mesh into molten glass during rolling process. It is weak in resisting thermal stress and therefore has a high rate of breakage due to sunlight etc. Polished wired glass is generally used for fire rating since after its breakage, it is stuck to the wire mesh and prevent passage of smoke.

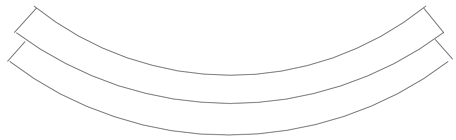
Damaged wired glass in center bays

Laminated glass
This is a very common form of glass formed by bonding two or more glass panes by interlayers like pvb or resin. The thickness of this interlayer is normally 0.38mm, 0.76mm 1.52mm etc. The major problem for laminated glass is the validity of composite action. Can we assume a composite action that, for example, a 8+6mm thick laminated glass equivalent to 14mm thick glass ? If not, does it behave as two separated panes of 8 and 6mm thick ?

The actual response for a laminated glass is somewhere between these two extremes. For short term load, the behavior is closer to composite assumption whilst for long term load, it behaves as a separated panes because of creeping effect in the interlayer. However, as the actual response is dependent on the property of the interlayer and it may not be over-generalized. One method is to use a simple test to measure the deflection of the panel under a specific load and then compare this deflection calculated by a finite element program. We can then adjust the equivalent thickness in the program to give the same deflection so that we can determine the equivalent thickness of the laminated glass pane and use it for economical and rational design. ASTM C1172 is a relevant standard for further information and testing.



Laminated glass with full composite action



Laminated glass without any composite action

Glass staircase

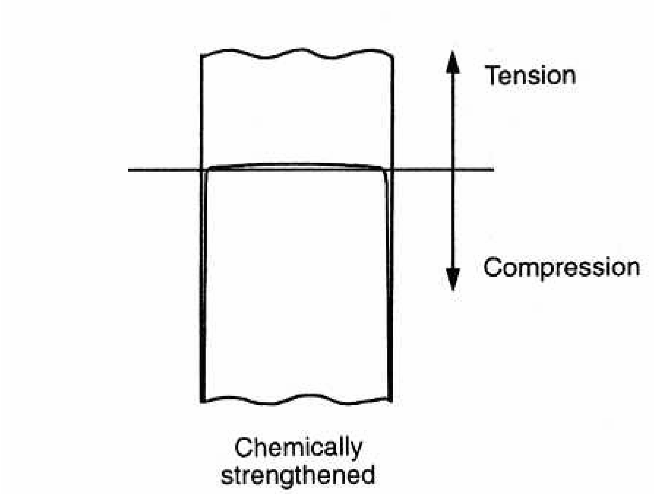
Damaged laminated glass panels at a cover walkway

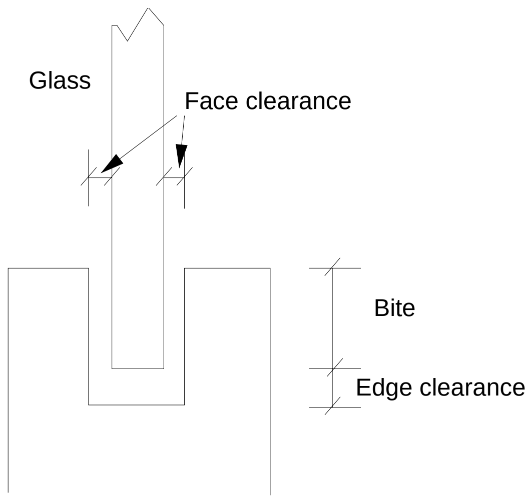
Insulating glass unit

Insulating glass is popular since it insulates sound and heat. They can further be made of reflective and low-e glass. The common form uses edge construction with a metallic spacer of roll-formed aluminum, stainless steel, coated steel or galvanised steel, sealed with polysulfide, polyurethane or hot-melt butyl etc. materials. The air-gap between the two or more panes of glass provide a good insulation. The filled gas can be hexafluoride which is a good sound insulator.

ASTM E773 is a relevant standard for checking the quality of insulating glass.

Chemically strengthened glass
It is seldom used in building industry. The strengthening is carried out by ion-exchange process of submerging glass in a molten salt at temperature below the annealing range of glass. The larger size potassium ions exchange with the smaller size alkali sodium ions. It is used for very thin glass in aeronautical industry (t=3mm).

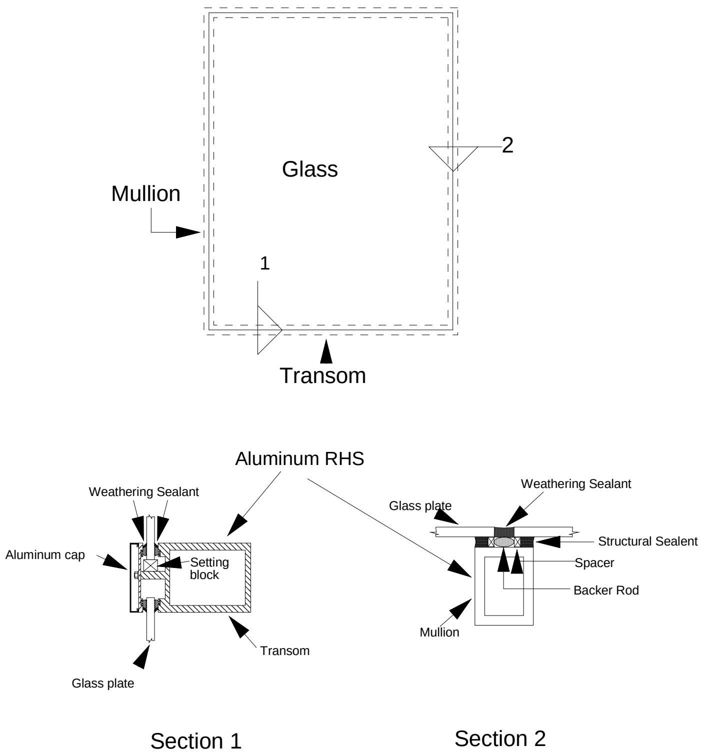




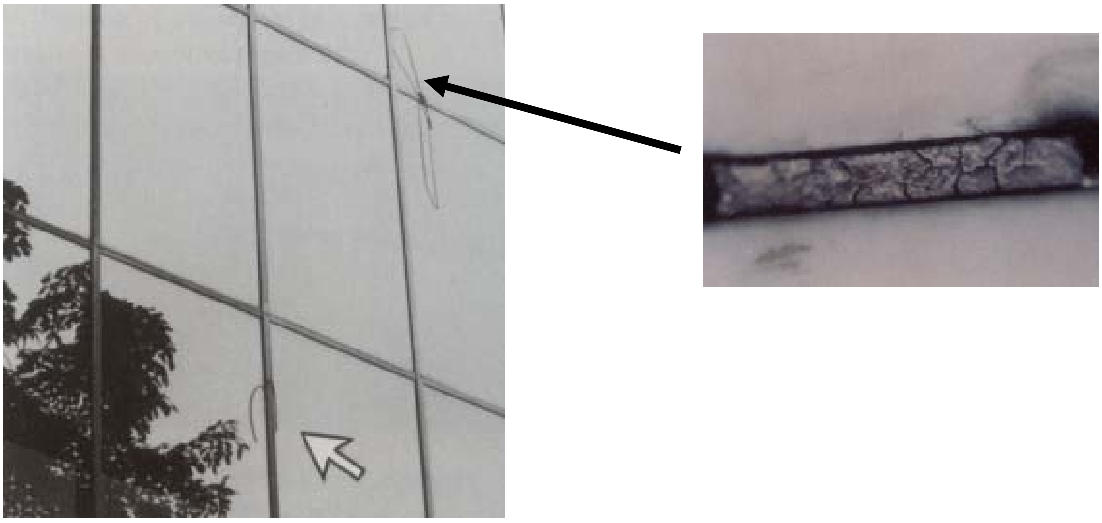
Bit and Clearance

Sealant

Weather sealant is used for prevention of water penetration. Sealant is used for both the purpose of holding structural the glass pane and prevention of water leakage. The structural strength of common type of structural sealant is 138 kPa and it fails at a strain about 25%. The sealant bite is calculated from this permissible stress value and the thickness of sealant is determined from the calculated thermal movement (i.e. too thin will tear the sealant apart during thermal movement). Note that sealant can only take short term load and the stress is reduced to 7 kPa for long term load during the creeping.



Typical 2-side structural glazing system



The glass panes should be designed to “float” onto a supporting frame that metal contact and local bending effects are eliminated.

Common causes of sealant failure

(a) Material factor

Wrong choice of sealant. The usage of unsuitable sealant material for a given substrate.

(b) Quality of installation

Poor workmanship due to lack of skillful labour training.

(c) Joint design

Incorrect type of joint required with respect to dimensions, location, joint spacing related to expected movement, shape and nature of backing material.

(d) Sealant dimension

Improper or inadequate sealant dimension in the joint due to incompatibility.

(e) Sealant manufacturer

Error in quality control or poor formulation.

(I) Applicator or user fault

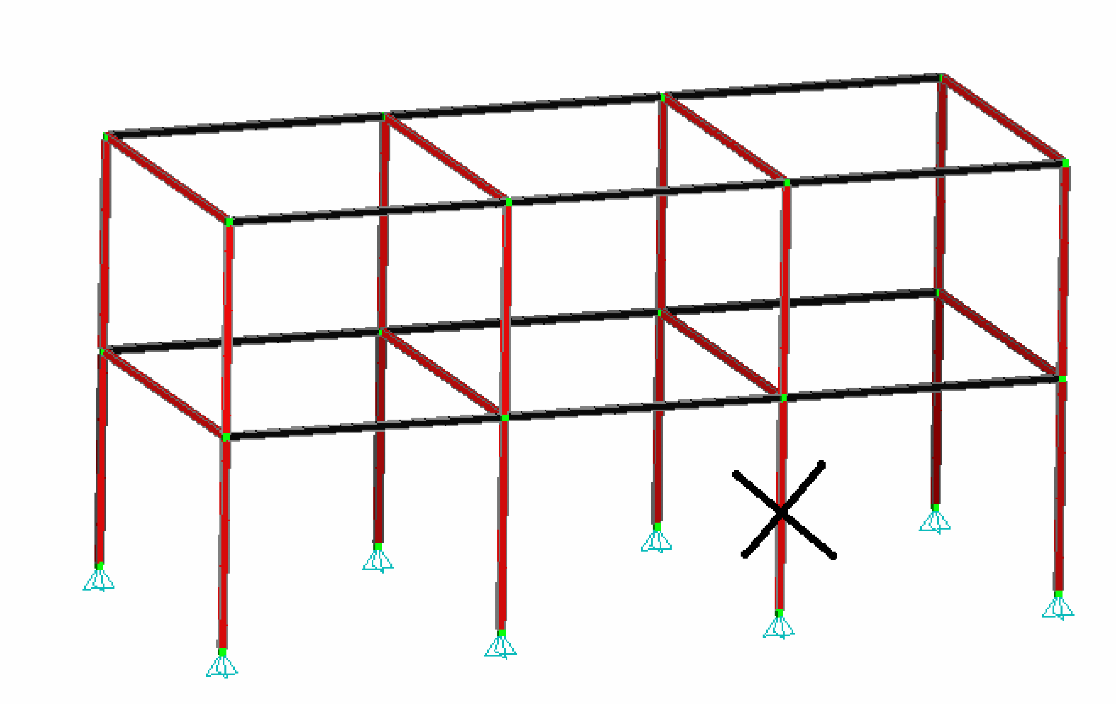
Unable to communicate with the supplier and manufacturer or lack of sealant knowledge properties.

(g) Environmental factor

Ultra-violet, moisture and temperature.

Design concept

Whenever possible consider robustness and progressive collapse under unfactored load or with load factor less than 1 because of probability. One may refer to Code of Practice for Structural Uses of Steel, Hong Kong 2005 for reference of load factors for progressive collapse.

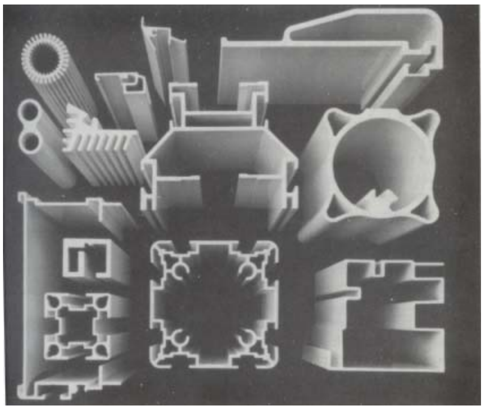


2.3.4.3 *Avoidance of disproportionate collapse*

Steel-framed buildings designed to the Code may be assumed not to be susceptible to disproportionate collapse provided that the following conditions are met.

New requirement in non-proportional collapse in Hong Kong Steel Code (2005)

Aluminum



Most supporting frames for glass are made of aluminum. Aluminum is corrosion resistant and oxide will be coated for exposed surface. Young's modulus of aluminum is 70,000 N/mm^2 which is close to glass. Coefficient of thermal expansion is 23x10^{-6}/^{0}C therefore they are good partners when used together.

Table 4.1 Limiting stresses, heat-treatable alloys

Alloy	Condition	Product	Thickness		Limiting stress		
			Over	Up to and including	p_o	p_a	p_v
			mm	mm	N/mm^2	N/mm^2	N/mm^2
6061	T6	Extrusion	—	150	240	260	145
	T6	Drawn tube	—	6	240	265	145
			6	10	225	260	135
6063	T4	Extrusion	—	150	65	85	40
	T4	Drawn tube	—	10	95	120	60
	T4	Forgings	—	150	80	100	50
	T5	Extrusion	—	25	110	130	65
	T6	Extrusion	—	150	160	175	95
	T6	Drawn tube	—	10	180	190	110
	T6	Forgings	—	150	160	170	95

Aluminum grades commonly used in buildings (BS8118)

Design of aluminum can follow the old allowable stress code CP118 or the new limit state BS8118. The main grades of aluminum used are the Alloy 6063, T-4, T-5 and the T-6 grade aluminum of same Young's modulus but with different proof stress respectively of 110 and 160 N/mm^2. Building aluminum is made of 6xxx series and T represents the tempering process. T6 has a greater strength than T4 which has a greater ductility. Note that aluminum stress is taken as the 0.2% proof stress since it does not have a sharp yield point.

As for all any glass-supporting framework, transoms and mullions supporting a glass panel should not deflect too much to cause additional bending on the glass. The deflection of span/180 or 20mm is generally adopted for this purpose.

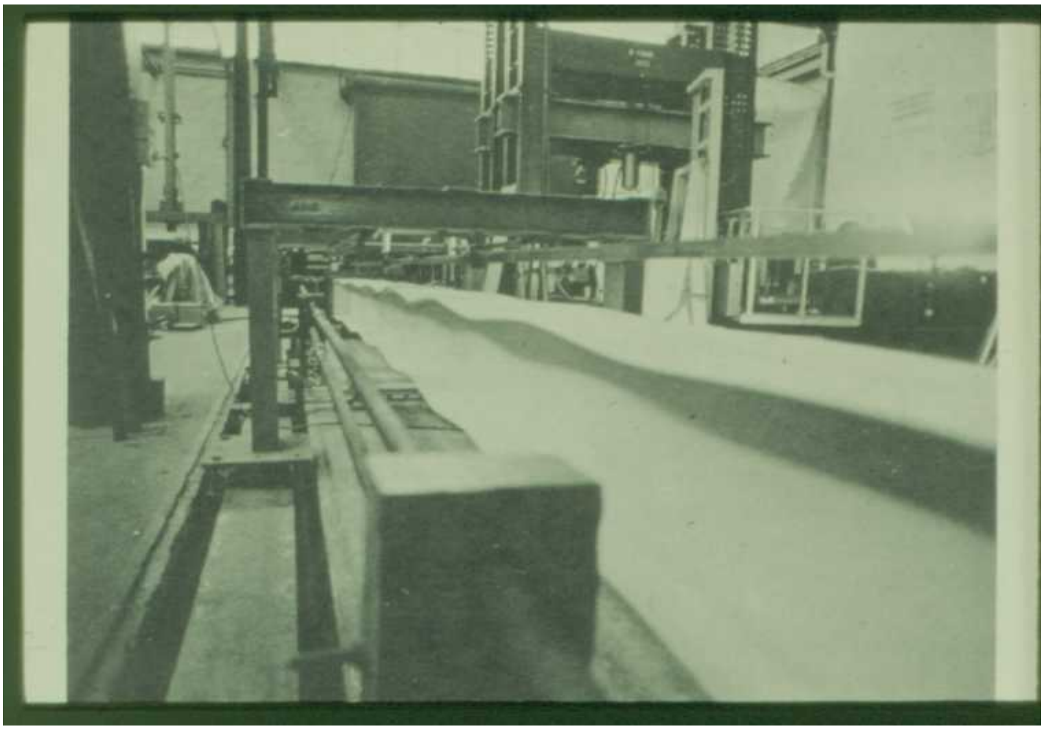
One important checking for aluminum members used in curtain wall is the lateral-torsional buckling. For beams of open section and bent about the major axis, it will have a tendency to buckle laterally when the laterally unrestrained length is long. This is the case for mullions or transoms of curtain wall systems, especially the unitized system where units are pre-fabricated. However, one may argue that glass panel provides a lateral restraint that the unsupported length is zero. On the other hand, some curtain wall consultants do not allow the use of glass panels for lateral support. In reality, the beams is partially supported by glass through **flexible** sealant in lateral direction and this is a subject of further research and studies. Before this, it is more reasonable to carry out the lateral buckling check.

Structural design of aluminum members

Local plate buckling, lateral-torsional and flexural axial buckling are common causes of buckling in aluminum structural members. Conceptually the design is similar to that of steel.

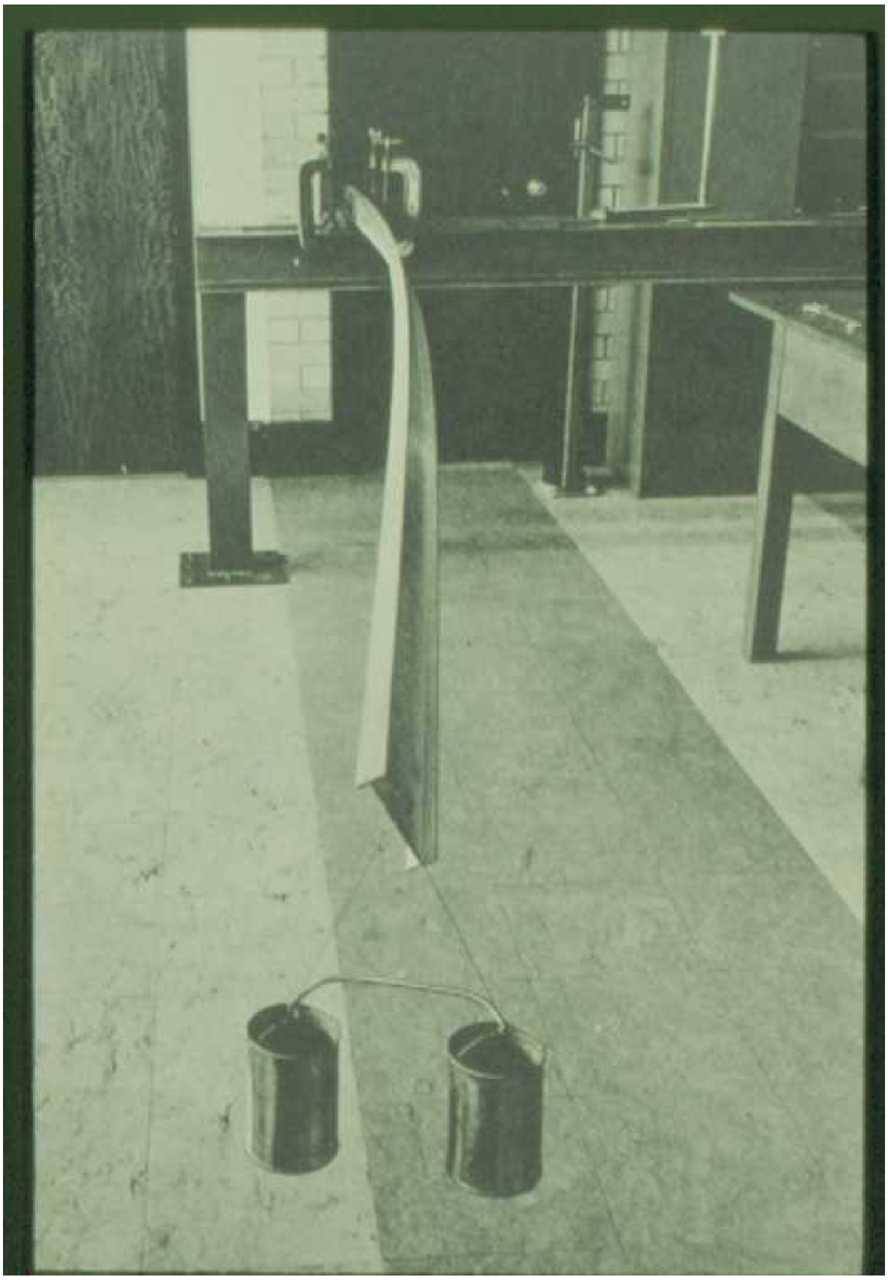
Local buckling check

The factor β is calculated for two modes, being by plate itself or together with reinforcing ribs. In general, it is taken as b/t when under uniform compression in mode 1 or other modified values. For mode 2, β is hb/t where h is a coefficient depending on the size of rib and thickness in Figure 4.4 of BS8118. The largest value of β for all plate elements should be used for classification of section into plastic, compact, semi-compact and slender section. For plastic and compact sections, plastic modulus can be used for finding the plastic moment capacity. For semi-compact sections, the elastic modulus should be used for finding the moment capacity. For slender sections, the coefficient k_L is used to reduce the thickness. A material factor of 1.2 is commonly used but the load factor is lesser than other codes as live load factor is only 1.33 (see Table 3.1 in BS8118).



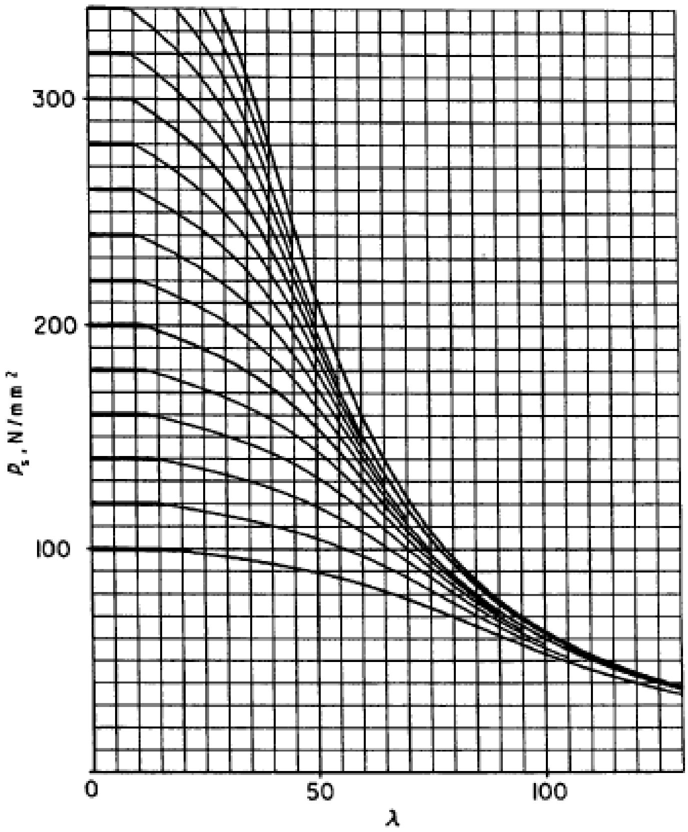
Lateral-torsional buckling

To prevent a beam from buckling in figure below, the slenderness ratio is required as $\lambda = L/r_y$ from which the buckling stress p_s can be found.



Column flexural buckling

When an aluminum column is under axial force, it may buckle before the stress reaching the design strength. The checking is carried out by finding of slenderness ratio L/r and then p_s as follows.



(a)

NOTE. To find p_s at $\lambda > 130$ refer to figure K.1.

Figure 4.10 Column buckling stress p_s for struts

Buckling stress p_s in columns

Torsional buckling

For short thin-walled aluminum under compression, the member may buckle torsionally by twisting. This buckling mode is quite uncommon as aluminium members are normally used as beams in curtain walls and reference should be made to BS8188 for details.

Conclusions

The design method and concept for glass and aluminium structures is reviewed. As the cost of façade occupies a high proportion of the total construction cost, the design of glass and aluminium requires special consideration as the linear theory of analysis and design applicable to design of concrete structures is not valid in many cases. The use of non-linear analysis not only leads to a safer design, but also to a more economical solution as no critical members will be under-designed and redundant members over-designed. Also the nonlinear larger deflection theory utilizes the membrane action that leads to a more accurate and economical prediction of deflection in glass panels.

Acknowledgement

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