GUARDS & BARRIERS 4B
LIMIT STATE DESIGN FOR GLASS & GLAZING

Limit state design is a design methodology for structural elements which considers both the effects of actions and resistance of a material or component to the effects of actions. Limit state design forms the basis or Eurocodes [1], which now forms the basis of structural design throughout Europe, including the UK.

EUROCODES

Despite the harmonization of Eurocodes throughout Europe, the application of Eurocodes to glass and glazing is still not fully in place, with a continued reliance on local regulations. With regards to actions and effects of actions relevant to glass, the Eurocodes provide determinations for;

- Imposed Loads; EN 1991-1-1:2002 [2]
- Wind Loads; EN 1991-1-4:2005 [3]
- Snow Loads, EN 1991-1-3:2003 [4]

With regards to materials; concrete, steel, composite steel and concrete, timber, masonry and aluminium, structures all have individual Eurocode documents, whilst glass does not. Whilst some countries, including Germany (DIN 18008-1:2010-12 [5]), Austria (ÖNORM B 3716-1:2013 [6]) and the Netherlands (NEN 2608:2014 [7]) have adopted Eurocodes into their local regulations concerning glass design, the UK still bases reliance upon BS 6180:2011 [8] with regards glazing design for guarding and barriers. However, this code of practice provides no guidance as to material factors for limit state design.

Due to the lack of UK standards to assist with glass properties with regards glass design, consideration is instead given to existing European standards and draft standards prEN 13474 [9] and prEN 16612 [10] for determining the load resistance of glass panes.

LIMIT STATES

Within limit state design, there are two limit states to consider; ultimate limit state (ULS) and serviceability limit state (SLS).

ULTIMATE LIMIT STATE

The ULS concerns the safety of people and/or the structure. In the case of full height glazing, the glazing is not expected to provide any structural support to the building, and should be considered an infill element. As such, the ULS is only concerned with the safety of people.

Where the glass is under consideration, verification of the ULS is concerned with failure by rupture, i.e. exceeding the strength of the glass and the resultant failure of the material. This is known as the STR ULS, and would be defined with consideration the characteristic strength of glass, appropriately factored as required by the load and installation conditions.

As such, and defined by EN 1990:2002, the design value of the effect of actions must be less than the design value of the corresponding resistance;

$$E_{ULS,d} \leq R_d$$

For glass, the design resistance would be expressed as a maximum ULS allowable stress.

SERVICEABILITY LIMIT STATE

The SLS concerns the comfort of people. With regards to barriers, this would consider the deflection limits provided in BS 6180:2011.

$$E_{SLS,d} \leq C_d$$

VERIFICATION BY THE PARTIAL FACTOR METHOD

The partial factor method incorporates design values for actions, material properties, geometrical data and resistance in order to allow the determination of ULS and SLS.

This document will consider the design methodology from both the action and effect of action, and resistance to action sides. Individual cases are also considered for ULS and SLS conditions.

ACTIONS AND THE EFFECTS OF ACTIONS

Actions that cannot occur together, due to physical restrictions, should not be considered together in combination. In the case of applied loadings (line, concentrated and uniformly distributed) in accordance with BS 6180:2011, this prescribes that all loads cases be treated independently. However, if the potential is there for combined loads then they should not be discounted based purely on this standard.

Design values are obtained using characteristic or representative values, in combination with partial and other factors. The design value of an action (F_d), defined by EN 1990:2002;

$$F_d = \gamma_f F_{rep}$$

$$F_{rep} = \psi F_k$$

Where;	F_k	Characteristic Load
	F_{rep}	Representative Load
	γ_f	Partial Factor – to account for unfavourable deviations of the action values from representative values
	Ψ	Factor for Combination, Frequent or Quasi-Permanent (1.00, Ψ_0, Ψ_1, Ψ_2)

The effect of the action is then determined through calculation, with the stress used for ultimate limit states and deflection for serviceability limit states.

The effect of action should take into account design values of geometrical data (a_d) and partial factors for modelling of the actions (γ_{Sd}). This may include unfavourable deviations with regards to load application positions.

$$E_d = \gamma_{Sd} E\{\gamma_{f,i} F_{rep,i}; a_d\} \quad i \geq 1$$

COMBINED ACTIONS – ULTIMATE LIMIT STATE

For the ULS, critical load cases are defined by a combination of actions that can occur simultaneously. Load combinations incorporate a leading variable action, and any accompanying actions. Consideration must also be given to permanent actions (G). Pre-stressing actions (P) consider pre-stressing of structural members, and as such are typically not relevant for glass.

From the combined load cases, the effect of the actions is generated through calculations or modelling of the structure under the prescribed load conditions;

$$E_{ULS,d} = E(F_{ULS,d})$$

EN 1990:2002 provides 3 expressions for the combination of actions, allowing either;

(6.10): $$E_{ULS,d} = E\{\gamma_{G,j} \cdot G_{k,j} + \gamma_P \cdot P + \gamma_{Q,1} \cdot Q_{k,1} + \textstyle\sum_{i>1}(\gamma_{Q,i} \cdot \psi_{0,i} \cdot Q_{k,i})\} \quad j \geq 1; i \geq 1$$

Or, for STR limit states, the worst case of the following 2 combinations;

(6.10a): $$E_{ULS,d} = E\{\gamma_{G,j} \cdot G_{k,j} + \gamma_P \cdot P + \gamma_{Q,1} \cdot \psi_{0,1} \cdot Q_{k,1} + \textstyle\sum_{i>1}(\gamma_{Q,i} \cdot \psi_{0,i} \cdot Q_{k,i})\} \quad j \geq 1; i \geq 1$$

(6.10b): $$E_{ULS,d} = E\{\xi_j \cdot \gamma_{G,j} \cdot G_{k,j} + \gamma_P \cdot P + \gamma_{Q,1} \cdot Q_{k,1} + \textstyle\sum_{i>1}(\gamma_{Q,i} \cdot \psi_{0,i} \cdot Q_{k,i})\} \quad j \geq 1; i \geq 1$$

COMBINED ACTIONS – SERVICEABILITY LIMIT STATE

For the SLS, as with the UL, critical load cases are defined by a combination of actions that can occur simultaneously, as well as any permanent actions.

From the combined load cases, the effect of the actions, with regards serviceability, is generated through calculations or modelling of the structure under the prescribed load conditions;

$$E_{SLS,d} = E(F_{SLS,d})$$

Eurocode EN 1990:2002 provides load cases relevant for the glazing with regards SLS, and in agreement with the DIN 18008 series of standards, are calculated from the following equation for the characteristic combination

(6.14a): $$E_{SLS,d} = E\{G_{k,j} + P + Q_{k,1} + \textstyle\sum_{i>1}(\psi_{0,i} \cdot Q_{k,i})\} \quad j \geq 1; i \geq 1$$

Under SLS conditions no partial factors are used, only combination (ψ) factors.

PARTIAL FACTORS FOR ACTIONS AND COMBINATIONS OF ACTIONS

Where actions and combinations of actions are under consideration, partial factors should be selected from the appropriate tables within the associated National Annex.

For the UK, the National Annex to EN 1990:2002 [11] provides partial factors where structural members are being designed without consideration to geotechnical actions. The partial factors, as below, are applied to form the design values of actions, shown in Table NA.A1.2(B) of the National Annex.

Table 1 – EN 1990/DIN 18008 Partial factors

Factor	Value
$\gamma_{Gj,sup}$	1.35
$\gamma_{Gj,inf}$	1.00
$\gamma_{Q,1}$	1.50 (0 where favourable)
$\gamma_{Q,i}$	1.50 (0 where favourable)
ξ	0.925

Table 2 – Application of partial factors

Persistent and Transient Design Situations	Permanent Actions		Leading Variable Action	Accompanying Variable Actions	
	Unfavourable	Favourable		Main (If Any)	Others
6.10	$1.35G_{kj,sup}$	$1.00G_{kj,inf}$	$1.5Q_{k,1}$		$1.5\psi_{0,1}Q_{k,1}$
6.10a	$1.35G_{kj,sup}$	$1.00G_{kj,inf}$		$1.5\psi_{0,1}Q_{k,1}$	$1.5\psi_{0,1}Q_{k,1}$
6.10b	$0.925 \times 1.35G_{kj,sup}$	$1.00G_{kj,inf}$	$1.5Q_{k,1}$		$1.5\psi_{0,1}Q_{k,1}$

Ψ VALUES

Values for ψ should be selected from the appropriate tables within the associated National Annex, and are based on the action, occupancy and circumstance. Table NA.A1.1 provides *ψ* values for the UK, as shown below;

Table 3 – EN 1990 ψ values

Action	Occupancy/Circumstance	Ψ_0	Ψ_1	Ψ_2
Imposed Loads (EN 1991-1-1:2002)	Category A: Domestic/Residential	0.7	0.5	0.3
	Category B: Office	0.7	0.5	0.3
	Category C: Congregation	0.7	0.7	0.6
	Category D: Shopping	0.7	0.7	0.6
	Category E: Storage Areas	1.0	0.9	0.8
	Category H: Roofs	0.7	0	0
Snow Loads (EN 1991-1-3:2003)	Altitude H>1000 m Above Sea Level	0.70	0.50	0.20
	Altitude H≤1000 m Above Sea Level	0.50	0.20	0
Wind Loads (EN 1991-1-4:2005)		0.50	0.20	0

However, these values differ from those provided by the DIN 18008 series of standards, and are less conservative. With the DIN 18008 values being better prescribed specifically for glazing, including specific load scenarios not necessarily relevant to other building elements, the following values may be used as *ψ* values;

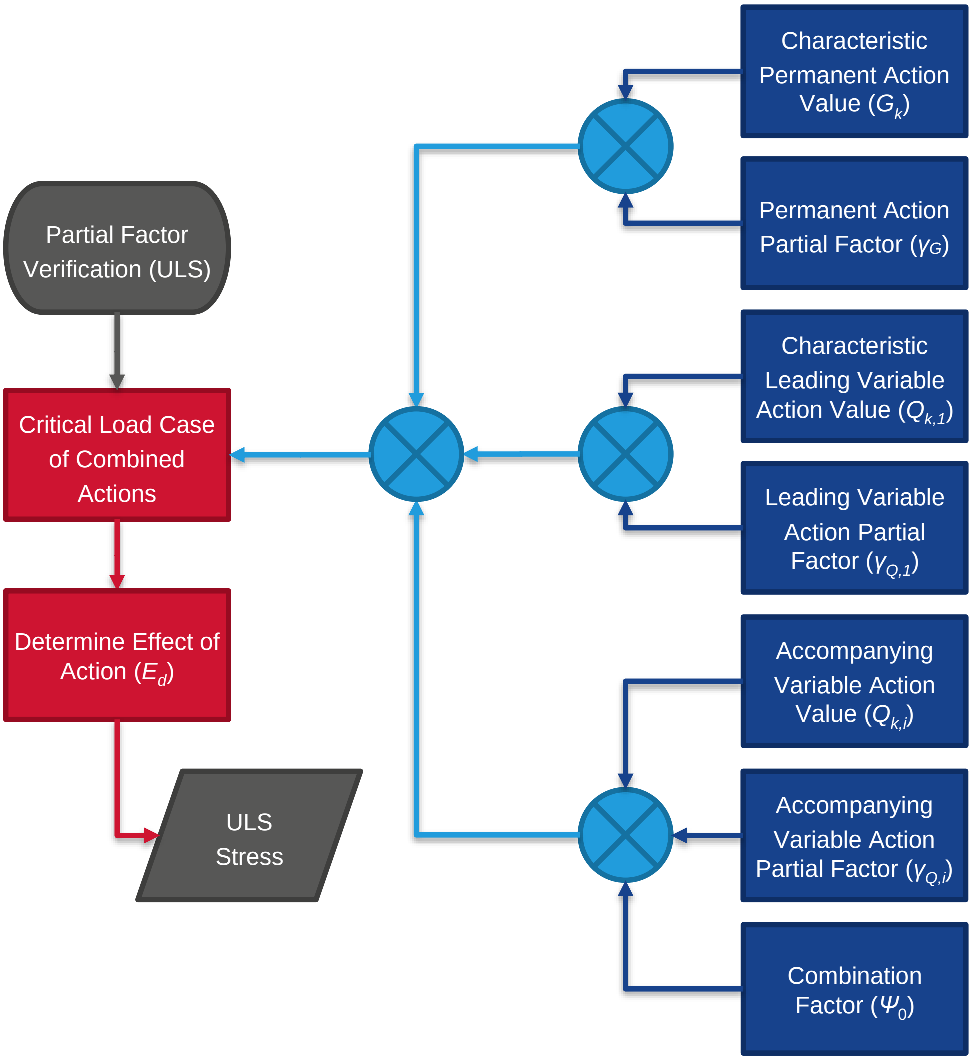
Table 4 – DIN 18008 ψ values

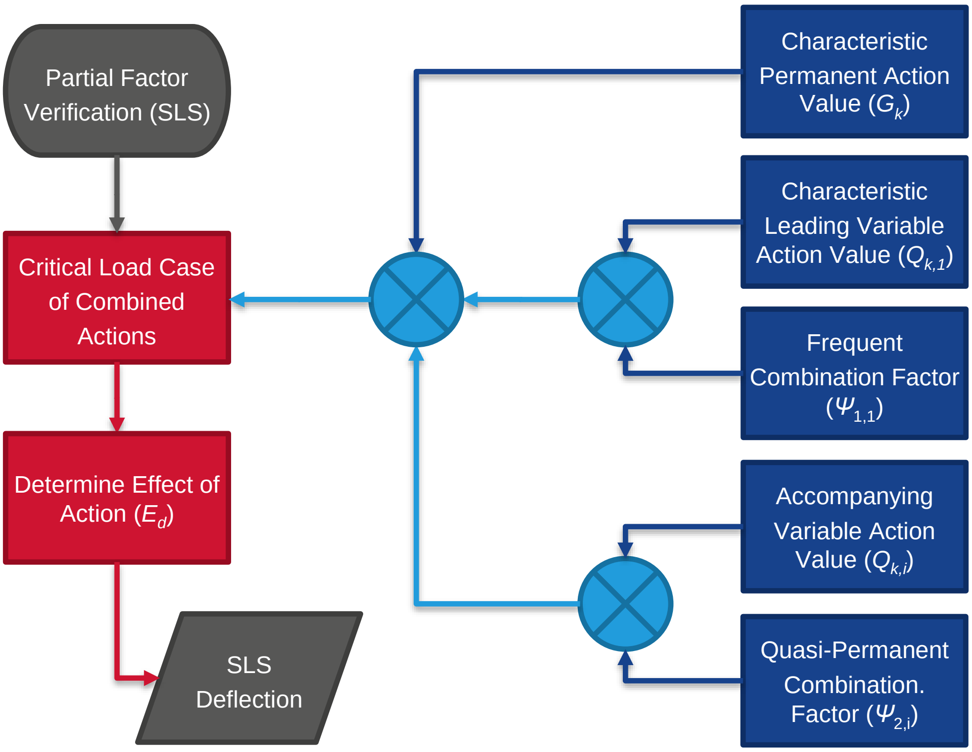
Load Scenario	Ψ
Self-Weight (Dead Load)	1.0
Wind	0.6
Snow	0.5/0.7*
Applied	0.7
Climatic (ΔT,ΔP)	0.6
Climatic (ΔH)	1.0

* 0.5 for altitudes less than 1000 m, 0.7 for altitudes equal to or greater than 1000 m.

DETERMINING EFFECTS OF ACTIONS

The following charts outline the determination of the actions and associated factors for ULS and SLS.





The effects of the actions, as well as being dependant on the combination of actions, will also be dependent upon the glazing construction on which the actions are taking place. As such, the determination of the ULS Stress and SLS Deflection will be dependent on the glass types and thicknesses, which will also influence the resistance to the actions.

RESISTANCE TO THE EFFECTS OF ACTIONS

Where ULS of glass is concerned, the key requirement is that the effect of actions on a material does not exceed the associated resistance;

$$E_{ULS,d} \leq R_d$$

The design resistance, R_d, is a function of the design value of a material and geometrical uncertainties.

$$R_d = \frac{1}{\gamma_{Rd}} R\{X_{d,i}; a_{d,i}\} \quad i \geq 1$$

γ_f Partial Factor – to account for uncertainty in the resistance model, plus geometric uncertainties if not modelled explicitly.

$X_{d,I}$ Design value of material (i) property.

Alternatively, for products made of a single materials, EN 1990:2002 allows the design resistance to be obtained directly from the characteristic value of a material or product resistance, using the following relationship;

$$R_d = \frac{R_k}{\gamma_M}$$

For multi-component materials, such as laminated glass, when modelled using a non-linear method, some finite element methods allow the shear behaviour of the interlayer to be modelled, and as such is incorporated into the determination of calculated stresses.

The key resistance parameter for glass is the stress limitation of the material. In order to determine the resistance of the glazing to the effects of actions (R_d) under ULS, partial factors for the material must be considered.

MATERIAL DESIGN VALUES

The design value, X_d, of a material or product property is defined as;

$$X_d = \eta \frac{X_k}{\gamma_m}$$

Where;	X_k	Characteristic value of material or product property
	γ_m	Partial Factor – to account for unfavourable deviations of material or product property from characteristic values
	η	Mean value of conversion factor taking into account; volume and scale effects, effects of moisture and temperature, other relevant parameters

Eurocodes allow the conversion factor to be taken into account within material characteristics or by utilising a material partial factor that incorporates uncertainties and dimensional variations, γ_M.

The design resistance should take into account design values of geometrical data (a_d) and partial factors for modelling of resistance (γ_{Sd}). In the case of glass, the geometrical design values would be expected to incorporate the allowable unfavourable deviation from nominal thickness of float glass. However, this variance would be incorporated into the γ_M material partial factor.

DESIGN VALUES FOR GLASS

As discussed earlier within this document, no Eurocode currently exists for glass, and as such local regulations and draft standards are commonly used to provide guidance.

For both annealed and thermally treated glass the design value for will be based upon characteristic strength values, an accompanying material partial factors and additional factors based on the glass surface profile and the load duration.

Whilst consideration can be given to all national standards that provide the following information as guidance for Eurocodes, for this document the DIN 18008 series of standards is considered, from which the following formulae can be derived;

Annealed Glass:

$$R_{d;A} = \frac{k_{mod} \cdot k_c \cdot f_{g;k}}{\gamma_{M;A}} \cdot f_{vsg} \cdot f_e$$

Pre-Stressed Glass:

$$R_{d;v} = \frac{f_{g;k}}{\gamma_{M;v}} \cdot f_{vsg}$$

Where;

k_{mod}:	factor for load duration
k_c:	construction coefficient
$f_{g;k}$:	characteristic value of the bending strength of glass
$\gamma_{M;A}$	material partial factor for annealed glass
$\gamma_{M;v}$	material partial factor for pre-stressed glass
f_e:	reduction factor for unsupported edges

Additional factors are also considered for glass within a laminate construction and where a free edge is present (annealed glass only). The laminated glass factor (f_{vsg}) is applied if the Young's modulus is less than the foil stiffness limit for shear, and increases the glass strength by 10%. Where annealed glass has a free edge under tensile stress, the glass strength is reduced to 80%.

CHARACTERISTIC STRENGTH VALUES ($F_{G;K}$)

Characteristic values ($f_{g;k}$) are provided by the various product/conformity standards:

Table 5 – Characteristic strength values

Glass Type		Product Standard	Mechanical Strength (5% Fractile) (N/mm²)
Soda-Lime-Silicate Glass	Float	EN 572-1 [12]	45
	Patterned/Drawn		24
Heat Strengthened Soda-Lime-Silicate Glass	Float	EN 1863-1 [13]	70
	Enamelled		45
	Patterned/Drawn		55
Thermally Toughened Soda-Lime-Silicate Glass	Float	EN 12150-1 [14]	120
	Enamelled		75
	Patterned/Drawn		90

Where a low mechanical strength is unfavourable the characteristic value should be defined as the 5% fractile value, as is the case with the product/conformity standards. This is the case with glass.

LOAD DURATION FACTORS (K_{MOD})

Various national and draft standards provide different values for the load duration factor, k_{mod}, with load durations related to the type of load. For the DIN 18008 series of standards, the k_{mod} only applies to annealed glass, and the values below are used;

Table 6 – Load duration factors

Action	Load Duration	k_{mod}
Wind Load	Short	0.70
Personnel Loads		
Snow	Medium	0.40
Temperature & Pressure Climatic Loads		
Self-Weight	Permanent	0.25
Dead-Weight		
Altitude Climatic Load		

It is likely the case that where multiple loadings are occurring at the same time, that these loadings will have their own durations. DIN 18008 allows for this by the selection of the highest k_{mod} value for determine the glass resistance.

However, all load combinations should be considered, for example, for wind, snow and self-weight;

k_{mod} = 0.70 for wind, snow and self-weight,

k_{mod} = 0.40 for snow and self-weight

k_{mod} = 0.25 for self-weight

MATERIAL PARTIAL FACTORS ($\gamma_{M;A}$ AND $\gamma_{M;V}$)

DIN 18008 provides the following values for the material partial factor;

Table 7 – Din 18008 material partial factor

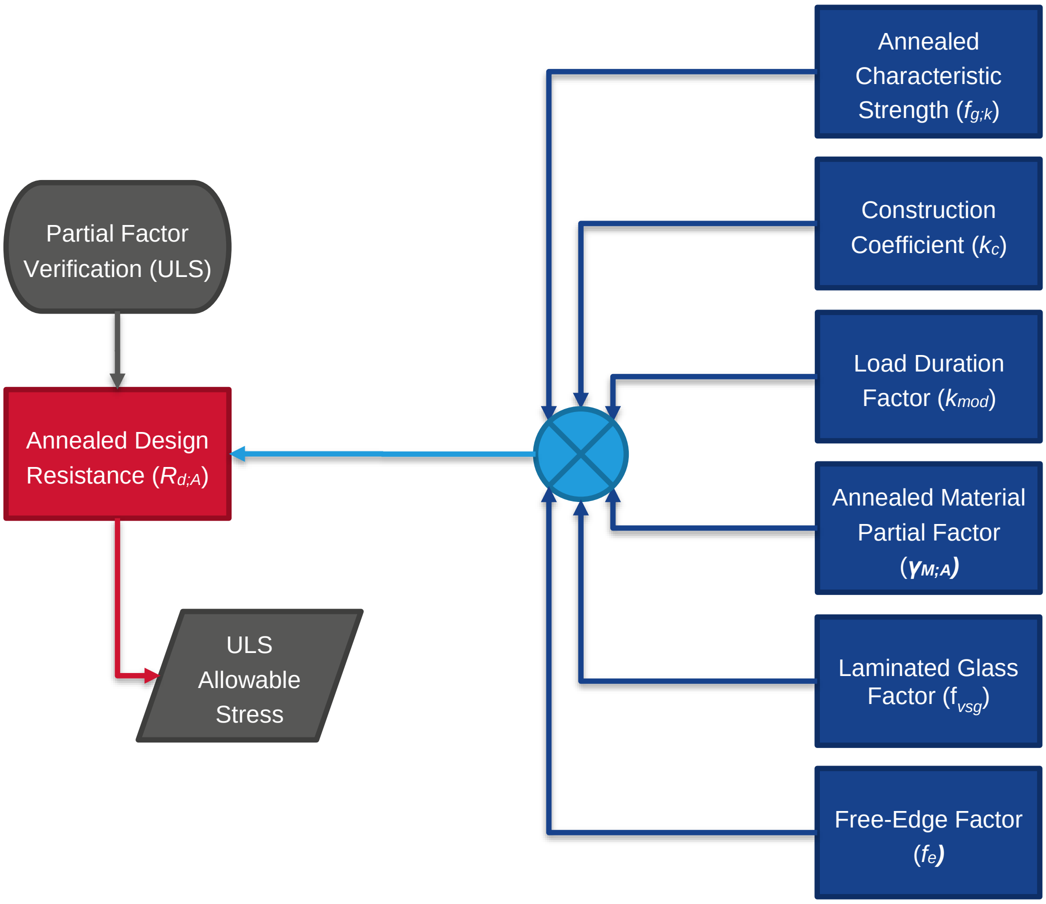
Glass Type	Partial Factor for ULS
Annealed	$\gamma_{M;A} = 1.8$
Pre-Stressed	$\gamma_{M;v} = 1.5$

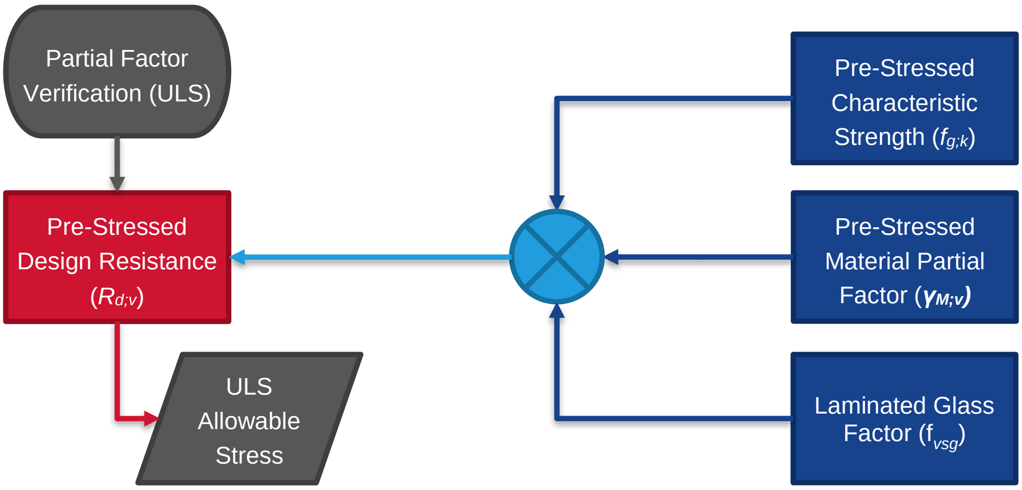
CONSTRUCTION COEFFICIENT (K_C)

The construction coefficient is a consideration for annealed glass only, and if at least two opposite edges are fully line supported, a factor of 1.8 is applied. For pre-stressed glass, k_c is equal to 1.0 in all cases.

DETERMINING RESISTANCE TO THE EFFECTS OF ACTIONS UNDER ULS CONDITIONS

With all appropriate load and material factors, the following outlines the stages to determine the design strength, and the associated resistance for annealed and pre-stressed glass.


Annealed Characteristic Strength ($f_{g;k}$)
Construction Coefficient (k_c)
Load Duration Factor (k_{mod})
Annealed Material Partial Factor ($\gamma_{M;A}$)
Laminated Glass Factor (f_{vsg})
Free-Edge Factor (f_e)
Partial Factor Verification (ULS)
Annealed Design Resistance ($R_{d;A}$)
ULS Allowable Stress


Pre-Stressed Characteristic Strength ($f_{g;k}$)
Pre-Stressed Material Partial Factor ($\gamma_{M;v}$)
Laminated Glass Factor (f_{vsg})
Partial Factor Verification (ULS)
Pre-Stressed Design Resistance ($R_{d;v}$)
ULS Allowable Stress

DETERMINING SERVICEABILITY LIMIT STATE CONDITIONS

The SLS for glass is deflection, not stress. BS 6180:2011 provides guidance on deflection limitations, depending on barrier type. For wind loading, building regulations and codes provide limited guidance, however the lower value of L/65, where L is the longest span, or 50 mm is commonly used as a guideline.

REFERENCES

[1] European Committee for Standardization, *EN 1990:2002 - Basis of structural design,* CEN, 2002.

[2] European Committee for Standardization, *EN 1991-1-1:2002 - Eurocode 1. Actions on structures. General actions. Densities, self-weight, imposed loads for buildings,* CEN, 2002.

[3] European Committee for Standardization, *EN 1991-1-4:2005+A1:2010 - Eurocode 1. Actions on structures. General actions. Wind actions,* CEN, 2005/2010.

[4] European Committee for Standardization, *EN 1991-1-3:2003+A1:2015 - Eurocode 1. Actions on structures. General actions. Snow loads,* CEN, 2003/2015.

[5] Deutsches Institut für Normung, *DIN 18008-1:2010-12 - Glas im Bauwesen - Bemessungs- und Konstruktionsregeln - Teil 1: Begriffe und allgemeine Grundlagen,* Beuth, 2012.

[6] Österreichisches Normungsinstitut, *ÖNORM B 3716-1 - Glas im Bauwesen - Konstruktiver Glasbau - Teil 1: Grundlagen,* Baudatenbank, 2013.

[7] Vlakglas, *NEN 2608:2014 - Vlakglas voor gebouwen - Eisen en bepalingsmethode,* NEN, 2014.

[8] British Standards Institute, *BS 6180:2011 - Barriers in and about buildings. Code of practice,* BSI, 2011.

[9] European Committee for Standardization, *prEN 13474-3:2009 - Glass in building - Determination of the strength of glass panes - Part 3: General method of calculation and determination of strength of glass by testing,* CEN, 2009.

[10] European Committee for Standardization, *prEN 16612:2013 - Glass in Building - Determination of the load resistance of glass panes by calculation and testing,* CEN, 2013.

[11] European Committee for Standardization, *NA to BS EN 1990:2002+A1:2005 - UK National Annex for Eurocode - Basis of structural design,* BSI, 2002.

[12] European Committee for Standardization, *EN 572-1:2012 - Glass in building. Basic soda lime silicate glass products. Definitions and general physical and mechanical properties,* CEN, 2012.

[13] European Committee for Standardization, *EN 1863-1:2011 - Glass in building. Heat strengthened soda lime silicate glass. Definition and description,* CEN, 2011.

[14] European Committee for Standardization, *EN 12150-1:2015 - Glass in building. Thermally toughened soda lime silicate safety glass. Definition and description,* CEN, 2015.