This Technical Note partly supersedes TN13. It describes the different ways in which glass may fracture. It is intended as guidance for those undertaking a detailed study to discover the cause of a failure and any underlying features that predispose the glass to failure.

This Technical Note is one of eight describing the use and performance of glass. They are:

- TN61 Glass types
- TN62 Specification of insulating glass units
- TN63 Glass breakage
- TN65 Thermal fracture of glass
- TN66 Safety and fragility of glazed roofing: guidance on specification
- TN67 Safety and fragility of glazed roofing: testing and assessment
- TN68 Overhead glazing
- TN69 Selection of glass to prevent falls from height

This Technical Note should also be read in conjunction with:

- TN35 Assessing the appearance of glass
- TN38 Acoustic performance of windows
- TN48 U-values of windows
- TN49 U-values of curtain walls

Introduction

The breakage of glass impairs the safety, security and comfort of buildings. Matching and installing replacement panes of glass or glass units can also be expensive. This Technical Note describes the causes of glass breakage and presents measures to minimise its occurrence and diagnose its cause(s).

Breakage characteristics depend on the glass type. Basic (annealed) glass breaks into sharp-edged shards, although these may remain in the frame, depending on the glazing method. Heat strengthened glass breaks in a similar way to basic glass. Thermally toughened glass, when broken, disintegrates into small, relatively blunt particles (‘dice’) that may fall out of the frame, preventing examination of the breakage pattern. With laminated glass the broken panes will remain adhered to the laminate, enabling the breakage pattern to be examined and the cause of breakage to be identified. The characteristics of different glass types are described in CWCT TN61.

Causes of glass breakage

Glass is theoretically very strong but its strength can be variable due to the presence of microscopic defects known as Griffith’s flaws, which cause stress concentrations allowing cracks to start. The intensity of Griffith’s flaws varies according to how the glass has been handled which leads to a variability in strength of the glass.

As a result of this variability glass thickness is selected to give stresses much lower than the theoretical strength. The glass selection charts in BS 6262-3 and in calculation methods are based on these lower stress levels to allow for the unavoidable presence of Griffith’s flaws.

Strength may be further reduced by larger visible defects. However, these are identifiable and the glass can be rejected if visibly flawed or damaged.

The potential causes of breakage of glass are as follows:

- Uniform load,
- Impact,
- Thermal stress.

Breakage of thermally toughened glass may also be caused by nickel sulfide inclusions.
The following factors may cause the glass to fracture at lower loads than those that can be resisted by glass that is undamaged and correctly installed:

- Edge damage,
- Poor glazing,
- Site damage.

Uniform load

The most common form of uniform loading on glass is wind load although other causes such as snow may occur in some situations. The ability of glass to withstand a load is related to the size of the pane and glass thickness. BS 6262-3 and BS 5516-2 give guidance on the selection of glass thickness.

If the glass has been incorrectly selected (i.e. it is not thick enough) or if the peak wind load has been incorrectly assessed, then the glass may deflect too much or not have adequate bending resistance and will ultimately break.

Figure 1 shows the glass fracture pattern due to excessive uniform load on annealed glass or heat strengthened glass. Whilst under low loads the glass may stay in position as shown; at higher loads it may fall from position.

Impact

Glass may break as a result of impact. The impact may be accidental, (e.g. from human collision), or deliberate, (e.g. through vandalism). Breakage may also be caused by thrown or wind borne projectiles (e.g. a pebble flicked up by a lawnmower or gravel blown from roofs).

For basic (annealed) glass and heat-strengthened glass the breakage pattern depends on whether the impact is soft (e.g. human impact), Figure 2, or hard (e.g. small projectile), Figure 3. Very occasionally a soft body impact with a small object such as a tennis ball will cause a punching failure of the glass and a small nearly circular cone of glass will be ejected from the pane of glass. This is known as a Hertzian cone.

When subject to moderate impact the glass may stay in position as shown; at higher impact energies it may fall from position.

Thermally toughened glass will disintegrate into small pieces (dice) when fractured under impact load and may fall from the frame or fixings.

Building Regulations AD N places limitations on the use of glass in locations vulnerable to human impact and BS 6262-4 gives recommendations on the use of glass in areas liable to human impact.

Thermally toughened glass will disintegrate into small pieces (‘dice’) when fractured under uniform load and is likely to fall from the frame or fixings if fracture is caused by imposed load.
Thermal stress

Glass can break as a result of excessive thermal stress. Thermally induced stress within a pane of glass results from a temperature differential between two areas of the pane.

In the UK thermally toughened glass will not fail as a result of thermal stress in conventional architectural usage. It is unlikely that heat-strengthened glass will fail under these conditions.

Nickel sulfide (NiS) inclusions

Glass may contain nickel sulfide impurities, in the form of small crystals which can cause toughened glass to break. As glass is heated during the toughening process these impurities change state. The high temperature $\alpha$-state of the impurities may be 'frozen' when the glass is quenched, and recovery to the low temperature $\beta$-state may then take several years. Spontaneous breakage of the glass may follow, as the low temperature $\beta$-state of the nickel sulfide impurities occupies a slightly greater volume and generates a local stress concentration. However, only the largest impurities will cause failure, and only then if they are in the core (tensile zone) of the glass.

Nickel sulfide failures can start to appear immediately after production, with a peak failure rate usually within four to five years after production, but may even occur 20 to 30 years after production.

Diagnosing NiS failure

Nickel sulfide breakage of glass exhibits a characteristic fracture pattern. However, it is not unusual for toughened glass to fall out of its frame when broken, thereby making it difficult to examine the fracture pattern and identify the origin.

Assuming that the fractured pane remains in place, at the origin of the fracture there should be located two fragments which are larger than the rest and which form a 'figure of eight' or 'butterfly', Figure 5.

This failure pattern is not conclusive proof that the failure was caused by a nickel sulfide inclusion. However, it does indicate that the failure was initiated at the centre of the 'butterfly'. Failure may for instance have been caused by penetration of the surface by a sharp object. To confirm that nickel sulfide is the cause of fracture it is necessary to locate the inclusion which is a small, round, shiny, yellow-black particle which may be as small as 0.05mm damaged (single crack) or clean cut (more than one crack).

The ability of glass to resist thermal fracture is reduced if the glass has poor or damaged edges.
Glass breakage

in diameter. Any particle should be sent for laboratory analysis for confirmation that it is nickel sulfide.

Figure 5 Nickel sulfide failure pattern

The risk of nickel sulfide failure can be reduced by heat-soaking as described in CWCT TN61. Further guidance on nickel sulfide failure and heat-soaking is given in ‘Glass in buildings, Breakage-the influence of nickel sulfide’, CWCT.

Failure of thermally toughened glass

Although thermally toughened glass will disintegrate into small pieces (dice) when fractured it should be noted that the size of fragments will depend on the glass thickness and how the glass is loaded.

Figure 5 shows the commonly assumed failure mode of fracture into small semi-rounded dice. BS EN 12150 sets a limit to the fragment size depending on the glass thickness.

Figure 6 shows the fragmentation pattern observed in a glass fin subjected to in-plane bending at the time of failure. Here the fragments are rectangular with the cracks following the stress trajectories in the unbroken glass.

Thermally toughened glass will always fragment on fracture but the fragments may not separate. In the case of glass falling from height as a result of nickel sulfide induced fracture the fragments can be described as falling in platelets of 200-300mm diameter or more and separating in to separate fragments only on impact with a hard surface such as a floor.

Figure 6 Fracture pattern of thermally toughened glass under a condition of anisotropic stress

Particular issues are associated with curved toughened glass. Susceptibility to breakage can result from a phenomenon of uneven toughening. This is caused by uneven cooling of the hot glass during the bending and toughening process.

Processing of curved glass cannot be carried out on standard flat glass processing equipment and thus special equipment is required. There have been instances where the glass movement during processing has been insufficient. Some types of toughening machine allow the glass to rest on insulated rollers while it is quenched rapidly with air jets to establish the desired residual compressive stress. Where the hot glass lies stationary against the insulated wrapping of the rollers, localised points are not cooled rapidly enough. Low compressive and even tensile stresses may then develop here in the glass surface. The effect may be visible as irregular anisotropy patterns when viewed in polarised light and it can also be measured quantitatively using specialist devices. These stress points have typically been found to be present in affected glass at numerous locations across the surface, typically around 5mm diameter, spaced more or less regularly. The remainder of the glass surface between these tension points has the required surface compressive stress.

In order to avoid the effect, better quality bending and toughening machines continuously move the glass on rollers as it is quenched, and so achieve more even cooling and a surface that is in a state of compression across its whole surface.

Unevenly toughened glass is vulnerable to breakage from even minor surface abrasion that is incident at the points where there is a surface
tensile stress. This can occur under normal service from window cleaning, wind-borne grit and by human contact. Minor scratches and shallow surface impacts that would be of no consequence to properly toughened (or even to basic annealed) glass then cause spontaneous fracture.

Such breakages have often been misdiagnosed as being caused by nickel sulphide. Clues suggesting that uneven toughening may be the cause of failure include the presence of some irregular and large fragments; typically twice as large as would normally be associated with toughened glass. These may be irregular in shape rather than the familiar dice-shaped pieces.

**Edge damage**

Edge damage, which is usually caused by poor handling, can impair the strength of a pane of glass by creating stress concentrations. Edge damage can also occur when cutting glass although this is much less likely to lead to breakage than damage caused by poor handling.

There are no standard acceptance criteria for the edge condition of glass, although glass with edges that are severely feathered or have deep, pointed shells/vents are generally unacceptable, especially in glass types that absorb a high percentage of solar energy. Figure 7 illustrates some edge conditions of glass.

**Poor glazing**

Insufficient clearance between the glass edge and glazing frame may cause the glass to come into contact with the frame as a result of frame movement or glass expansion. This increases the likelihood of breakage, especially if there is localised contact (e.g. with a fixing screw). Insufficient clearance may result from the incorrect sizing of glass, or deviations of size. CWCT TN56 gives guidance on accommodation of structural movement.

Before glazing, the glass should be checked for size against that of the glazing opening. Glass that is wrongly-sized must not be glazed, nor should its size be reduced by nipping or grinding as this could damage the edge of the glass and the seal of IGUs.

The wrong width of setting block may result in uneven support across the bottom of an IGU or piece of laminated glass. In general, the width of setting blocks should be equal to the sum of the glass unit thickness and the back face clearance to guarantee full support across the width of the IGU.

Glass breakage can also arise from setting blocks being too rigid (e.g. very hard nylon) and damaging the edge of the glass; a slightly softer compound would eliminate this risk and may also prevent relative movement between the block and glass unit. Too soft a material may cause the glass to sink into the setting block and cause localised frame contact.

Recommendations on good workmanship in relation to glazing are given in BS 8000: Part 7.

**Site damage**

Spatter from nearby site welding or grinding/cutting operations can cause pitting of the glass surface and in some cases hot metal particles can fuse into the surface, Figure 8.

The embedded metal may subsequently corrode and expand inducing a high, local stress in the glass causing it to crack or shatter.

Even if the glass does not fracture this is unacceptable as the products of corrosion will stain the surface of the glass impairing its appearance and environmental properties.

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Figures:

- Acceptable – clean cut edge
- Acceptable – good edge with little feather
- Just acceptable – severely feathered edge
- Unacceptable – vented edge

Figure 7 Degrees of edge damage
Contamination of glass at site by contact with cements, concrete and mortar can damage the glass surface and glass at risk on site should be protected from other trades until there is less risk of contamination.

**Response to glass breakage**

Glass will often remain in place after breakage and it may be necessary to take action to prevent injury from subsequent falls of glass. This may include:

- Removal of remaining glass
- Removal of glass and boarding up
- Boarding over remaining glass
- Applying a film to the glass
- Screening off areas beneath the glass

Note that applying a film to the glass may increase the hazard if the glass then falls as a blanket rather than as individual pieces of glass.

An appropriate action will firstly ensure the safety of any passers-by and operatives. Secondly it should aim to preserve evidence of the failure mode and fracture pattern.

**Safety**

The risk of any failed glass falling from height should be assessed along with the probability of further glass breakage. Further glass may break due to:

- A repeat of the earlier failure mechanism
- Transfer of load as a result of the earlier failure. For instance a single pane of an IGU carrying the full wind loading.
- Exposure of a pane of glass in an IGU to impact load as a result of the earlier failure.

Glass that can only fall a short distance onto a flat roof presents a lower hazard than glass that may fall directly onto a thoroughfare.

Glass fragments that remain bonded to the frame present little risk in the short term. Glass that has failed as a result of thermal fracture is unlikely to fall from position immediately but should be replaced as soon as possible.

Toughened glass may remain in position following fracture. If such a pane of broken toughened glass is complete and part of an insulating glass unit it will be stabilised by the other pane of glass and the air cushion in the cavity and will have some residual resistance to wind load. However, glass should not be left in this situation and should be replaced as soon as possible as thermal movement will cause the glass fragments to loosen.

If fragments of the toughened glass have fallen from place it is likely that further fragments will fall from the glass at any time.

Laminated glass in which one sheet of glass remains unbroken is unlikely to fall from place in the short term. If all sheets of the laminate are fractured there is a greater risk that the glass may fall from place as a blanket. If the laminated glass is a laminated toughened-toughened construction and if all the sheets of glass are fractured the laminated glass will have little residual strength and may fall as a blanket at any time, Figure 9.

**Diagnosis**

It is important to collect evidence of the failure mode of the glass. Even if this is the first failure experienced on the building and it appears to be of little significance it may be the first of a sequence of similar failures.

It is important to record the failure pattern. This may be done by photograph or sketching and if possible retaining the glass, by attaching an adhesive film to it prior to removal.
The weather conditions may have been a causal factor of the breakage and should also be recorded.

It is also important to inspect the glazing rebate for debris and raised screws and to inspect the edges of the failed glass where possible. For capped systems the proximity of fixing screws to any break should be noted.

Summary

Glass breakage can be prevented by:

- Selecting glass thickness to resist loading;
- Selecting glass type (e.g. annealed, thermally toughened) to resist predicted thermal stress. This is particularly important where thick glass or solar control glass is used;
- Specifying that thermally toughened glass be heat-soaked for installations where glass may fall from height or the replacement cost of the glass is high;
- Handling and storing glass carefully, and ensuring the edges are undamaged;
- Ensuring that the glazing rebate is free of protrusions (e.g. screws) and there is adequate clearance between it and the glass to accommodate expansion and movement;
- Ensuring that the glazing system is appropriate and that pressure plate screws are correctly tightened.

References


BS 6262: Glazing for buildings,

Part 3, 2005, Code of practice for fire, security and windloading,


BS EN 12150-1, 2000, Glass in building - thermally toughened soda lime silicate safety glass – Definition and description.

The following Building Regulations Approved Documents may be accessed at:

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CWCT  
The Studio, Entry Hill, Bath, BA2 5LY

T: +44 (0) 1225 330945  
cwct@cwct.co.uk  
www.cwct.co.uk