University of Bath: Department of Architecture & Civil Engineering

MSc Façade Engineering: AR50247

September 2015

The consequences of panelisation on visual inconsistency of curved glazed façades

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Word count: 19,697

DECLARATION

I hereby declare that my dissertation “**The consequences of panelisation on visual inconsistency of curved glazed façades**” is comprised of my own personal work and research except where mentioned and referenced within the body of the text. A complete list of the references is included.

Neesha Gopal

September 2015

ABSTRACT

Increasingly designers are producing inspirational building images with seamless curved façades. The reality of producing the vision is not easy to achieve with the challenge of providing a visually consistent glazed façade allowing views out and light in with minimal distortion and interference.

This study aimed to identify factors influencing panelisation of curved glazed façades, the subsequent impact on visual consistency and finally how quality may be improved. It illustrated that architectural division/panelisation for a curved façade can be achieved in different ways using both flat and bent glass. Curvature may be formed by: triangulating flat elements; cold bending by forced or laminated methods or hot bending by radial or slump formed processes. Other key influencing parameters include: safety; post breakage failure behavior, thermal and acoustic performances, visual quality, cost and programme requirements.

The study appraised current specification methods and processes for state of the art production of flat and bent glass. This highlighted omissions and inconsistencies in standards/guidelines and inadequate visual assessment criteria. It identified that defects/attributes for different glass and bending types vary and this can lead to visual inconsistency if different types are used simultaneously.

Case study experience was used to illustrate the challenges faced when designing and procuring curved façades. However, the confidentiality of the façade industry was a limitation for the study as information was not readily available for review and certain project information was not permitted to be published. Another difficulty in assessing the inconsistency issue is the very subjective nature of visual assessment as this is not a measurable objective.

Dialogue was therefore carried out with architects, façade consultants, specialist façade contractors, main contractors, clients and glass processors in order to corroborate and reaffirm the issues. This was supported by a pilot survey.

Having identified the potential issues, a preliminary design roadmap was devised. It used hypothetical examples based on key project drivers to illustrate how the risks of visual inconsistency might be identified for different scenarios. This could be used to assist with improved specification due to a better understanding of the characteristics and risks of different glass types and bending methods. Finally, the study and survey informed outline proposals for future investigations and studies to improve the overall specification, production and visual assessment of bent glass and curved glass buildings.

ACKNOWLEDGEMENTS

THANK YOU

My wonderful family for your encouragement and care.

The University of Bath, CWCT, colleagues and friends for your support during my journey through the MSc in Façade Engineering. It has been a great experience and widened my façade horizons.

Dr Stephen Lo for tutoring this study and keeping me positive and encouraging me to go the final distance! Your incredible dedication to the course and the students is truly appreciated.

My colleagues at Meinhardt Façade Technology for their consideration and assistance. Also to Ramboll for their support at the start of the course.

The inspirational façade, design and construction industry for your interest and sharing your knowledge on this fascinating subject – there is still much work to do!

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ABBREVIATIONS

IGU	Insulating glass unit
DGU	Double glazed unit
SGU	Single glazed unit
EVA	Ethylene-vinyl acetate
SGP	SentryGlas® (licensed to Kuraray Co., Ltd)
PVB	Polyvinyl butyral
BS EN	Eurocode - British Annex
CWCT	Centre for Window Cladding Technology
TN	Technical Note
ASTM	American Society of Testing and Materials
GGF	Glass and Glazing Federation
SOTA`	State of the art
A mono	annealed monolithic
A lam	annealed laminated
HS mono	heat strengthened monolithic
HS lam	heat strengthened laminated
FT mono	fully toughened monolithic
FT lam	fully toughened laminated
CA	Curved annealed glass (BF-Bulletin 009/2011)
CTS	Curved thermally toughened safety glass (BF-Bulletin 009/2011)
CHS	Curved heat-strengthened glass
CL `	Curved laminated glass
CLS	Curved laminated safety glass
CIG	Curved insulating glass units
TN	Technical note
CVD	Chemical vapor deposition
MFT	Meinhardt Façade Technology
UK	United Kingdom

NOMENCLATURE

°C	=	degree Celsius
L	=	The width of flat laminated glass (BS EN ISO 12545-5:2011)
H	=	The length of flat laminated glass (BS EN ISO 12545-5:2011)
L	=	The length of curved laminated glass (BS ISO 11485-2:2011)
G	=	The girth of curved laminated glass (BS ISO 11485-2:2011)

d	=	displacement – misalignment at any one edge of the constituent glass panes or plastic glazing sheet material making up the laminated glass. (BS EN ISO 12545-5:2011)
d1	=	displacement – the maximum displacement in the sliding “d1” of one of the glass edges during the manufacturing of curved laminated glass (BS EN ISO 11485-5:2011).
U value	=	measure of heat loss in W/m^2k
g value	=	solar factor is a measure of solar heat gain and is measured between 0 to 1. Lower is less gain

1 INTRODUCTION

1.1 Background to the Study

This purpose of this study was to illustrate that panelisation of curved glazed façades affects visual consistency. It identified potential visual differences between different types of glass and bending methods used. In order to do this current design process and steps influencing panelisation were explained. Specification parameters and production methods were appraised to identify omissions/inconsistencies, risks and key criteria of visual inconsistency. The understanding and identification of visual manifestations was used to assist with the production of a preliminary design roadmap which illustrates how risk of visual inconsistencies might be better managed through an improved understanding of the characteristics of different glass types and bending methods.

The challenge starts at the concept of the project with the image of the seamless curved façade which is a design aspiration that is becoming more familiar. The increase in the use of curvature has been reaffirmed in a number of recent papers “Curved or bent glass units are used more and more often in modern architecture. The curved elements can create flowing contours, organic bodies or bold arch and vault constructions.” (Elstner and Kramer 2012). “In the last years an increase of the number of building projects with built-in curved glass can be observed.” (Neugebauer 2014). This was reiterated by Nelli Diller, Managing Director of Seele, that there has been an increase in the orders for curved façades and curved glazing in the last 5 years. (Diller, N. *(pers.comm.)* 1st July 2015).

Depending on the building use and design intent, the curved façade may be opaque, fully glazed or have a certain area of opaque and vision façade. The materiality of the envelope will influence how the façade is manufactured and constructed. Solid opaque areas may be formed from stone, concrete or plastic for example. These materials can be sculpted, ground, moulded and shaped to meet the visual requirements of the design. These processes do require more thought and come at a cost premium for curved façades compared to flat components, but are not generally considered a prohibitive risk to the success of the project. The glazed façade element is not always such a simple element to resolve and is implemented as allowing natural daylight into a space is considered a key human comfort parameter. Section 11 in BS 8206 states: “In the UK there is no general statutory requirement for a particular daylighting level. However Regulation 8 of the Workplace (Health, Safety and Welfare) Regulations 1992 (as amended) [10] requires that “Every workplace shall have suitable and sufficient lighting” and that this lighting “shall, as far as is reasonably practicable, be by natural light”. The British Council for Offices (BCO) Guide to Lighting recommends an average daylight factor of 2% on a minimum 50% of the floor area as a guide to good practice. This requires the use of transparent materials and so there is the challenge of providing bent glass with optical consistency and views without distortion or optical variances.

Figures1.1 and 1.2 exemplify the complexity of the curvature that can be proposed for a glazed façade. This office building project in Abu Dhabi by Zaha Hadid Architects. It was designed to tender, but not built.

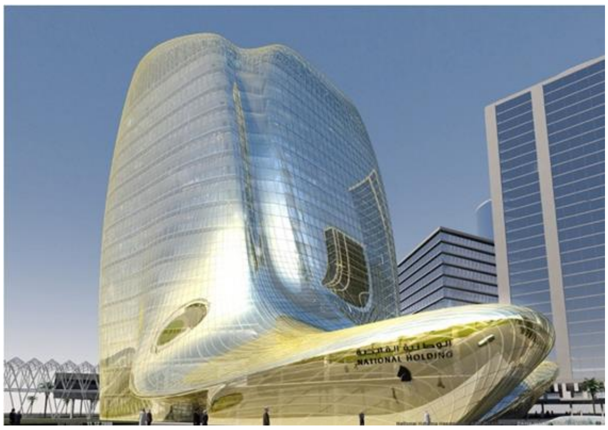


Figure: 1.1 National Holdings Headquarters Building, Abu Dhabi. (Mathematics in industry, 2015)

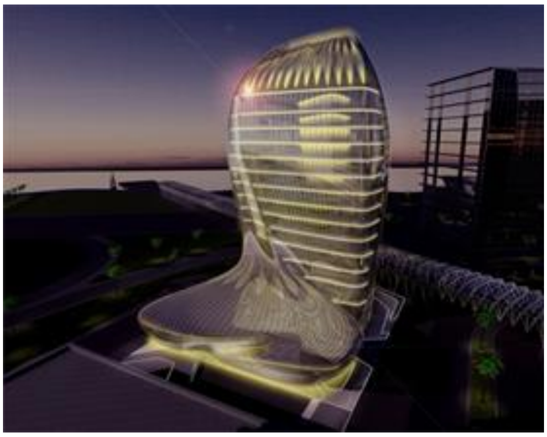


Figure 1.2: National Holdings Headquarters Building, Abu Dhabi. (pjc light studio, 2015)

Improved techniques for understanding the geometry of the panels and how this can be translated into the building components for construction has been essential in achieving these challenging building forms. The curvature needs to be modelled, analysed and measured. Programmes such as Rhino and Grasshopper are often used to form the geometry, also programmes that generate algorithms are now commonly applied and these can have limiting parameters that will influence the curvature and the panel divisions. Figure 1.3 illustrates the initial isocurves the architect proposed to panelise the façade and figure 1.4 the analysis of the offset of the curvature.

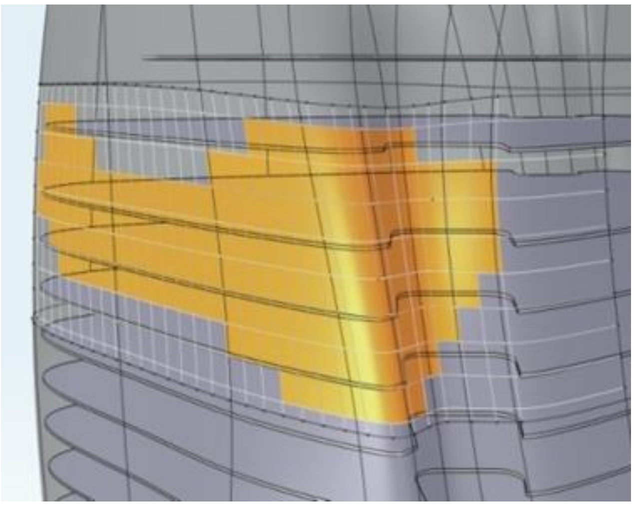


Figure 1.3: Identifying curvature. National Holdings Headquarters Building, Abu Dhabi. (Ramboll, 2009)

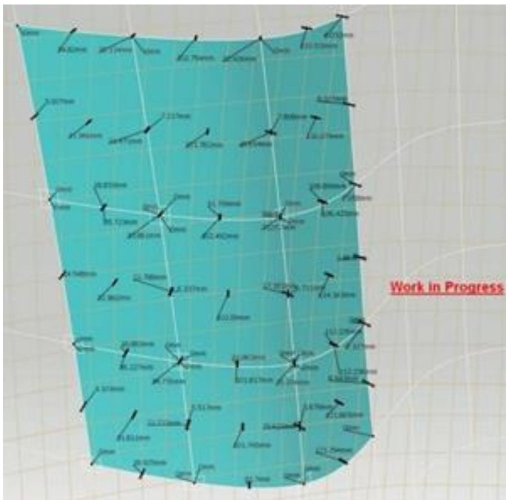


Figure 1.4: Identifying curvature measuring the offset. National Holdings Headquarters Building, Abu Dhabi. (Ramboll, 2009)

Categorising the geometry identifies if the panels are flat or curved. Both can be used to achieve the design intent. 30 St Mary’s Axe is an example where triangulation of flat panels has been successfully adopted to provide a curved façade. Although curvature was not totally avoided as the lense on the apex is a double curved glass element.

Figure 1.5: Triangulated flat glass panels. 30 St. Mary Axe. (The Guardian, 2015)

The type of curvature can be grouped into certain families which for this study are defined as single point, 2 point radial/conical and doubly curved or free form curved. This categorisation informs the most appropriate bending type.

The bending types generally considered for commercial buildings are cold bent using forced or laminated methods or hot bent using radial/conical or free form slumped methods and these methods reaffirmed (Hoenicke, G. *(pers.comm.)* 22 April 2015).

Cold bent glass is derived from flat glass which is bent to moderate curvature due to the limitation of the processes. Hot bent glass is also derived from flat glass but the bending methods are able to achieve more extreme geometries than cold bending. Both types have visual attributes particular to the base glass used and the bending method adopted.

How then can the specification safeguard the desired aesthetic? Is it possible to specify the seamless façade? Although the desired geometry may be possible to manufacture, how visually seamless is the material cladding of the building? In respect of glass clad buildings, what are the limitations and the effect on visual consistency and how can the visual assessment be qualified?

1.2 Objectives

1.2.1 Objectives of the Study

The objectives of this study were to:

- Identify how panelisation of curved glass buildings is informed and facilitated by current building procurement strategy.
- Explain the classification of the geometries used for identifying panelisation.
- Describe the manufacture and processing of glass types and bending methods used for the types of panelisation to understand the potential visual defects/attributes.
- Appraise current specification and standards/guidelines of curved glass buildings and identify omissions and inconsistencies.
- Evaluate selected case studies to illustrate omissions and inconsistencies as a consequence of panelisation and bending types.
- Collate visual manifestations associated with different glass types and bending methods.
- Devise a preliminary road map to assist with the decision making process and improve specification through better understanding of the attributes and defects of different glass and bending types and subsequent risk to visual inconsistency of curved glass buildings.
- Propose potential future improvements that could better inform the specification and reduce visual inconsistency.

1.2.2 Objectives and Research Methodology

The objectives were not all easily researched through desk based literature review due to the confidentiality of the industry. Also acceptable visual consistency of bent glass is a subjective parameter and not documented as a measured boundary. Subjective is defined in the online Oxford English Dictionary, item 4a “Of, relating to, or proceeding from an individual's thoughts, views, etc.; derived from or expressing a person's individuality or idiosyncrasy; not impartial or literal; personal, individual.” And 4b “Existing in the mind only, without anything real to correspond to it; illusory, fanciful.” (Oxford dictionaries, 2015). Consequently, how can visual quality be assessed against a standard or industry accepted benchmark?

It was therefore appropriate to augment the study using an online pilot to those in industry designing, specifying, procuring and constructing. To obtain a representative spread of opinion through the industry, the survey was circulated to architects, façade consultants, glass processors, specialist façade contractors, main contractors and clients. The 64 participants are listed in the references section. However the individual responses were provided as confidential and therefore the overall results only are given in Appendix A.

Item	Objective	Desired output	Research method	Chapter
A	Overview of the design and procurement route for producing curved glazed façade building.	• Identify the stages at which panelisation/repanelisation occur. • Identify factors that may influence the type of bending method.	Desk based literature review. Case study review.	2
B	Review of panelisation methods and classify panel geometry.	• Explain options for panelisation. • Identify panel geometry categories.	Desk based literature review. Case study review. Standards review.	2
C	Identify glass types from which bent glass may be processed.	• To describe the different glass types generally used to establish the current state of the art (SOTA) in bent glass. • To highlight the potential visual defects/attributes associated with the types.	Desk based literature review.	2
D	Classify the range of bending and the methods to achieve them.	• To clarify the terms used to geometrically define the different bending types and their limitations. • Identify visual defects/attributes of the different types.	Desk based literature review. Pilot survey to industry. Meetings with industry specialists. Factory based research – glass processor and façade contractor.	2

Item	Objective	Desired output	Research method	Chapter
E	Identify and review UK/ European glazing standards/ guidance for flat and curved glass.	• Clarify standards/guidance used in current industry SOTA in bent glass production. • Evaluation of current BS EN standards, relevant international standards, professional bodies/ specialists and industry guidance to identify conflicts and potential omissions in specification.	Pilot survey to industry to identify standards used. Desk based standards and guidance review.	2
F	Produce inventory of the potential manifestations associated with hot/cold bent glass methods.	• Summarise the potential consequences associated with the use of different types of bent glass.	Desk based literature review. Pilot survey to industry to reaffirm issues.	2
G	Illustrate potential manifestations. Use case studies to illustrate design methodology for panelisation and procurement and production challenges.	• Relate examples to the manifestations inventory to illustrate the issue of visual inconsistency. • To illustrate the complexity of panelisation options and the potential impact on the visual consistency at design and production stages.	Desk based literature review. Existing images compilation. Desk based case study review.	3
H	Develop preliminary design road map to assist improved specification.	• Example of methodology to inform decision making during the design process, assist with specification and highlight risks of visual inconsistency.	Pilot survey to industry to identify the key issues of visual consistency concern.	4
J	Identify items for future production and specification improvements.	• Identify the key areas where improvements are considered to be needed. • Provide potential research areas that might improve visual consistency in the future.	Pilot survey to industry to identify potential improvements.	5

Table 1.1: Objectives methodology and desired output.

1.2.3 Pilot Survey Summary

The objectives table highlighted the importance of the survey for input into this study. The table below presents the questions administered and indicates which objectives were informed by the survey. The questions and summary of the responses were incorporated in the appropriate sections of the study. Additional participant comments were also included within the context of the study where applicable. The full survey and the responses are provided in Appendix A.

Survey question	Input to objective item	Desired outcome from the question	Presented results
Please indicate awareness / type of experience with the following types of bent glass.	D	To confirm types identified in the study are used.	Graph
Are you aware of potential visual differences between coated glasses comparing flat glass, hot bent glass and cold bent glass?	D	To confirm whether there is an issue to be considered and establish whether industry is aware.	Pie chart
Do you think there are adequate standards and guidance for the specification and visual assessment of bent glass?	E	Validate that there are omissions/inconsistencies and that improved guidance is required.	Pie chart
Have you used any of the following standards/guidance for the specification and visual acceptance criteria for bent glass?	E	Establish current specification state of the art practice.	Graph
HOT BENT GLASS. Have you experienced poor visual quality of curved glass used in buildings due to any of the following for hot bent glass?	F	Input into the list of manifestations that are an issue for bent glass.	Graph
COLD BENT GLASS. Have you experienced poor visual quality of curved glass used in buildings due to any of the following for cold bent glass?	F	Input into the list of manifestations that are an issue for bent glass.	Graph

Survey question	Input to objective item	Desired outcome from the question	Presented results
If you were concerned about the possible visual distortion when using bent glass how would you rate your preference for each of the following possible mitigation measures.	H	Provide understanding of the level of compromise that might be considered during the design process.	Graph
For the following panelisation criteria for the design, specification and procurement of a project with bent glass please rate your level of importance to each of the criteria.	H	Identify the project driver criteria most important from a cost, visual quality and programme perspective.	Graph
HOT BENT GLASS - To optimise the visual quality of hot bent glass how would you rate the importance of each of the following items.	H	Understand which measures are considered most important to optimise the visual quality.	Graph
COLD BENT GLASS - To optimise the visual quality of cold bent glass how would you rate the importance of each of the following items.	H	Understand which measures are considered most important to optimise the visual quality.	Graph
To improve the specification and production of bent glass please rate each of the following items for its level of importance to you.	J	Understand the key criteria considered most important by the different parties involved in design and procurement to improve quality in the future.	Graph

Table 1.2: Survey questions administered and desired outcome.

1.2.4 Boundaries and Limitations

The potential field of study for glass is vast and in order to limit study, the dissertation was related to glass being used in the mainstream commercial building industry as opposed to that being used in the automotive or ship building industries. The following limiting parameters were used to study the consequences of panelisation on the visual inconsistency of curved glazed façades. The black bold text identifies the subject field considered.

Figure 1.6: Limitations applied to study field.

2 DESIGN PROCESS FOR PANELISATION AND THE ASSOCIATED GLASS TYPES AND BENDING METHODS

The purpose of this section was to illustrate the following:

- Example of current building procurement strategy and at which stages panelisation review may occur during the process.
- Methods to categorise panelisation – simple and complex geometries.
- Glass types and processes and visual defects/attributes associated with each.
- Bending methods and visual defects/attributes associated with each.
- Standards and guidance currently used for specification and the identification of omissions and inconsistencies.

The review appraised state of the art production for flat and bent glass by communication with glass processors and façade contractors and visits to production facilities.

2.1 Example of Current Procurement Method with Panelisation Stages

The following key stages of a project were identified and based on experience of involvement with the projects illustrated in the case studies, whilst employed at whitbybird and Ramboll façade engineering. The stages identify when panelisation decisions may be made and the consequences of this on project drivers including cost and programme.

STAGE	PARAMETER	KEY IMPACT
CONCEPT DESIGN	Form/design	• Influences panelisation and individual panel geometry. • Different glass/bending types may cause visual incongruity.
	Cost	• Budget will limit the glass/bending type affordable.
	Programme	• Programme can limit the bending types feasible.
DETAILED DESIGN	Form/design	• Revisit panelisation to rationalise panel geometries for optimising similar types. • Can panel types meet façade performance criteria? • Different glass/bending types may cause visual incongruity.
	Specification	• How to specify glass types to meet the performance criteria for loads, thermal acoustic, post breakage failure requirements and still meet design intent? • Which codes/guidance are relevant? How to identify visual assessment criteria?
	Cost	• Bespoke design is difficult to cost and a risk to the feasibility of the project.

STAGE	PARAMETER	KEY IMPACT
	Programme	• Programme will limit the glass/bending type choice
TENDER	Compliance with design intent	• If the specification is not clear for visual criteria different glass build ups can be proposed for same type bending. • Different glass/bending types may cause visual incongruity.
	Cost	• Unclear specification can allow different glass types/build ups to be priced. Returned tenders are not possible to benchmark.
	Programme	• Different glass/bending types affect programme.
PRODUCTION	Form/ panelisation	• Contractor may re-panelise to meet cost/programme requirements. Different glass/bending types may cause visual incongruity.
	Specification	• Does the glass produced meet the performance specification? Can this be measured in accordance with code/guidance? • Are the tolerances achieved acceptable for visual quality? • How can the visual criteria be assessed in the factory?
	Cost	• If proposed glass is deemed unacceptable visually and the bending type has to be changed, this will impact cost.
	Programme	• Can samples be produced early to assess visual attributes? • If proposed glass is deemed unacceptable visually and the bending type has to be changed, this will impact programme
CONSTRUCTION	Visual criteria	• What is acceptable? Can this be measured in accordance with specification/samples and be backed by codes/guidance?
	Cost	• If the visual acceptance criterion is not clearly defined and the client does not like the appearance of the glass, then the client may have to pay to change it.
	Programme	• Disputes will delay project handover.

Table 2.1: Summary of potential key parameters impacting visual consistency during design and procurement.

The following summary of the design and procurement process highlights the points at which initial panelisation and repanelisation can occur and this can impact the programme.

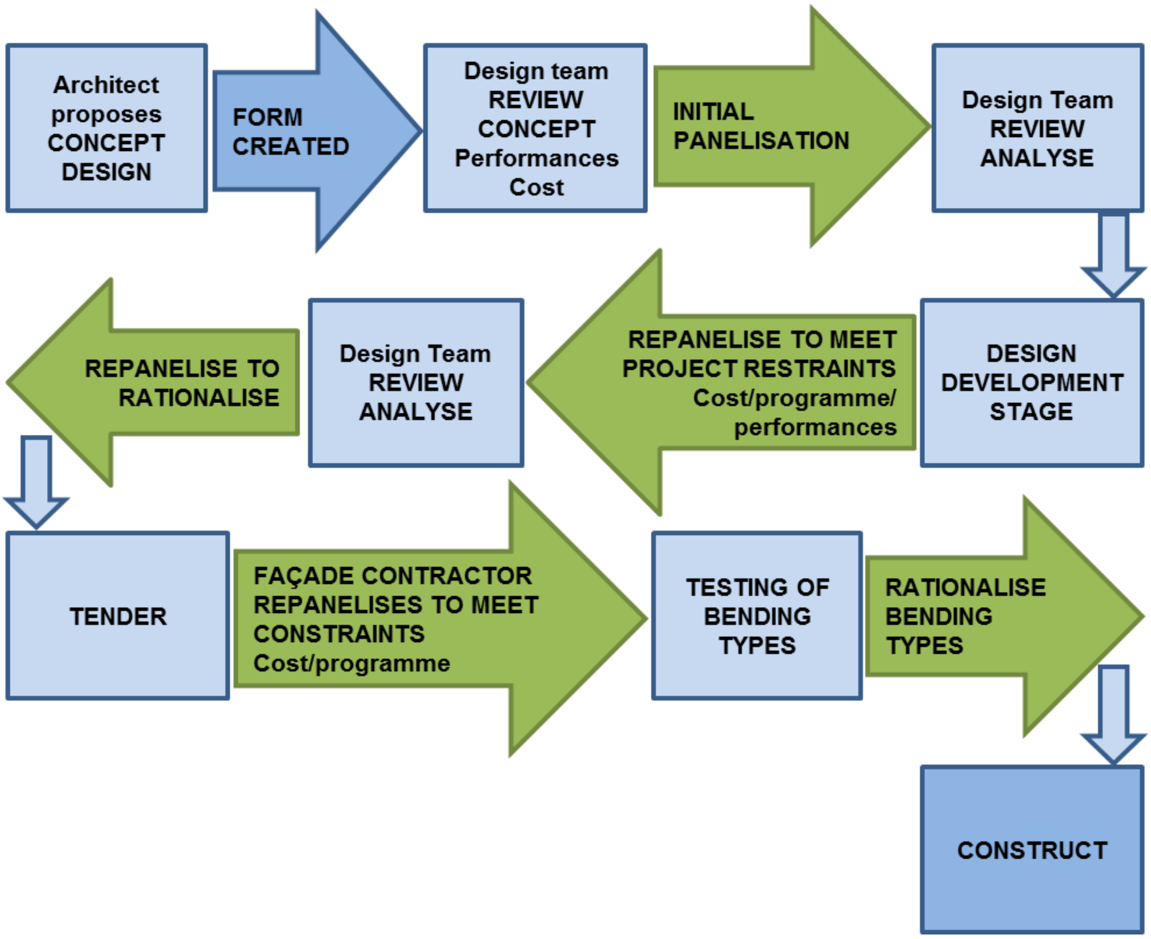


Figure 2.1: Potential panelisation stages during façade design and procurement stages.

2.2 Bending Methods

The bending methods commonly used for commercial buildings considered for this study were:

- Hot bending – radial/conical.
- Hot bending – slump formed.
- Cold bending – forced.
- Cold bending – laminated.

2.3 Bending Categorisation

The survey confirmed that bent glass in its different forms as hot and cold bent was designed/specified, commissioned/ordered and produced.

Question 1 of the survey:

Please indicate awareness / type of experience with the following types of bent glass (please tick all those that apply)

	Aware of but not used	Designed / specified	Produced	Commissioned /ordered	Unaware of this method of bending	Total Respondents
Cold bent glass - formed by forced bending either on or off site and restrained by a support member	43.55% 27	32.26% 20	14.52% 9	12.90% 8	12.90% 8	62
Cold bent glass - formed by bending due to applied pressure and then laminated in an autoclave	50.82% 31	19.67% 12	13.11% 8	11.48% 7	22.95% 14	61
Hot bent glass - formed with machinery to give regular geometry as a cylinder / radial / conical	18.33% 11	46.67% 28	20.00% 12	33.33% 20	6.67% 4	60
Hot bent glass - formed on a mould - slump formed - free form / organic geometry	40.32% 25	33.87% 21	11.29% 7	22.58% 14	6.45% 4	62

Figure 2.2: Survey results Question 1

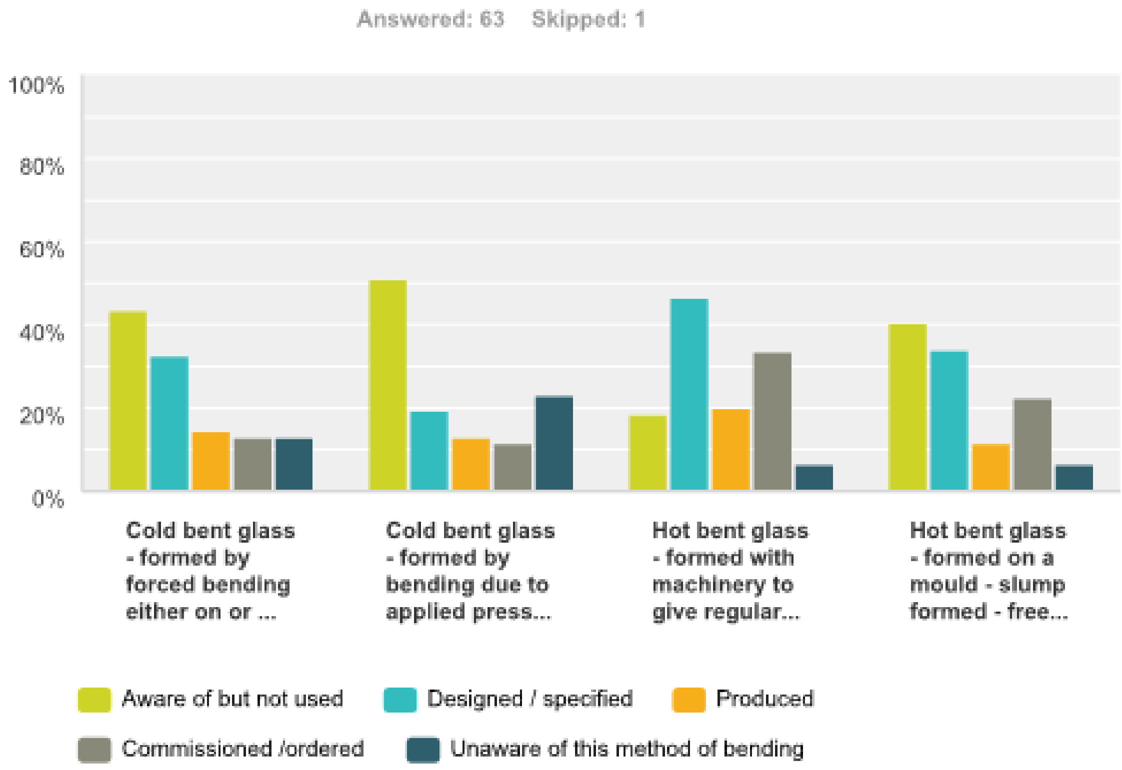


Figure 2.3: Graph results of survey Question 1.

The survey participants indicated that they are more familiar with hot bending methods of bent glass compared to cold bending methods.

2.3.1 Categorisation of the Panelisation and Defining Bending

The panelisation of curved glass façades to achieve the geometry might include both flat and curved panels. Categorising the panelisation identifies type of curvature of the bent panels and this determines the type of glass and method of bending most appropriate. The façade could be designed to more regular geometry curvature – such as a defined radius or arc as referenced in BS 952-2:1980 Glass for glazing – Part 2: terminology for work on glass:

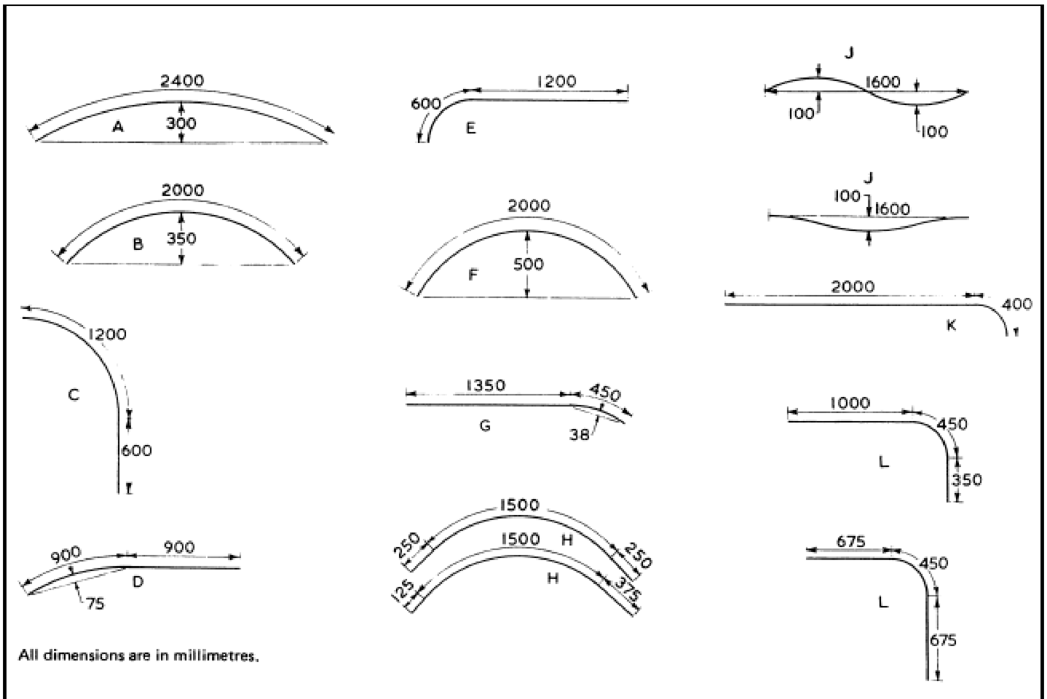


Figure 3 — Standard bends for glass *(continued)*

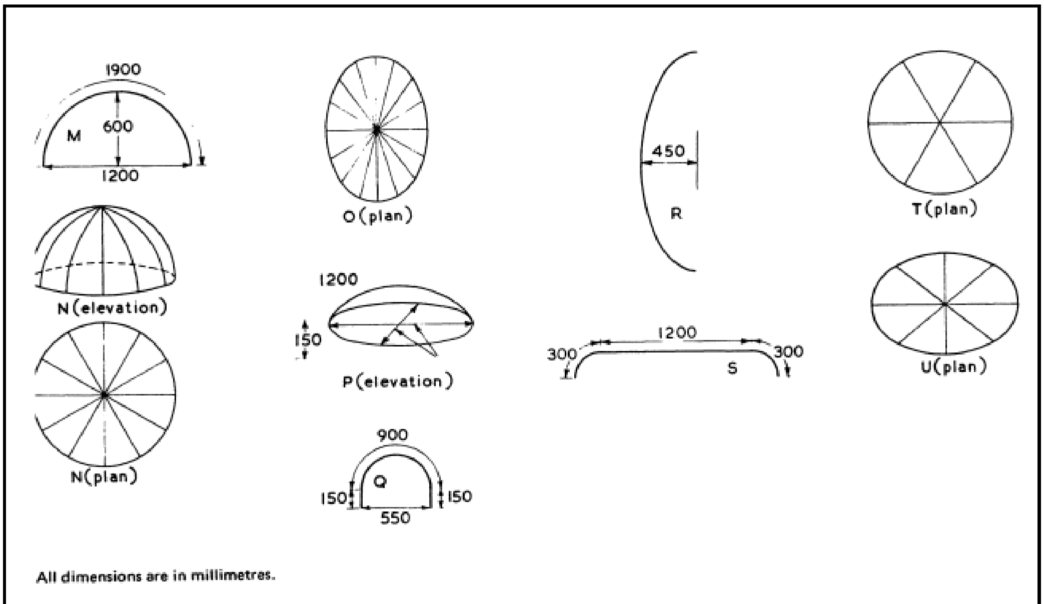


Figure 3 — Standard bends for glass *(concluded)*

Figure 2.4: Definition of bending. (BS 952-2:1980)

The surface could be defined as a free form flowing surface which requires panelisation using 3-D modelling programmes such as Rhino or Grasshopper. Advanced modelling techniques for determining geometry use algorithms to define certain parameters for the curvature and panelisation. These methods can be used to allocate panels into certain families for standardisation/repetition. The options in this case can be infinite depending on the drivers for the panelisation, such as repetiton of panels or smoothness of the surface.

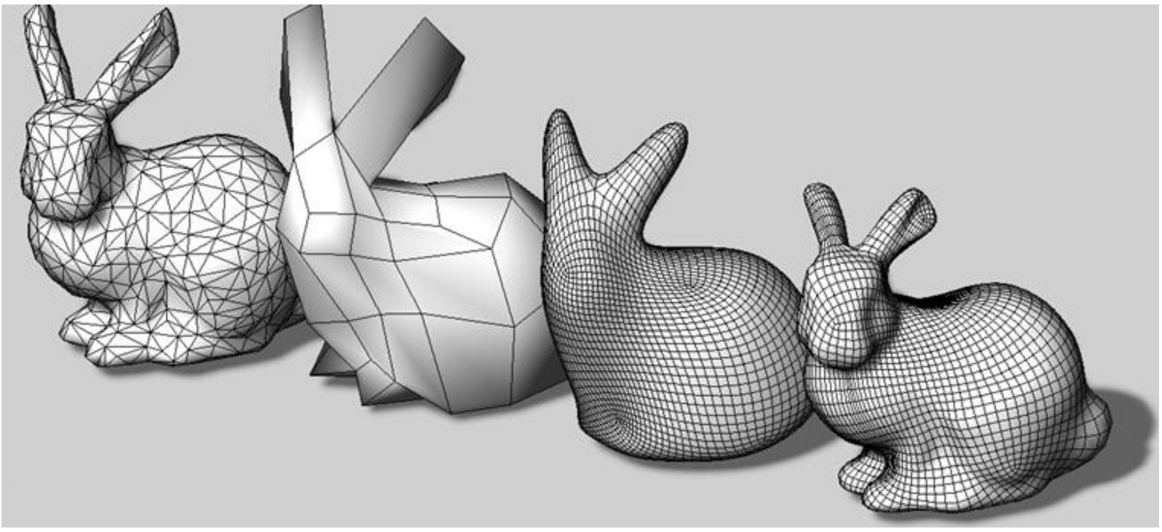


Figure 2.5: Examples of methods of panelisation. (grasshopper 3d, 2015)

This study categorised the curvature of panels as follows:

2.3.2 Single Point Bending

A panel has 3 points in a flat plane with a single point offset

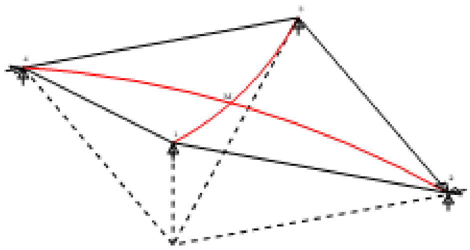


Figure 2.6: Single point bent panel. (de Wit, J. 2009)

2.3.3 2 Point Bending

A panel has 2 points in a flat plane with a 2 points offset – may be referred as warped.

Figure 2.7: Twisted/warped panel. (Cricursa 2014)

2.3.4 Radially Curved Façade

Panel formed with a uniform radius. This is also 2 point bending.

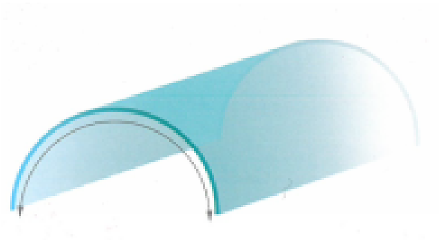


Figure 2.8: Radial curved. (Cricursa 2014)

2.3.5 Conical Curved Panels

Panel formed from a cone.

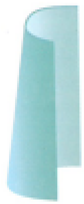


Figure 2.9: Conical curved. (Cricursa 2014)

2.3.6 Freeform Panels

These are panels of irregular form and may take the shape of organic free form geometries.

They may be curved in one direction or two directions in the form of for example a saddle or they may have varying radii/arcs within the same panel and be unique.

Figure 2.10: variations of freeform curved. (Cricursa 2014)

The curvature of the panels categorised can be formed through different bending methods and using different types of glass. Each has their particular visual defects/attributes and can be visually incongruous when viewed together.

2.4 Potential for Inconsistency Between Glass Types

The survey was used to confirm that there is an understanding in the industry of visual inconsistency between bending glass types.

Question 2 of the survey:
Are you aware of potential visual differences between coated glasses comparing flat glass, hot bent glass and cold bent glass?

Answer Choices	Responses	
Yes	93.75%	60
No	3.13%	2
Do not know	3.13%	2
Total		64

Figure 2.11: Survey results Question 2.

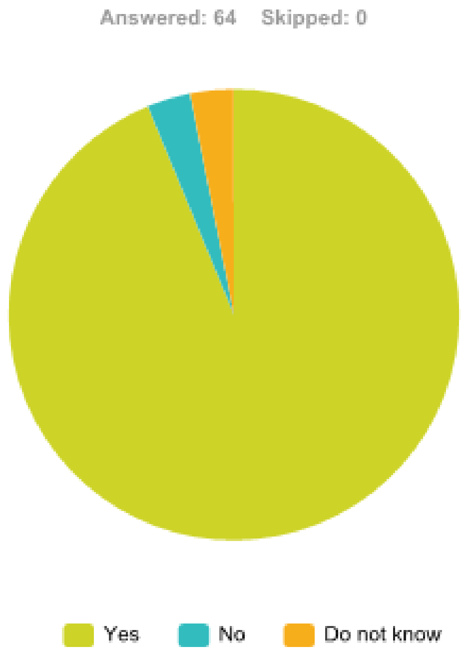


Figure 2.12: Pie chart results of survey Question 2.

The survey highlighted that a majority of the participants were aware there are potential visual differences between flat glass, cold bent glass and hot bent glass.

In order to understand these potential visual issues, a review of the current state of the art practise for glass production, processing and bending methods was carried out and the visual defects/attributes associated with each identified.

2.5 Glass Production

Glass is a versatile material – it can be produced using varying base materials with different chemical compositions which provide unique properties for the different types. It can be produced in different thicknesses, sizes, strengths, colours, have surface treatments applied and it can also be curved. This study considered the process to provide a curved glazed façade as follows:

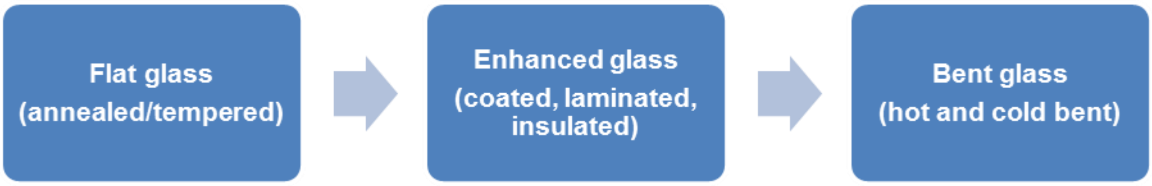


Figure 2.13: Process for curved glass façade production.

For the purposes of this study, an insulated glass unit (IGU) was considered as this is widely used for curved glass façades. The IGU is limited to a double glazed unit (DGU) as there are few examples of curved triple glazed installations (Hoenicke, G. *(pers.comm.)* 22 April 2015). A DGU is commonly specified to meet thermal and acoustic performance in the UK. Single glazing is not specifically being considered as many of the visual issues for the glass for a DGU will apply to a single glazed unit (SGU).

This section provides a description of the base glass types used to commonly form a DGU for simple and complex geometry curved façades. In respect of the visual quality expected of the curved façade, the starting point is the flat glass that is the basis for producing bent glass. Flat glass imperfections inherent in annealed, heat strengthened, fully toughened, laminated, coated and insulated glass are described in this chapter. The process of bending will have further visual effects on the base glass material and this differs between the types of cold bent and hot bent glass. For complex façades, a number of these types could be applied simultaneously to a façade to achieve the desired geometry. However, if different types are installed adjacent to each other, visual inconsistencies between them can be an issue. To understand the potential visual characteristics the study starts with the float glass process and follows with the subsequent processes.

2.6 Float Glass

This study is limited to the most common glass constituent and most commercially used for glass in buildings – soda lime silicate glass. The float glass standard BS EN 572-1: 2012, defines the material in clause 3.1 "float flat transparent, clear or tinted soda-lime silicate glass having parallel and polished faces obtained by continuous casting and floatation on a metal bath".

Soda Lime-Silicate glass is composed of the following different chemical components as defined in BS 952-1:1995:

1.4.2 Soda lime-silicate glass (see BS EN 572-1)

The proportions by mass of the principal constituents of all the soda lime-silicate glass products covered by BS EN 572 and this standard are:

Silicon dioxide	SiO_2	69 %	to	74 %
Calcium oxide	CaO	5 %	to	12 %
Sodium oxide	Na_2O	12 %	to	16 %
Magnesium oxide	MgO	0 %	to	6 %
Aluminium oxide	Al_2O_3	0 %	to	3 %

Figure 2.14: BS 952-1: 1995. Section 1.4.2

Float glass uses raw materials of soda, lime, silica and oxide/aluminium/magnesia with a percentage of waste recycled glass (cullet) that are heated to extremely high temperatures 1,500 degree Celsius (°C). The controlled and efficient melting of the particles reduces the risk of visible inclusions and bubbles. When the material becomes molten, the liquefied glass from the melter is floated on a molten tin bath. Due to the difference in density, the flowing soda lime silica mix floats on the molten tin. At this stage the material is at a temperature of 1,100°C. As the glass is drawn through the length of the molten tin bath, the glass thickness is derived – based on how quickly the glass is drawn through. When it reaches the end of the bath, the material is at a temperature of 600 °C. The glass will then normally be cooled in a controlled manner to allow it to be annealed. The glass continues along the processor. Whilst still on the line a coating might be applied. These are chemical vapour deposition (CVD) hard coatings and will allow the reflection of visible and infrared wavelengths and thus change the optical properties of the glass. The glass reaches the end of the line where it is cut and then removed from the line, inspected and stacked. The base material produced at the completion of this process is annealed float glass. The annealed flat glass can then be further processed. The following figures illustrate the process.

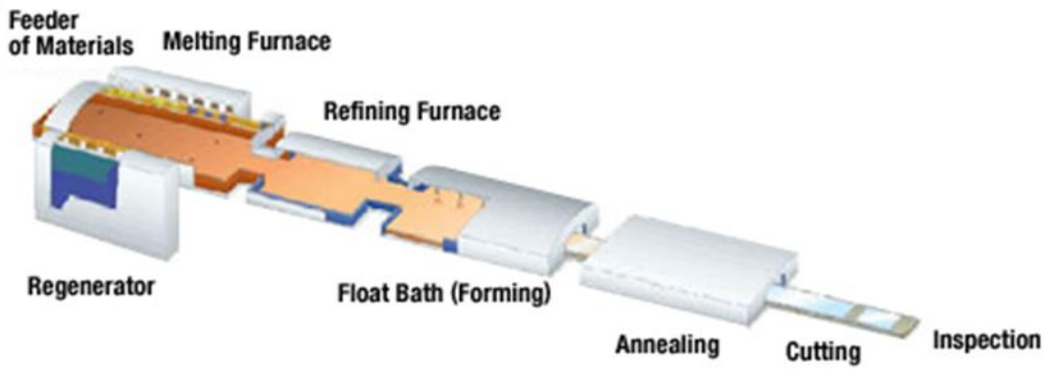


Figure 2.15: The float process. (AGC, 2015)

Figure; 2.16: The raw material and cullet are melted. (Chicago Window Expert, 2015)

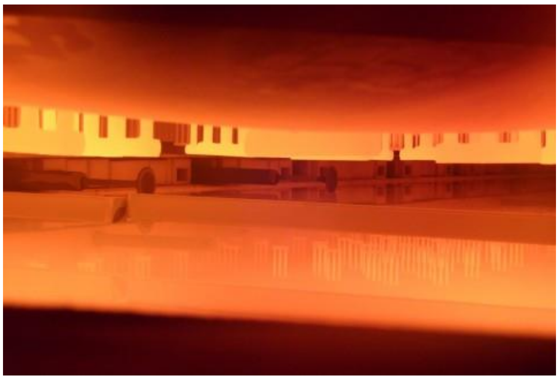


Figure: 2.17: The glass is molten and floated on a tin bath. (Imgbuddy, 2015)

Figure: 2.18: The glass line length may be several hundred metres. (Glass for Europe, 2015)

Figure: 2.19: The glass is cut and ready for stacking. (Noval Glass, 2015)

2.7 Glass Types

Further processes applied to annealed float glass can alter the strength and properties of the material.

- The glass can be heated and be subjected to controlled cooling to become tempered glass which has greater strength than annealed float glass. This can be heat strengthened or fully toughened – the latter having the greater mechanical and thermal strength. (The glass can also be toughened using a chemical process, however this process is not being considered in the scope of this dissertation.)

- The glass may be laminated, which involves bonding the panes together with an interlayer to enhance properties and visual appearance. Depending on the material in the laminate this can improve strength (SGP), enhance the acoustic properties (acoustic PVBs), alter the appearance (coloured/textured interlayers) and provides different post breakage failure performance compared to monolithic glass.
- Coatings can be applied to alter the thermal and solar characteristics. These are coatings made of fine layers of metals and are termed hard or soft coatings. The latter will deteriorate if exposed and are generally encapsulated to maintain their integrity.
- The glass can also be introduced into an insulated glass unit (IGU). The IGU has a dry cavity with air or gas infill and is retained with an edge spacer.

The following section identifies the visual attributes associated with the glass types.

2.7.1 Description of Potential Visual/Optical Faults and Attributes

The following visual/optical faults and attributes were identified in the standards/guidance for flat and curved glass reviewed for the study. The full list of standards and which identify these traits is in the standards/guidance review section. The defects/attributes are summarised in the table below. The glass and bending types they are relevant to are described in the subsequent types and standards/guidance sections.

VISUAL/OPTICAL FAULT/ATTRIBUTE	DESCRIPTION
Spot faults	Bubbles, inclusions, halo, stains – marks caused by contaminants/foreign bodies in the substrate or poor quality control of the environment.
Linear faults	Scratches, marks – marks caused by contaminants during the manufacturing process or mechanical damage.
Tong marks	Marks/indentations caused by support for vertical toughening (this process is not commonly used for commercial applications, therefore the impact of this is not considered in this study).
Roller wave	Surface distortion due to the flatness due to the glass being in contact with rollers during tempering (due to the horizontal tempering and commonly used for commercial applications).

Roller pick up	Marks caused by contaminants on the rollers during the tempering process. May be referred to as white haze.
Edge lift	Edge visual distortion due to the tempering process.
Vents, interlayer defects	Cracks/creases caused by damage to the interlayer material and poor lamination process.
Anisotropy	Visual distortion due to the tempering process and is not classed as a defect as it is inherent. Sometimes referred to as leopard spots.
Bow, pillowing	Visual distortion due to deflection and atmospheric differences.
Brewsters fringes	Oily distortion effect due to the 'interference' effects of light wavelengths. This is not considered a defect but is inherent to good quality glass used in IGUs.
Newton rings	Affects an IGU when the panes come into contact due to deflection or atmospheric conditions.
Coating colour variation	patchy inconsistent colouring due to poor application or damage to the coating after application.

Table 2.2: Summary of visual/optical faults and attributes.

The following are examples of glass defects/attributes:

Figure 2.20: Bubbles in glass due to poor lamination. (Ramboll 2013)

Figure 2.21: Scratches in glass. (Glassworks, 2015)

Figure 2.22: Contamination of rollers causes marks on the glass - white haze. (Ramboll 2013)

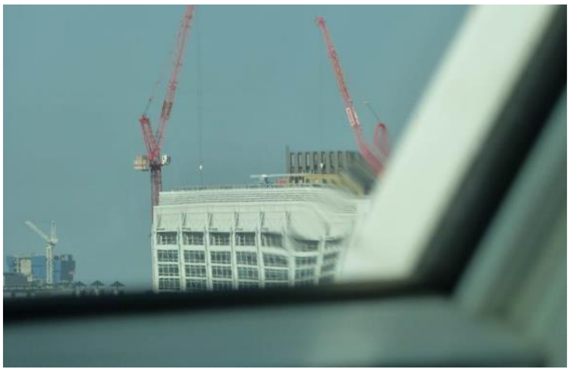


Figure 2.23: Edge lift. (Ramboll 2013)

Figure 2.24: Roller wave distortion. (Ramboll, 2013)

Figure 2.25: Lensing effect due to roller wave and multilayer glass lamination. (Ramboll, 2013)

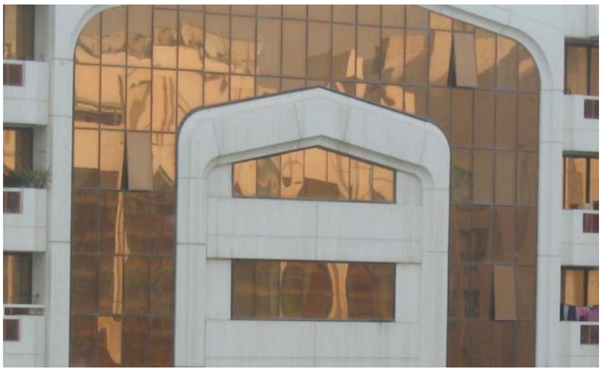


Figure 2.26: Pillowing causes distortion in the highly reflective glass.

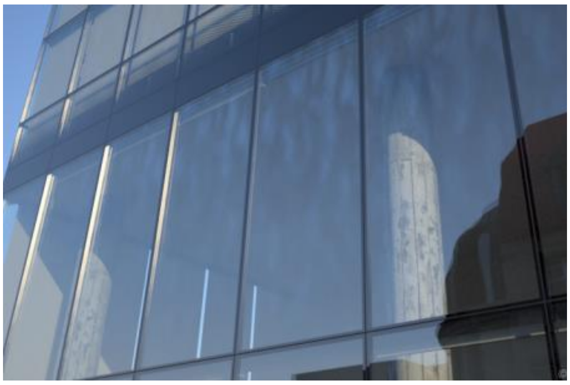


Figure 2.27: Anisotropy or leopard spots. (Eclat Digital Recherche, 2015)

The following section describes the different glass types and the associated visual/optical faults and attributes for each.

2.7.2 Annealed Glass

”glass that has been subjected to controlled cooling to reduce the presence of residual stresses in the glass thus allowing easy cutting. It is ordinary glass which includes float glass, sheet glass, patterned glass and wired glass and is independent of the glass composition.” (BS 952-1:1995) This is glass with no further treatment to enhance its mechanical or thermal strength properties.

- The glass is cooled slowly in a controlled manner to minimise the stresses internally and the surfaces are not put into compression. Therefore it does not have enhanced mechanical or thermal strength.
- Limitations to the use of annealed glass may be due to susceptibility to thermal shock (breakage due to thermal differences across the pane).
- When annealed glass breaks, it forms larges shards which are dangerous and therefore it is not considered to be a safety glass.

2.7.2.1 Potential visual/optical defects of annealed glass

The following are noted in BS EN 572-1:2012 and BS EN 572-1:2012:

- spot faults (bubbles, stones, etc.);
- linear/extended faults (scuff marks, scratches, lines, deposits, impressions, etc.) pattern faults;
- wire faults;
- surface distortion;
- lack of surface homogeneity.

2.7.3 Tempered Glass

The glass is heated to 630-640°C and then cooled rapidly on both sides in a strictly controlled manner known as quenching. As the external surface cools quickly, the inner core contracts during cooling whilst still in a viscous state; this forces the surface into compression and therefore gives the tempered glass material greater strength than annealed glass. Tempered glass is classified as heat strengthened or fully toughened. The glass is more commonly tempered horizontally and is passed through the process on a series of rollers as illustrated in figure 2.28. The process for producing tempered glass gives rise to certain visual defects and effects. These are noted in the following section and in the relevant codes which are provided in more detail in Appendix B.

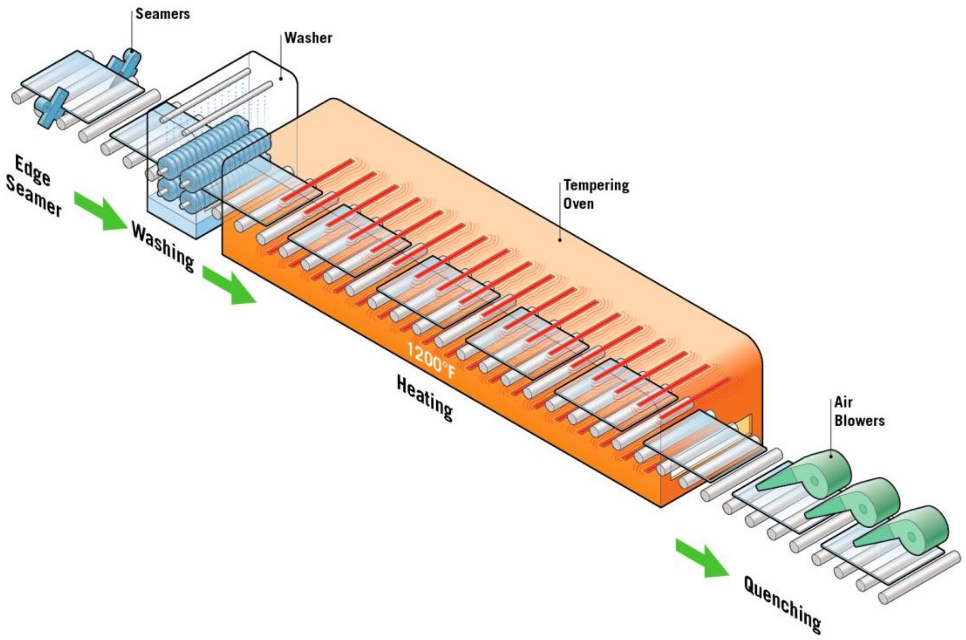


Figure 2.28: The tempering process. (Construction Specifier, 2015)

2.7.3.1 Heat strengthened glass

- Heat Strengthened glass. The glass is rapidly cooled, but not as rapidly as for fully toughened glass. This glass has greater mechanical and thermal strength than annealed glass, but not as great as fully toughened glass.
- Its greater thermal strength allows it to be used where there may be a risk of breakage due to thermal stress.
- When heat strengthened glass breaks, it forms larges shards which are dangerous and therefore it is not considered to be a safety glass.

2.7.3.2 Toughened glass

- Toughened (fully tempered). Once heated the glass has to be quenched in a matter of seconds to achieve the surface compression in order for it to meet the criteria for fully toughened glass. The quenching time for fully toughened glass is shorter than that for heat strengthened glass and therefore it has more compressive stress in its surface and has a higher mechanical and thermal strength.
- Its greater thermal strength allows it to be used where there may be a risk of breakage due to thermal stress.
- When thermally fully toughened glass breaks, it forms small fragments and is therefore considered to be a safety glass. However, as it breaks it will no longer stay in place and will not provide a barrier if used in a monolithic application. A further characteristic is the thermally toughening process may promote nickel sulfide inclusions which can enlarge over time and cause the glass to spontaneously

explode. A further procedure of heat soak testing can be carried out to accelerate this process and cause the glass with the inclusions to break by subjecting the glass to a heating, holding and cooling phase. The glass breaks during the procedure and avoids it being installed on the building.

- Chemical toughening is a process also used for toughening glass, but is not included in this study. Chemically toughened glass does not meet the requirements to be considered a safety glass.

2.7.3.3 Potential visual/optical defects of tempered glass

The following are noted in BS EN 1863-1:2011 and BS EN 12150-1: 2000:

- roller wave;
- roller pick up;
- edge lift;
- tong marks;
- overall bow;
- anisotropy.

2.8 Glass Strength

The potential defects noted in annealed and tempered glass are varied. Annealed glass will have inherent defects in its surface. Those which are easily detectable with the eye will generally render the glass defective. However there are invisible flaws in the surface that will affect the strength of the glass and will cause it to fail if concentrated stress is applied. These flaws are known as Griffith flaws as identified by A.A. Griffiths in 1921. These are flaws which are further exacerbated by microscopic defects such as vents, shells and cracks. The flaws will cause failure under tensile stress. However, these can be resisted if the glass surface is put into compression. This is the principle used for heat strengthened and fully toughened glass. Design criteria must accommodate impact loads, thermal and bending stresses. The glass choice will be influenced by these performances.

The value of the characteristic bending strength $f_{g,kk}$ or mechanical strength of the glasses considered are as follows:

Annealed	45N/mm^2	(BS EN 572-1:2012, section 6.2);
Heat strengthened	70N/mm^2	(BS EN 1863-1:2011, section 9.4, table 8);
Fully toughened	120N/mm^2	(BS EN 12150-1:2000, section 9.4, table 6).

Certain bending methods require glass that can resist greater stresses than annealed glass. The process for strengthening the glass will affect the visual characteristics of the glass with attributes such as roller wave and anisotropy and have an increased cost compared to annealed glass. Annealed glass may be more visually desirable, however, it is not always possible to employ due to its lower mechanical and thermal performance compared to tempered glass.

2.9 Enhanced Glass Processes

The base material whether annealed, heat strengthened, fully toughened or heat soaked fully toughened glass can be further processed to provide additional characteristics. This may include: introducing a coating to enhance solar/thermal properties; laminating to improve safety/strength, enhance acoustic performance or alter the visual appearance by introducing a different material in the interlayer or constructing an IGU for improved performance.

2.9.1 Coated Glass

- Coatings applied to improve thermal performance and enhance U values to provide better insulation are referred to as low e coatings. Coatings to mitigate solar gain through a glazed façade by reducing the g value are known as solar control coatings.
- The coatings may be termed organic/inorganic and defined as soft or hard (pyrolytic) coatings which are determined by their chemical characteristics and application method. Certain coatings deteriorate when exposed to atmospheric conditions and therefore they need to be encapsulated within a laminate or an IGU. Generally only hard or pyrolytic coatings can be applied on monolithic glass.
- The coatings may affect the visual appearance of the glass. Solar control coatings tend to have a colour effect on the glass. They may also limit further processes being carried out on the glass once the coating is applied, such as fritting, silicone application and hot bending.
- If glass coating is to be subsequently heated/tempered, then the appropriate coating must be used. Soft coatings if temperable should not come into contact with rollers/moulds . Hard coatings are more durable to tempering and can be placed face down on rollers/moulds (Wassink, H. *(pers.comm.)* 31st August 2015).

2.9.1.1 Potential visual/optical defects of coated glass

BS EN 1096-1:2012 notes appearance defects that may be due to the glass substrate or due to the coating:

- Uniformity defects and stains;
- spots/pinholes;
- scratches and clusters.

2.9.2 Laminated Glass

- This process introduces an interlayer which is used to bond the glass plies together. The interlayers may vary, but the most common used for enabling the glass to be a safety glass is polyvinylbutyral (PVB). Other materials include EVA (ethylene and vinyl acetate), SGP (SentryGlas ®) and also resins. These different interlayers have particular properties some with enhanced thermal and mechanical strength.
- Laminated glass is considered a safety glass as it will bond the glass to the interlayer and the glass will stay in place once broken if captured by the support/framing. It is used for overhead applications as it aids keeping the glass in place during post breakage failure. The interlayer material chosen has to consider its application in respect of temperature. Generally PVB will become soft and fail above 55°C as the shear modulus decreases with increase in temperature therefore making it difficult to use in hot climates. SGP also softens above 55°C, however it can withstand greater heat before failure. EVA can also withstand higher temperatures up to 70 °C, however it fails more dramatically than PVB.
- The type of glass used in the build-up will also affect the post breakage failure. If 2 plies of fully toughened are used and both break, this will quite rapidly slump and fall from its support. 2 heat strengthened or annealed will stay in place longer as the breakage patterns do not align.

2.9.2.1 Potential visual/optical defects of laminated glass

BS EN 12543-6:2011 notes appearance defects that may be due to the lamination process:

- Spot defects including bubbles, foreign bodies and opaque spots;
- Linear defects including scratches or grazes and foreign bodies;
- Other defects including vents, interlayer defects of creasing, shrinkage and streaking.

2.9.3 IGU

- This is a sealed unit consisting of at least 2 panes of glass with a moisture free cavity that is filled with air or gas. The space is formed by introducing a spacer bar at the edge. This is then hermetically sealed to prevent moisture entering the cavity and prevent the escape of the dry air or gas from the cavity. The gap is kept dry with the use of a desiccant within the spacer bar. The units may typically be double glazed or triple glazed.
- The IGU provides improved performance of the glazing. This includes thermal performance and acoustic performance and provides protection to glass coatings

that cannot be exposed to atmospheric conditions. It encapsulate infills such as materials for visual enhancement, aerogels or vacuum insulation etc.

- The safety of the glass for an IGU is dependent on the glass types used and these are subject to the breakage characteristics noted in annealed, heat-strengthened, heat soaked thermally toughened and laminated glass.

2.9.3.1 Potential visual/optical defects of insulated glass units

BS EN 1279-1: 2004 notes appearance defects/attributes of insulating glass units:

- Newton's rings;
- Brewster's fringes;
- pillowing;
- external condensation.

2.9.4 Flat Glass Types Summary

Glass types used as the basis for the different types of bending have potential visual/optical defects as summarised in this section. These flat glass types if viewed simultaneously can potentially have visual inconsistency between types. The methods of hot and cold bending of the base glass as described in the following section can have additional effects on the visual/optical quality.

2.10 Hot Bending Glass

The base glass is heated to between 540-600°C so that the material loses any stress in its surface (if heat strengthened or fully toughened glass is used as the base glass, this reverts to annealed glass). The glass is curved using machinery which will roll/guide the glass into a regular form such as a radial or conical curvature or it is slumped by gravity into a mould to produce a free-form shape. The hot bending method for the curvature will determine whether the newly formed glass can be tempered or not.

2.10.1 Hot Bending (Radial/Conical)

- This process provides a regular curve based on a radius.
- The glass is heated and when malleable rollers form the curvature by gravity or by pressure. Once the curvature is achieved, the glass can be tempered by the rapid cooling of both surfaces and can be heat strengthened or fully toughened.

Figure 2.29: Radial curved hot bending equipment allows glass to be tempered. (Glass machinery China, 2015)

Figure 2.30: Radial curved hot bending equipment allows glass to be tempered. (Xinglass, 2015)

2.10.1.1 Considerations and attributes of tempered hot bent radial glass

- The glass can be a regular shape to a single radius – certain processors produce conical glass also.
- The glass thickness can vary but is limited to certain thicknesses to achieve the tempering in a controlled manner. Above 12mm thickness is problematic (Tarrus, J. *(pers.comm.)* 27th July 2015).
- If laminated, it is preferred that the panes are the same thickness.
- Hard coatings can go on either side – the coating manufacturer should be consulted.
- A flat zone of approximately 100mm at the edge is a feature of this process and should be considered in the panelisation. (Figuerola, F. *(pers.comm.)* 27th July 2015).
- Edge working cannot take place once the glass is tempered.
- This process is not used for producing radial formed annealed glass as the glass would take too long to cool on the rollers.

2.10.1.2 Visual/optical defects of tempered hot bent radial glass due to bending process

- The base glass will be subject to the visual defects noted for each type.
- Roller wave and edge lift due to the bending method.
- If the glass is laminated it will be subject to bubbles and delamination.
- Laminated glass with roller wave could have lensing effects which cause visual/optical distortion in the glass.
- Coated glass may experience discolouration depending on the coating used.

2.10.2 Hot Bending (Free Form – Slumped)

- The glass is heated to above the weakening point and then cooled slowly in order that the glass is annealed to avoid any compression in the surfaces.
- This uses gravity to slump form the shape on to a steel mesh mould which has a ceramic mat on the surface in order to maintain a smooth surface.

2.10.2.1 Considerations and attributes of annealed free form hot bent glass

- The glass can be a simple shape or be a freeform organic complex shape.
- The glass thickness can vary. Varying thicknesses can be laminated together.
- The visual optical quality is better than radially formed hot bent glass as there are no inherent stresses in the glass surfaces or roller wave. However, the smoothness of the mould surface must be maintained.
- Often this method is used for bespoke and unique projects. The requirement for one-off moulds makes this method costly and time consuming. Costs may be up to 3,000 Euros for a single mould and each panel may take over 16 hours to produce (Diller, N. *(pers.comm.)* 1st July 2015).
- Process of hot bending on a mould with a steel mesh and ceramic blanket prevents panels being toughened through the quenching process as both surfaces cannot be rapidly cooled at the same time. If toughened glass is used as the initial material, the process of heating it relaxes the compression in the surfaces so it becomes annealed.
- Any coatings on the glass may distort. Generally only hard coatings are bent with this method. The coating will be affected differently if mould side up or mould side down. The manufacturer must be consulted before coatings are bent with this method.
- Edge working can take place after the glass is curved.

2.10.2.2 Visual/optical defects of annealed free form hot bent glass due to bending process

- The base glass will be subject to the visual defects noted for each type.
- If the glass is laminated it will be subject to bubbles and delamination.
- Inconsistencies in the glass surface due to mould marks.
- Coated glass may have discolouration depending on the coating used.

Figure 2.31: BBC W1 – Breathing sculpture (whitbybird 2006).

This glass was produced using a mould and was therefore annealed. Façade Contractor was Tuchschmid.

2.11 Cold Bending Glass

This process bends the glass at ambient or low temperatures. The base glass tends to be heat strengthened or fully toughened as the bending processes are likely to induce stresses into the glass which need to be accommodated.

2.11.1 Cold Bending Forced

The glass is either cold bent to a mould or profile as illustrated in figure 2.32 and then fixed by mechanical means such as with a pressure plate or bonded with structural silicone. The latter method puts stress into the silicone and this has to be designed and calculated accordingly to meet the shear stresses induced.

If the bending is carried out off-site at the fabricator, this will be a unitised system.

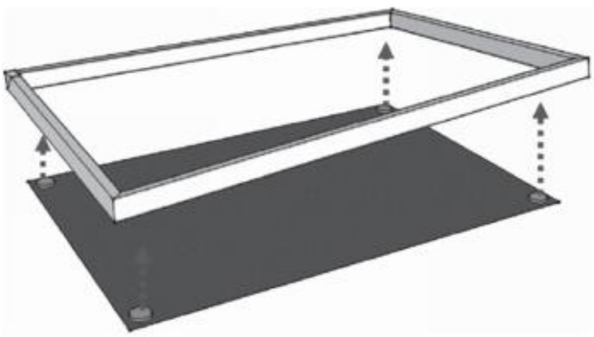


Figure 2.32: One point of the panel is move out of plane to create a curved surface. (Neugebauer, J. 2014 p68)

Unitised panels may also be bent into shape on site as shown in figure 2.34.

Figure 2.33: The Gehry designed IAC Building New York, USA. (Permasteelisagroup, 2015)

Figure 2.34: Installing the panels for the IAC Building New York, USA.
(enr construction, 2015)

2.11.1.1 Considerations and attributes of cold bent forced glass

- The glass has good visual quality compared to hot bent radial glass.
- The glass will be subject to stress when bent and laminated glass must take account of this.
- The spacer of an IGU has to accommodate the stress due to bending.
- Annealed glass is not used due to the enhanced strength required for this process due to stresses induced in the glass.

Figure 2.35: Sample testing cold bent glass for the Opus. (Ramboll, 2008)

The test illustrated in figure 2.35 was a good example of how the colour of the flat and the bent glass are visually consistent after bending.

2.11.1.2 Visual/optical defects of cold bent forced glass due to bending process

- The base glass will be subject to the visual defects noted for each type.
- The glass is likely to be heat strengthened or fully toughened and may have roller wave and edge lift due to the tempering process of the base glass.

- If the glass is laminated it will be subject to bubbles and delamination.
- Laminated glass with roller wave could have lensing effects which cause visual distortion in the glass and this may be exacerbated by the bent form.
- Dishing or creasing of the glass due to over bending.
- Failure of the IGU due to overstressing of the spacer.

2.11.2 Cold Bending Laminated

- Another method is to load the glass as laminated sheets and then place it in the autoclave heated to approximately 150 °C. When removed, the glass has laminated into the cold bent form. 2 step cold bending is the process involving the laminated glass being elastically bent on a jig and the placed in an autoclave. When released, the shape is maintained by the interlayer. (Fildhuth, T et al. 2014).
- Research was being carried out as to the efficiency of the types of interlayers in respect of preventing springback over time. (Fildhuth, T et al. 2014)

Figure 2.36: Strasbourg Station by Seele. (Open Buildings, 2015)

Example of cold bent single glazing with good visual consistency.

2.11.2.1 Considerations and attributes of cold bent forced glass

- The glass has good visual quality compared to hot bent radial glass. Figure 2.36 illustrates good visual consistency of the glass.
- The glass may be subject to springback which could impact design life.

2.11.2.2 Visual/optical defects of cold bent laminated glass

- The base glass will be subject to the visual defects noted for each type.
- The glass is likely to be heat strengthened or fully toughened and may have roller wave and edge lift due to the tempering process of the base glass.
- The glass is laminated and will be subject to bubbles and delamination.
- Laminated glass with roller wave could have lensing effects which cause distortion in the glass and this may be exacerbated by the bent form.

2.12 Summary of Potential Visual/Optical Defects/Attributes for Glass Build-Ups

The following table summarised defects particular for each flat and bent glass type, identified whether the type can be considered a safety glass and notes any further attributes. Glass types not applicable to a bending method are noted.

Table 2.3: Table of visual manifestations and attributes for glass build ups

Key:

PANE

A mono	= annealed monolithic.
A lam	= annealed laminated.
HS mono	= heat strengthened monolithic.
HS lam	= heat strengthened laminated.
FT mono	= fully toughened monolithic.
FT lam	= fully toughened laminated.

POTENTIAL VISUAL DEFECTS/ATTRIBUTES

Visual defects:	spots, scratches.
Tempering defects:	roller wave, edge lift, anisotropy.
Coating defects:	Soft/hard coating visual irregularity due to poor application.
Laminated defects:	bubbles, delamination.
Multi-layer defects:	lens effects.
IGU defects:	pillowing, Newton's rings, Brewster's fringes.

MARKERS

●	denotes NOT applicable to glass type.
x	denotes applicable to glass type.

GLASS PANEL	PANE	POTENTIAL VISUAL DEFECTS/ATTRIBUTES							NOTES
		Visual defects	Tempering defects	Coating defects	Laminated defects	Multi-layer defects	IGU defects	Safety glass (UK)	
FLAT GLASS	A mono	x	●	x	●	●	x	NO	
	A lam	x	●	x	x	●	x	YES	
	HS mono	x	x	x	●	●	x	NO	
	HS lam	x	x	x	x	x	x	YES	

GLASS PANEL	PANE	POTENTIAL VISUAL DEFECTS/ATTRIBUTES							NOTES
		Visual defects	Tempering defects	Coating defects	Laminated defects	Multi-layer defects	IGU defects	Safety glass (UK)	
	FT mono	x	x	x	•	•	x	YES	
	FT lam	x	x	x	x	x	x	YES	
COLD BENT SINGLE POINT FORCED	A mono	•							Method not applicable
	A lam	•							Method not applicable
	HS mono	x	x	x	•	•	x	NO	
	HS lam	x	x	x	x	x	x	YES	
	FT mono	x	x	x	•	•	x	YES	
	FT lam	x	x	x	x	x	x	YES	
COLD BENT LAMINATED	A mono	•							Method not applicable.
	A lam	x	•	x	x	•	x	YES	Bending process does not affect coatings.
	HS mono	•							Method not applicable.
	HS lam	x	x	x	x	x	x	YES	Bending process does not affect coatings.
	FT mono	•							Method not applicable.
	FT lam	x	x	x	x	x	x	YES	Bending process does not affect coatings.
HOT BENT RADIAL	A mono	•							Method not applicable.
	A lam	•							Method not applicable.
	HS mono	x	x	x	•	•	x	NO	Bending process can affect coatings-subject to which face applied.
	HS lam	x	x	x	x	x	x	YES	Bending process can affect coatings-subject to which face applied.
	FT mono	x	x	x	•	•	x	YES	Bending process can affect coatings-subject to which face applied.
	FT lam	x	x	x	x	x	x	YES	Bending process can affect coatings-subject to which face applied.

<table>
<tr><th>GLASS PANEL</th><th>PANE</th><th colspan="7">POTENTIAL VISUAL DEFECTS/ATTRIBUTES</th><th>NOTES</th></tr>
<tr><td></td><td></td><td>Visual defects</td><td>Tempering defects</td><td>Coating defects</td><td>Laminated defects</td><td>Multi-layer defects</td><td>IGU defects</td><td>Safety glass (UK)</td><td></td></tr>
<tr><td rowspan="6">HOT BENT SLUMPED</td><td>A mono</td><td>x</td><td>•</td><td>•</td><td>•</td><td>•</td><td>x</td><td>NO</td><td>Bending process can affect coatings-subject to which face applied.</td></tr>
<tr><td>A lam</td><td>x</td><td>•</td><td>•</td><td>x</td><td>•</td><td>x</td><td>YES</td><td>Bending process can affect coatings-subject to which face applied.</td></tr>
<tr><td>HS mono</td><td colspan="7">•</td><td>Method not applicable.</td></tr>
<tr><td>HS lam</td><td colspan="7">•</td><td>Method not applicable.</td></tr>
<tr><td>FT mono</td><td colspan="7">•</td><td>Method not applicable.</td></tr>
<tr><td>FT lam</td><td colspan="7">•</td><td>Method not applicable.</td></tr>
</table>

2.13 Standards/Guidance for Curved Glass Buildings

This section assessed the relevance of the UK and European standards/guidance for flat and curved glass generally referred to in UK specification for visual/optical requirements and visual assessment. The purpose of the review was to identify if there were applicable criteria available and whether there were inconsistencies and omissions. Initial discussion with those involved in the specification, procurement and construction of buildings suggested there was lack of information/guidance available for specification and visual assessment of curved glass.

2.13.1 Identifying Requirement for Improved Specification

The following parties contacted initially agreed that improved information and better understanding of curved glass specification and design would be welcomed. Details of those consulted are provided in the reference section:

Designers / Consultants:

- Carpenter Lowings, Flanagan Lawrence, Rogers Stirk Harbour + Partners, Interface Façade Engineering, Meinhardt Façade Technology.

Façade contractors / Glass processors:

- Interpane, Saint Gobain, Seele, Finiglas, Schueco.

Main contractors:

- Sir Robert McAlpine, Mace, Brookfield Multiplex, Lend Lease, Skanska.

This was acknowledged by the survey participants as a majority of the participants agreed there were inadequate standards/guidance:

Question 3 of the survey:
Do you think there are adequate standards and guidance for the specification and visual assessment of bent glass?

Answer Choices	Responses	
Yes	4.84%	3
No	80.65%	50
Don't know	14.52%	9
Total		**62**

Figure 2.37: Survey results Question 3

Figure 2.38: Pie chart results of survey Question 3.

Additional comments to question reaffirnmed the perceived lack of guidance available. "I don't consider that Standards are adequate for any type of glass" (ANON, 14th June 2015). "Some standards and guidelines are available however more clarity and reconciliation required" (ANON,15th June 2015) "are there any for the visual assessment?" (ANON,15th June 2015).

2.14 Current Standards/Guidance Referred for Specification

The survey was used to confirm which flat and bent glass standards/guidance are used by the industry for the specification and visual acceptance criteria for bent glass.

Question 4 of the survey:

Have you used any of the following standards/guidance for the specification and visual acceptance criteria for bent glass?

Answer Choices	Responses	
BS EN Standards for basic soda lime silicate glass - standards for flat / processed glass	52.46%	32
BS EN Standards for insulating glass units	52.46%	32
ASTM C1464 Standard Specification for Bent Glass: 2011	19.67%	12
BS ISO 11485 Glass in Building - Curved glass	31.15%	19
GGF Manual Section 4 Curved Glass: 2011	24.59%	15
BF-Bulletin 009/2011 Guidelines for thermally-curved glass in the building industry	11.48%	7
CWCT TN 35	39.34%	24
Hadamar 06/09 Guidelines to Assess the Visible Quality of Glass in Buildings	55.74%	34
None	18.03%	11
Total Respondents: 61		

Figure 2.39: Survey results Question 4.

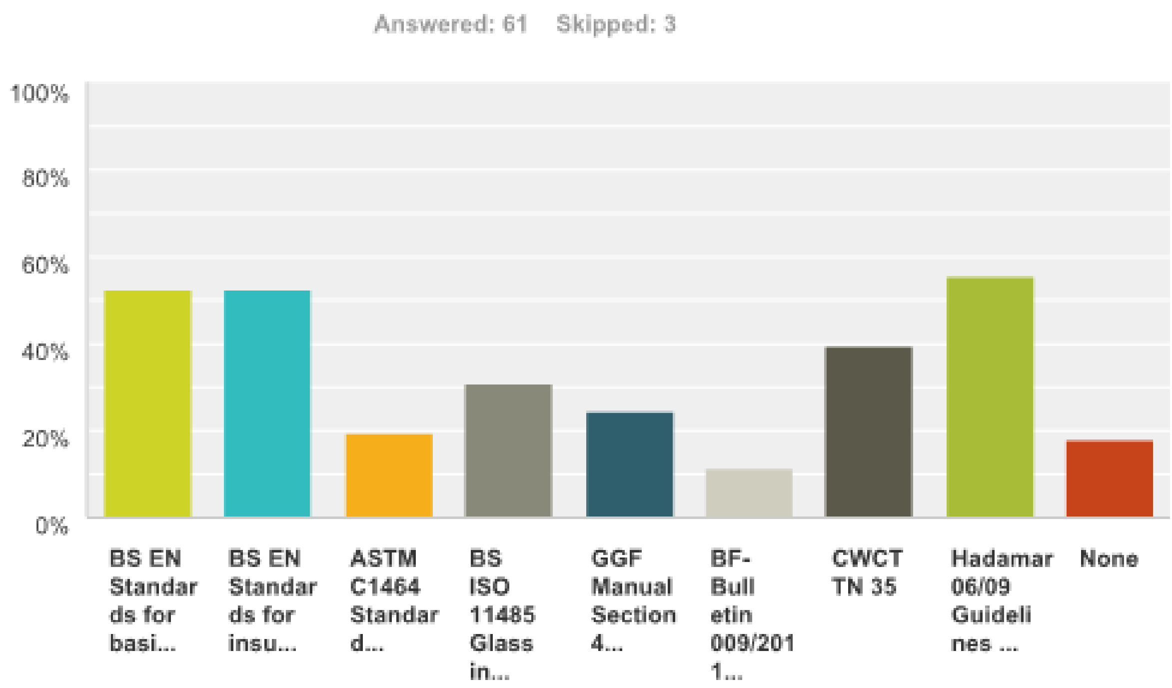


Figure 2.40: Graph results of survey Question 4.

The survey confirmed the participants use flat glass standards/guidance for specification of bent glass and therefore indicating a lack of bent glass references. Additional comments reaffirmed the limitations of the current standards for visual assessment, "Have previously specified criteria according Hadamar, but with distance according to BF-Bulletin 009. GGF Section 4 is incomplete. BS ISO 11485 and ASTM offer very limited guidance." (ANON, 23rd July 2015).

2.14.1 Standards and Guidance Reviewed

The following table lists the standards and guidance reviewed for this study and the relevance to glass types identified for use in curved glass buildings

Table 2.4: Table of relevance of standards/guidance for different glass types.

Key:

MARKERS

● denotes no relevance to glass type

xx denotes standard specific to glass type

x denotes standard with reference to glass type

STANDARD/GUIDANCE	GLASS TYPE						
	Flat	Curved	Annealed	Tempered	Laminated	Coated	IGU
BS EN 572-1:2012	xx	●	xx	●	●	●	●
BS EN 572-2:2012	xx	●	xx	●	●	●	●
BS 952-1:1995	x	●	x	x	x	x	●
BS 952-2:1980	x	x	x	●	●	●	●
BS EN 14179-1:2005	xx	●	●	xx	●	●	●
BS EN 12150-1:2000	xx	●	●	xx	●	●	●
BS EN 1863-1:2011	xx	●	●	xx	●	●	●
BS EN 12543-1:2011	x	●	●	●	x	●	●
BS EN 12543-6:2011	xx	●	●	●	xx	●	●
BS EN 1096-1:2012	xx	●	●	●	●	xx	●
BS EN 1279-1:2004	xx	xx	●	●	●	●	xx
BS ISO 11485-1: 2011	●	xx	xx	xx	xx	xx	xx

STANDARD/GUIDANCE	GLASS TYPE						
	Flat	Curved	Annealed	Tempered	Laminated	Coated	IGU
BS ISO 11485-2:2011	•	xx	xx	xx	xx	x	xx
BS ISO 11485 3 2014	•	x	•	x	x	•	•
ASTM C1464-06 (2011)	•	xx	x	x	x	•	•
BF Bulletin 009/2011	•	xx	x	x	x	•	x
GGF Part 1:2011	•	xx	x	x	x	•	•
GGF Part 2:2011	•	x	x	•	•	•	•
GGF Part 3:2011	•	x	•	x	x	•	•
HADAMAR 2009	xx	•	xx	xx	xx	x	xx
CWCT TN 35	xx	•	x	x	x	x	x

2.14.2 Relevance of Standards and Guidance Reviewed for Curved Glass Buildings

The following section summarises that the review identified there are limited standards/guidance that relate to the visual/optical quality of curved glass and often these reverted to flat glass standards for visual quality criteria. The review also highlighted that the key acceptance criteria for visual quality is a subjective parameter which is not objective or measurable. How therefore can visual quality be assessed against a standard or industry accepted benchmark?

It was evident during the research of this section that the detailed review of the standards was expansive and had limited relevance to the visual quality or comparison of different bent glass types. Therefore the detailed review is provided in Appendix B.

The following table lists the standards and guidance reviewed for this study and identifies relevance to curved glass and summarises inconsistencies and omissions for specification and visual assessment.

Table 2.5: Summary of key inconsistencies/omissions noted in Standards and Guidance

STANDARDS/GUIDANCE		Inconsistencies/omissions and notes for specification of curved glass
Float glass standards		
BS EN 572-1:2012.	Glass in building – basic soda lime silicate glass products. Part 1: Definitions and general physical and mechanical properties. BSI.	No reference to curved glass.
BS EN 572-2:2012	Glass in building – basic soda lime silicate glass products. Part 2: Float glass. BSI.	No reference to curved glass. Not possible to use the viewing methodology for optical quality (zebra board) for curved glass.
Additional flat glass standards		
BS 952-1:1995	Glass for glazing – Part 1: Classification. BSI.	No reference to curved glass.
BS 952-2:1980	Glass for glazing – Part 2: Terminology for work on glass. BSI.	Mentions some distortion may occur in coated glass if bent. No measurable criteria given.
Tempered glass standards – heat strengthened / fully toughened		
BS EN 1863-1:2011	Glass in building – Heat strengthened soda lime silicate glass. Part 1: Definitions and classification. BSI.	No reference to curved glass.
BS EN 12150-1:2000	Glass in building – Thermally toughened soda lime silicate safety glass. Part 1: Definitions and classification. BSI.	No reference to curved glass.
BS EN 14179-1:2005	Glass in building – Heat soaked thermally toughened soda lime silicate safety glass. Part 1: Definitions and classification. BSI.	No reference to curved glass.

STANDARDS/GUIDANCE		Inconsistencies/omissions and notes for specification of curved glass
Laminated glass standards		
BS EN 12543-1:2011	Glass in building – Laminated glass and laminated safety glass. Part 1: Definitions and description of component parts (ISO 12543-1:2011) BSI.	No reference to curved glass.
BS EN 12543-6:2011	Glass in building – Laminated glass and laminated safety glass. Part 6: Appearance. BSI.	No reference to curved glass. 2m viewing criteria – conflicts with other standards. Notes disturbing visible defects should be marked – this is subjective and not measurable.
Coated glass standards		
BS EN 1096-1:2012	Glass in Building – Coated glass Part 1: Definitions and classification. BSI.	No reference to curved glass. States defects should not be visually disturbing, – this is subjective and not measurable. 3m viewing criteria – conflicts with other standards.
Insulating glass standards		
BS EN 1279-1:2004	Glass in Building – Insulating glass units Part 1: generalities, dimensional tolerances and rules for the system description. BSI.	No reference to curved glass. Refers to single glass for visual quality.
Curved glass standards		
BS ISO 11485-1: 2011	Glass in building. Curved glass. Part 1. Terminology and definitions. BSI.	Makes no reference to visual assessment.
BS ISO 11485-2: 2011	Glass in building. Curved glass. Part 2: Quality	Less onerous dimensional tolerances of IGU compared to flat panels.

STANDARDS/GUIDANCE		**Inconsistencies/omissions and notes for specification of curved glass**
	requirements. BSI.	3m viewing criteria – conflicts with other standards. View vertically – this may not be the final position for the actual project and could look different in position.
BS ISO 11485 3: 2014	Glass in building. Curved glass. Part 3. Requirements for curved tempered and curved laminated safety glass. BSI.	Makes no reference to visual assessment.
ASTM C1464-06: 2011	Standard Specification for Bent Glass: C1464 – 06 (Reapproved 2011)	Reverts to flat glass standards for visual defects. 2m viewing criteria – conflicts with other standards. View vertically – this may not be the final position for the actual project and could look different in position.
Curved glass guidance		
BF Bulletin 009 / 2011	Guidelines for thermally-curved glass in the building industry.	Reverts to flat glass standards as a base due to lack of curved glass standards. 3m viewing criteria inside to out – conflicts with other standards.
Curved glass Part 1:2011	Generalities – Definitions, Terminology, Properties and Basis of Measurement and Test. GGF.	Notes curved glass will be of lower quality than the base glass and that the reflection will highlight surface distortion. Also laminating the glass will exacerbate this. 3m and normal to the area observed viewing criteria – conflicts with other standards. May not be possible to view to the normal.
Curved glass Part 2:2011	Curved annealed glass. GGF.	Reverts to Part 1 for visual and optical quality.
Curved glass Part 3:2011	Curved thermally treated glasses. GGF.	Notes curved glass will be of lower quality than the base glass and that the reflection

STANDARDS/GUIDANCE		Inconsistencies/omissions and notes for specification of curved glass
		will highlight surface distortion. Also body tinting coating or enamelling can exacerbate this. 3m and normal to the area observed viewing criteria – conflicts with other standards. May not be possible to view to the normal. Reverts to flat glass standard for body faults.
Visual assessment guidance		
HADAMAR 2009	Guideline to Assess the Visible Quality of Glass in Buildings.	No reference to curved glass 1m viewing criteria inside to out – conflicts with other standards.
CWCT Technical Note No 35	Assessing the appearance of glass.	Notes that generally visually assessment procedures are subjective. Advises 3m viewing distance if any doubt on distance.

2.15 Identifying the Parameters That Affect the Visual Quality of Curved Glass Buildings

Using the information consolidated from the review of the potential defects/attributes, this section summarises the parameters that were relevant to the visual consistency and assessment of bent glass for the specification and production of curved glass façades. This summary was limited by lack of literature information found on this subject in the desktop review. This was noted, "Furthermore, the quality features of flat and curved glass can be significantly different and that there is an absence of product standards." (Schuler, C et al. 2012). The summary is based on: review of the standards/guidance and glass production; the survey feedback and communication with industry. The aim was to:

- Identify the visual/optical defects which are relevant to the different glass/bending types and that cause inconsistencies due to panelisation.
- Indicate which standards refer to visual defects and visual assessment
- Reaffirm that there is limited support from the standards/guidance for visual consistency for curved glass buildings.

For this study the following relevant specification parameters affecting visual consistency were identified:

- Visual and optical/attributes for the particular glass types,
    - Roller wave.
    - Laminated glass lensing effects.
    - Coating colour variation.
- Tolerances for glass production.
    - Shape accuracy between panels.
    - Inconsistent reflection patterns.
- Visual acceptance measurement/criteria.
    - Distance for assessment.
    - Appropriate assessment position.
    - Assessment criteria.

The relevance of the standards/guidance to these key parameters is summarised in the following sections. The detailed review of the standards is in Appendix B.

2.15.1 Optical/Visual Defects – Defining and Evaluating

Optical/visual defects were noted in the standards/guidance.

BS EN 572-1:2012 provides a definition of optical and visual defects: Clause 6.5.1 Optical, optical quality faults are generally due to "distortion of the surface and lack of homogeneity" and these should use visual observation methods for evaluation.

Clause 6.5.2 Appearance, states "The visual quality can be affected by the presence of spot faults (bubbles, stones, etc.) linear/extended faults (scuff marks, scratches, lines, deposits, impressions, etc.) pattern faults and wire faults.

Spot faults are evaluated by specifying numbers and dimensions.

Linear/extended faults are evaluated by visual observation.

Pattern faults are evaluated by measuring deviation."

The distortion effects are a contributor to visual inconsistency. Spot and linear faults are defects that are not relevant to visual consistency of panelisation. The following table summarises the review of the standards in respect of visual/optical defects/attributes

Table 2.6: Table of standards/guidance reference to visual/optical defects/attributes.

Key:

(beige)	Not relevant to visual inconsistency.
(green)	Contributor to visual inconsistency.

MARKERS

- ● not referred in the standard/guidance.
- **X** defect/attribute noted within standard/guidance.

STANDARD/ GUIDANCE	DEFECT/ATTRIBUTE											FURTHER OBSERVATIONS
	Spots faults	Linear: faults	Tong marks	Roller wave	Roller pick up	Vents, interlayer defects	Anisotropy	Bow, pillowing	Brewsters fringes	Newton rings	Coating colour variation	
BS EN 572-1:2012	**X**	**X**	●	●	●	●	●	●	●	●	●	
BS EN 572-2:2012	**X**	**X**	●	●	●	●	●	●	●	●	●	
BS 952-1:1995	●	●	●	●	●	●	●	●	●	●	●	No reference to visual defects.
BS 952-2:1980	●	●	●	●	●	●	●	●	●	●	●	No reference to visual defects.
BS EN 1863-1:2011	●	●	**X**	**X**	**X**	●	**X**	●	●	●	●	
BS EN 12150-1:2000	●	●	**X**	**X**	**X**	●	**X**	●	●	●	●	
BS EN 14179-1:2005	●	●	**X**		**X**	●	**X**	●	●	●	●	
BS EN 12543-1:2011	●	●	●	●	●	●	●	●	●	●	●	No reference to visual defects.
BS EN 12543-6:2011	**X**	**X**	●	●	●	**X**	●	●	●	●	●	Does not allow ‘disturbing’ visual defects. This is subjective.
BS EN 1096-1:2012	**X**	**X**	●	●	●	●	●	●	●	●	●	Does not allow visually ‘disturbing’ defects. This is subjective.
BS EN 1279-1:2004	●	●	●	●	●	●	●	**X**	**X**	**X**	●	Reverts to the base glass standards for visual quality.
BS ISO 11485-1: 2011	**X**	**X**	●	●	●	●	●	●	●	●	●	Does refer to optical distortion due to the bending process.
BS ISO 11485-2:2011	**X**	●	**X**	●	●	●	●	●	●	●	●	

STANDARD/ GUIDANCE	DEFECT/ATTRIBUTE											FURTHER OBSERVATIONS
	Spots faults	Linear: faults	Tong marks	Roller wave	Roller pick up	Vents, interlayer defects	Anisotropy	Bow, pillowing	Brewsters fringes	Newton rings	Coating colour variation	
BS ISO 11485 3 2014	•	•	•	•	•	•	•	•	•	•	•	No reference to visual assessment.
ASTM C1464-06 (2011)	X	•	•	•	•	•	•	•	•	•	•	Refers to flat and laminated glass standards for blemishes.
BF Bulletin 009/2011	•	•	•	•	•	•	•	•	•	•	•	Refers to flat glass standards and Hadamar 2009 for optical quality.
GGF Part 1:2011	X	X	•	•	•	X	•	•	•	•	•	States bent glass will be lower quality than bent glass.
GGF Part 2:2011	•	•	•	•	•	•	•	•	•	•	•	Refers to part 1.
GGF Part 3:2011	•	•	•	•	•	•	•	•	•	•	•	Notes bent glass will be lower quality than flat glass. Refers to 575-2 for body faults.
HADAMAR 2009	X	X	•	X	•	X	X	X	•	•	X	
CWCT TN 35	X	X	•	X	•	X	X	X	•	•	X	

2.15.2 Tolerances - Defining and Evaluating

There were a number of tolerances referred in the standards/guidance that will influence the visual quality. Inconsistent reflection is noted as an issue and the GGF document Part 1 reiterates that reflection will highlight surface distortion. Tolerances were reaffirmed by industry specialists as a key contributor to visual quality (Figuerola, F. and Tarrus, J. *(pers.comm.)* 27th July 2015 and Arbós, F. *(pers.comm.)* 28th July 2015).

The following table summarises the review of the standards in respect of these tolerances.

Table 2.7: table of standards/guidance reference to tolerances effecting visual quality.

Key:

(beige)	not relevant to visual inconsistency.
(green)	contributor to visual inconsistency.

MARKERS

● not referred in the standard/guidance.

X noted within standard/guidance.

STANDARD/ GUIDANCE	DIMENSIONAL TOLERANCES NOTED							COMMENTS
	Dimensional tolerances (thickness)	Difference between diagonals/squareness	Edge Straightness	Shape tolerances girth/length	Cross curve deviation/sag	Twist tolerance deviation	Shape accuracy (IGU)	
BS EN 572-1:2012	●	●	●	●	●	●	●	
BS EN 572-2:2012	X	X	●	●	●	●	●	
BS 952-1:1995	X	●	●	●	●	●	●	
BS 952-2:1980	●	●	●	●	●	●	●	
BS EN 1863-1:2011	●	X	●	●	●	●	●	
BS EN 12150-1:2000	●	X	●	●	●	●	●	
BS EN 14179-1:2005	●	X	●	●	●	●	●	
BS EN 12543-1:2011	●	●	●	●	●	●	●	
BS EN 12543-6:2011	●	●	●	●	●	●	●	
BS EN 1096-1:2012	●	●	●	●	●	●	●	
BS EN 1279-1:2004	X	X	●	●	●	●	X	
BS ISO 11485-1: 2011	●	●	●	●	●	●	●	
BS ISO 11485-2:2011	X	X	X	X	X	X	X	Thickness tolerances refers back to flat glass standards.
BS ISO 11485 3 2014	●	●	●	●	●	●	●	
ASTM C1464-06 (2011)	X	X	●	X	●	X	●	Thickness tolerances refers back to flat glass standards.
BF Bulletin 009/2011	X	X	●	●	●	X	X	
GGF Part 1:2011	X	●	X	X	X	X	●	

STANDARD/ GUIDANCE	DIMENSIONAL TOLERANCES NOTED							COMMENTS
	Dimensional tolerances (thickness)	Difference between diagonals/squareness	Edge Straightness	Shape tolerances girth/length	Cross curve deviation/sag	Twist tolerance deviation	Shape accuracy (IGU)	
GGF Part 2:2011	x	x	x	•	x	x	•	
GGF Part 3:2011	•	x	x	•	x	x	•	
HADAMAR 2009	•	•	•	•	•	•	•	
CWCT TN 35	•	•	•	•	•	•	•	

2.15.3 Measurement/Assessment Criteria

Certain standards provided guidance for measurement and assessment of visual/optical defects and for dimensional tolerance criteria. These can be used for specification and quality control. However, Table 2.3, Table of standards/guidance reviewed and relevance to glass types indicates, a number of different standards overlap for a glass type and these may conflict if the visual acceptance measurement criteria are not aligned.

The following table indicates key items identified in the standards for assessment of visual/optical quality and dimensional tolerances and highlighted the lack of coherency in the standards/guidance where relevant.

Table 2.8:Summary of standards for assessment of visual/optical quality and dimensional tolerances

Standard/Guidance	Visual/Optical faults and Dimensional Tolerance key criteria	Means of observation/distance of assessment
BS EN 572-1:2012	Optical faults: *6.5.1: 'main faults that can affect the visual quality are distortion of the surface and lack of homogeneity in the body of the glass'.*	*6.5.1: 'optical quality shall be evaluated by means of a visual observation method'.*

Standard/Guidance	Visual/Optical faults and Dimensional Tolerance key criteria	Means of observation/distance of assessment
BS EN 572-2:2012	Zebra board methodology for assessing optical quality. Spot fault measurement.	2m.
BS 952-1:1995	*2.2.1: 'there is always some distortion of vision and reflection.'*	No reference.
BS 952-2:1980	*7.1 ' Some types of annealed glass may exhibit changed characteristics in the process of bending (eg. Shade in some coloured glasses).'*	No reference.
BS EN 1863-1:2011	*6.3.1 'By the very nature of the toughening process, it is not possible to obtain a product as flat as annealed glass'.* Measurement for bow, roller wave, edge lift, local distortion. Refers to anisotropy as an effect.	No reference.
BS EN 12150-1:2000	*6.3.1 'By the very nature of the toughening process, it is not possible to obtain a product as flat as annealed glass'.* Measurement for bow Roller wave noted, but no measurement, rollerpick up. Refers to anisotropy.	No reference.
BS EN 14179-1:2005	*8.3.1 'By the very nature of the toughening process, it is not possible to obtain a product as flat as annealed glass'.* Measurement for bow Roller wave noted, but no measurement. Refers to anisotropy.	No reference.
BS EN 12543-1:2011	No reference	No reference.
BS EN 12543-6:2011	Limiting criteria for all spot and linear defects.	2m perpendicular to the glass.

Standard/Guidance	Visual/Optical faults and Dimensional Tolerance key criteria	Means of observation/distance of assessment
	Notes does not allow *disturbing* visual defects. Criteria is subjective.	
BS EN 1096-1:2012	Observation guidance detection of defects. Limiting criteria for spot and linear defects. Table 1 notes that defects should not be *'visually disturbing'* Criteria is subjective.	Minimum distance 3m.
BS EN 1279-1:2004	Refers to the single glazing standards for optical and visual requirements. Refers to glass deflection due to temperature and barometric differences but no acceptance criteria.	No reference.
BS ISO 11485-1: 2011	Definitions of defects and dimensional terms given.	No reference.
BS ISO 11485-2:2011	Measurement for shape accuracy, edge straightness deviation, cross curve deviation, twist deviation.	3m in a vertical position.
BS ISO 11485 3 2014	No reference.	No reference.
ASTM C1464-06 (2011)	Measurement for dimensional tolerances shape accuracy, twist and cross-bend. Visual inspection for blemishes.	2m in a vertical position.
BF Bulletin 009/2011	Refers to Hadamar 2009 Notes reflectance of curved glass influences transparency and optical quality.	3m looking from the inside to the outside.
GGF Part 1:2011	Measurement for dimensional tolerances shape accuracy, edge straightness, side straightness, cross deviation and twist. *6.1 Any bending process will inevitably result in a product whose optical quality is lower than that of the glass from which it was produced'.*	3m and be normal (90 degrees) to the area being observed.

Standard/Guidance	**Visual/Optical faults and Dimensional Tolerance key criteria**	**Means of observation/distance of assessment**
	Refers back to the different glass types for assessment of visual defects.	
GGF Part 2:2011	Refers to Part 1. Criteria for dimensional tolerances.	No reference.
GGF Part 3:2011	Measurement of dimensional tolerances refers to GGF Part 1. *8.1 Any bending process will inevitably result in a product whose optical quality is lower than that of the glass from which it was produced'.* *8.1.2 The pane will be deemed acceptable if there is no significant distortion of the image in transmission'.* This is subjective.	3m and be normal (90 degrees) to the area being observed.
HADAMAR 2009	Visual/optical defect limitations.	1m from the inside to the outside.
CWCT TN 35	Summarises the different standards and guidance.	Suggests 3m if no criteria given.

2.15.4 Summary of Review of Glass Standards/Guidance for Curved Glass Buildings

The review highlighted the following key issues:

- Comparing the flat glass material standards highlighted the lack of consistency for assessing visual defects. A detailed study of this has been carried out "Improved Methodology for Visual Assessment of Glass" I'Anson. Z (2011).
- There are defects noted that are not relevant to visual consistency of curved glass buildings.
- Standards did not provide clear guidance on achieving or assessing the visual quality/consistency of bent glass.
- There are limited standards for hot bent glass and none specific to the process of cold bent glass (although testing standards are available).

- The bent glass standards provided limited advice for visual quality and often reverted to the flat glass standards for guidance, which have been identified as inconsistent or cannot be applied practicably.
- There are overlaps of criteria between standards that conflict.
- There was no guidance found for assessing visual quality between the different bending types.

An example of conflicts is the reference back to flat glass standards for bent glass. It is not possible to apply the same measuring criteria for visual defects and assessment as bent glass is not viewed in the same way. For example the zebra board methodology in BS 572-2: 2012 for assessing optical quality could not practicably be applied to bent glass as due to the curvature the glass would never be possible to be viewed without distortion of the zebra marks. Refer to Appendix B for the methodology. Subsequently there is incoherence for assessing the visual and performance criteria for the different types of glass applied to curved glass buildings.

2.16 Further Statutory Requirements and Guidance Influencing Glass Type

The specification of the glass will be influenced by further performance parameters. These will impact the choice of glass type and in the case of bending, the methods possible to achieve the curvature required.

2.16.1 Safety and Strength

If the glass is in an overhead position, then post breakage failure/safety glass requirements will necessitate the glass to be laminated in order that it stays in place when any or all plies are broken. Further guidance can be sought in the CWCT Technical Notes: TN 66, 67, 68 and 92.

Glass has to accommodate loads including, barrier, wind and snow loads. These will determine the glass thicknesses or whether glass with enhanced strength should be used, such as tempered or chemically toughened.

The type of fixing system will also influence and point fixed systems require tempered glass or chemically toughened glass.

2.16.2 Thermal/Solar Requirements

U and g value requirements influence the glass build up. To meet the required U value for a commercial building an IGU will be required. The glass may be subject to thermal stress and therefore a tempered glass may be required. This will negate the use of annealed hot bent slump formed glass.

The g value required may necessitate coatings and these can distort if subjected to hot bending processes. Often the colour of the coating will be different when hot bent compared to flat glass application.

2.16.3 Acoustic Requirements

Acoustic criteria influence on the glass build up may require acoustic PVB or for the units to be triple glazed. This adds a further complication to the dimensional tolerances of a curved glass unit.

Lamination of tempered and curved glass may also lead to visual distortion due to lensing effects.

2.17 Summary of Visual Consistency Limitations Due to Deficiencies of Standards/Guidance for Curved Glass Buildings

The standards and guidance review identified that information available to determine visual and optical quality was very limited and that measurement/assessment techniques are deficient.

It was identified in the curved glass standards/guidance that that the limitations on dimensions and geometry twist for example provided a basis for controlling the deviation between panels and as such may assist in controlling the visual quality between adjacent panels, which is highlighted due to the reflection given.

It is not possible with the current standards and guidance to identify the key acceptance criteria for the different types of bent glass or their relationship to flat glass.

In summary:

- The production of flat glass and the enhanced processes affect visual characteristics.
- To achieve the building form different types of bending method may be required for the panelisation and each differ in performance and visual attributes.
- The visual characteristics vary between flat, cold bent and hot bent glass.
- The consequence of panelisation using several types is visual inconsistency is more likely.
- There is very limited written guidance or industry standards to address the production and quality of curved glass or how to measure visual assessment.
- Visual acceptance criteria is subjective and not measurable.
- There is no guidance on managing the potential visual inconsistencies between different types.

- Different glass types are required to meet building performance – strength thermal acoustic requirements etc. This will impact the types possible to use.
- Good production methods and controlling the tolerances of the material assist visual quality.
- The reflection properties of glass highlight visual inconsistency issues.

Having identified the limitations within the standards/guidance for visual defects/attributes and visual inconsistency of curved glazed façades, understanding what these manifestations were and how they impact the design process and the bending procurement choice was a key part of the study.

3 CONSEQUENCES OF PANELISATION – EXAMPLES AND CASE STUDIES

3.1 Challenge to Achieve Visual Consistency

The purpose of this chapter was to illustrate the inconsistencies in curved glass façades using:

- Examples of visual manifestations from built examples illustrating:
    - Hot bent defects/attributes due to the glass type/bending method.
    - Cold bent defects/attributes due to the glass type/bending method.
- Case studies for hot and cold bent projects illustrating:
    - The challenge of rationalising the number of panel types to meet the curved geometry.
    - The impact of fixing methodology.
    - How performance criteria can impact the glass types and bending method choice.
    - How the panelisation might be rationalised and the effect on the overall building form.
    - The importance of sampling, benchmarking and quality control during production.

3.2 Examples of Hot and Cold Bent Defects/Attributes Causing Visual Inconsistency

Visually inconsistent glazed façades can have adjacent panels which appear incongruous. A key issue identified during the study was the impact of inconsistent reflections caused by defects to the glass or excessive tolerances. “Consistent reflection is the key.” (Arbós, F. *(pers.comm.)* 28th July 2015). Reflectivity and subsequent perceived distortion is a subjective parameter that is not possible to measure.

Figure 3.1: Curved glass adjacent to flat glass, Aldersgate, London – visually similar.

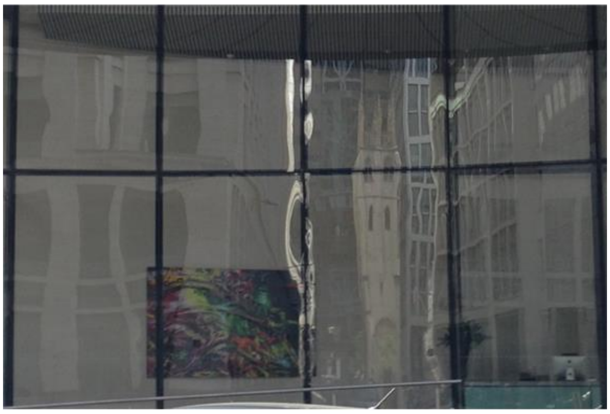


Figure 3.2: Curved glass, Gresham Street, London – visual distortion in adjacent curved panels.

The potential issues were acknowledged by the participants of the survey.

3.3 Summary of Potential Defects in Hot Bent glass

These key visual issues for hot bent glass were identified for the pilot survey from early consultation with designers and producers. They were included in the survey so the extent of each could be assessed in respect of the visual quality of curved glass buildings.

Question 5 of the survey:

HOT BENT GLASS. Have you experienced poor visual quality of curved glass used in buildings due to any of the following for hot bent glass? (Please tick all that apply)

Answer Choices	Responses	
Visual inconsistency of flat glass adjacent to hot bent glass	57.38%	35
Visual inconsistency of cold bent glass adjacent to hot bent glass	16.39%	10
Poor visual quality due to soft coatings on hot bent glass	36.07%	22
Poor visual quality due to hard coatings on hot bent glass	22.95%	14
Excessive roller wave on regular radial/conical formed hot bent glass	52.46%	32
Poor visual quality due to distortion in laminated hot bent glass	49.18%	30
Have not noticed poor visual quality in hot bent glass	16.39%	10
Have no experience of hot bent glass	9.84%	6
Total Respondents: 61		

Figure 3.3: Survey results Question 5.

Figure 3.4: Graph results of survey Question 5.

Additional participant comments highlighted certain additional parameters to influence visual consistency, “The bend radius has a big influence on the final appearance of the glass and on the coating selection”. (ANON., 15th July 2015).

The participants confirmed key issues of flat glass adjacent to hot bent glass and excessive roller wave. The following are examples of some of these manifestations.

Visual inconsistency of flat glass adjacent to hot bent glass

Figure 3.5: Flat glass adjacent to radial formed curved tempered glass.

The flat glass appears consistent, whereas the curved glass indicates roller wave.

Poor visual quality due to different coatings on hot bent glass

Figure 3.6: Coating inconsistency between the curved and flat glass. (MFT, 2015)

The façade contractor proposed different low e soft coatings for the flat and the curved glass with the intention that they would match.

The following images illustrate that the visual appearance between flat and bent glass can be different depending on the light and reflection. The subject on London Wall, London is hot bent radial glass adjacent to flat glass. The appearance is less consistent on a bright day.

Figure 3.7: Colour appears more consistent on a dull day.

Figure 3.8: Colour appears inconsistent on a bright day.

Figure 3.9: Colour appears inconsistent on a bright day.

Poor visual quality due to hard coatings on hot bent glass

Figure 3.10: Slump formed hot bent glass Coating air side caused colour distortion (Ramboll, 2009).

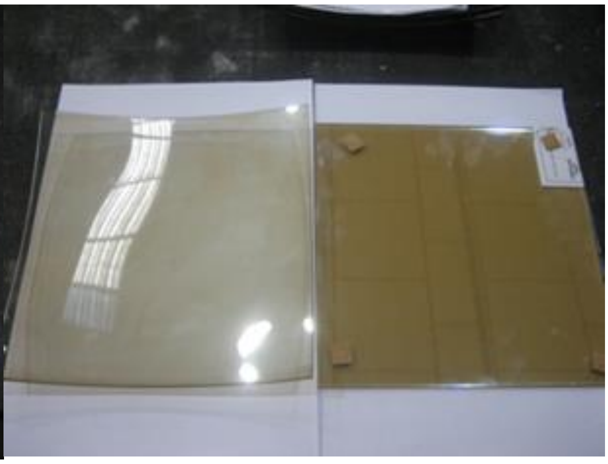


Figure 3.11: Slump formed hot bent glass Coating mould side caused colour distortion. (Ramboll, 2009).

The glass can display distortions due to roller wave and pillowing effects and these are very visible on brighter days

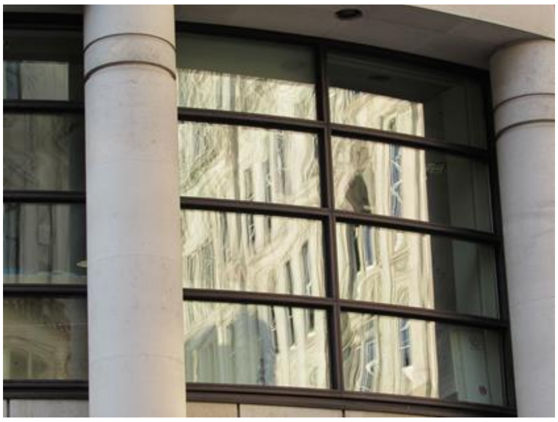


Figure 3.12: Distortions in the radial bent glass.

Figure 3.13: Distortions in the radial bent glass.

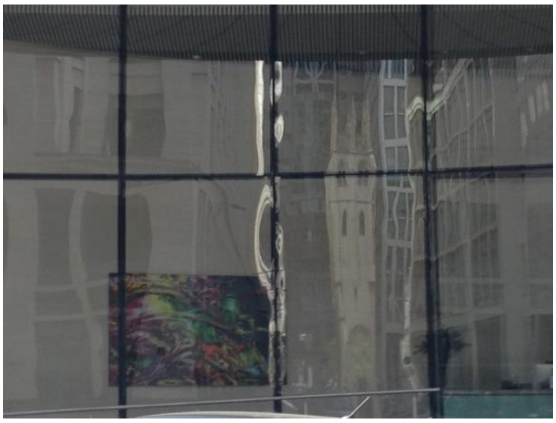


Figure 3.14: Excessive edge distortion due to the radial formed process.

Figure 3.15: Excessive edge distortion due to the radial formed process.

Poor visual quality due to inherent attributes of tempering

Figure 3.16: Anisotropy viewed due to tempering.

Figure 3.17: Anisotropy viewed due to tempering.

3.4 Summary of Potential Defects in Cold Bent glass

These key visual issues for cold bent glass were identified for the pilot from early consultation with designers and producers. They were included in the survey so the extent of each could be assessed in respect of the visual quality of curved glass buildings.

Question 6 of the survey:

Have you experienced poor visual quality of curved glass used in buildings due to any of the following for cold bent glass?

Answer Choices	Responses	
Visual inconsistency of flat glass adjacent to cold bent glass	18.97%	11
Visual inconsistency of hot bent glass adjacent to cold bent glass	15.52%	9
Poor visual quality due to coatings on cold bent glass	6.90%	4
Excessive roller wave of cold bent tempered glass	6.90%	4
Poor visual quality due to distortion in laminated cold bent glass	18.97%	11
Have not noticed poor visual quality in cold bent glass used on a project	17.24%	10
Have no experience of cold bent glass	51.72%	30
Total Respondents: 58		

Figure 3.18: Survey results Question 6.

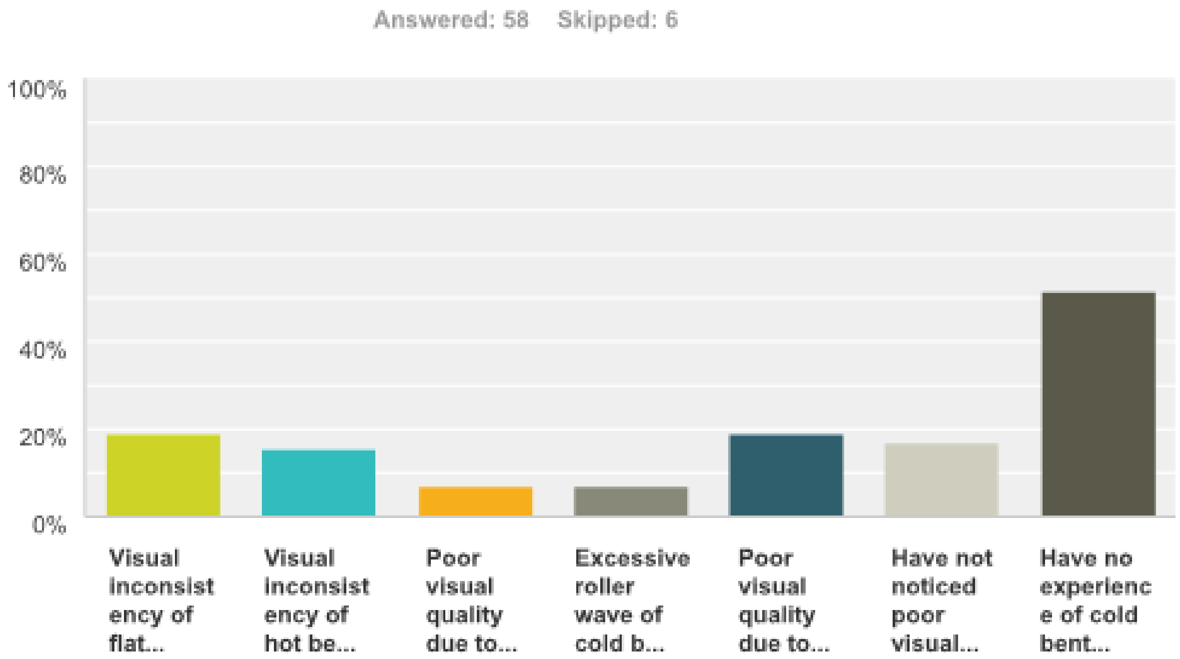


Figure 3.19: Graph results of survey Question 6.

Additional participant comments highlighted certain additional parameters to influence visual consistency, “The appearance is highly dependent of how much the glass is cold bent”. (ANON., 15th July 2015).

The participants indicated there was less experience of the cold bent formed glass. The key issue raised was visual inconsistency of laminated cold bent glass. The following are examples of some of these manifestations.

Excessive roller wave of cold bent tempered glass and poor visual quality due to distortion in laminated cold bent glass

Figure 3.20: Anon project: Excessive roller wave in tempered cold bent glass.

Figure 3.21: Anon project: Subsequent multilayer lens effect due to lamination and roller wave.

3.5 Limitations Due to Visual Inconsistency of Bent Glass

The examples illustrate some of the potential inconsistencies that occur in bent glass. It has been identified that these are attributed to certain glass types and particular bending methods. The limitation therefore is if these are used simultaneously on a building there is potential for visual mismatch. The categorisation of the panelisation is therefore a key contributor to identifying potential visual inconsistencies.

3.6 Case Study 1: NHHQ – Example of Panelisation

This office project in Abu Dhabi designed by Zaha Hadid Architects is an example illustrating the potential complexity of the panelisation. The façade engineer was Ramboll.

The freeform design was based on a general concept of a double skin façade with an outer curved single glazed skin and inner facetted double glazed skin. This was to allow a majority of the bent glass to be single glazed which would be more cost effective than curving double glazed units. However, there were areas of the façade which would not have been practical to adopt a double skin solution and these were proposed to be a curved double glazed single skin. The areas affected were the triple height top level and the podium level.

Although the project was not completed, it can be used as an example to highlight some of the potential visual and specification issues for the different build ups which have been identified in the previous chapter. A limitation to the study was a request by Zaha Hadid Architects that certain material was not published due to the confidentiality of the project.

Identification of the panelisation can be carried out in a number of ways depending on the parameters used to analyse the curvature. The panel categories diagram by Ramboll in figure 3.22 identifying the curvature is simplistic as it does not identify where the different types of cold and hot bent curvature may occur within these bending types.

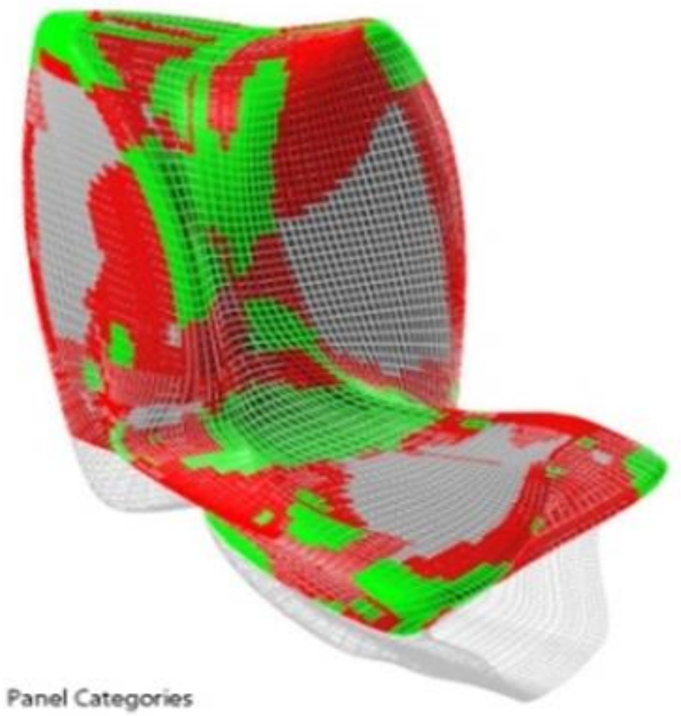


Figure 3.22: NHHQ – indicative panelisation.
Grey – flat glass.
Red – single curved (cold bent/hot bent to include radial).
Green – double curved (hot bent slumped).
(Ramboll 2009)

Additional studies were carried out by others and the following images illustrate options for the panelisation at design stage and the impacts on the visual consistency.

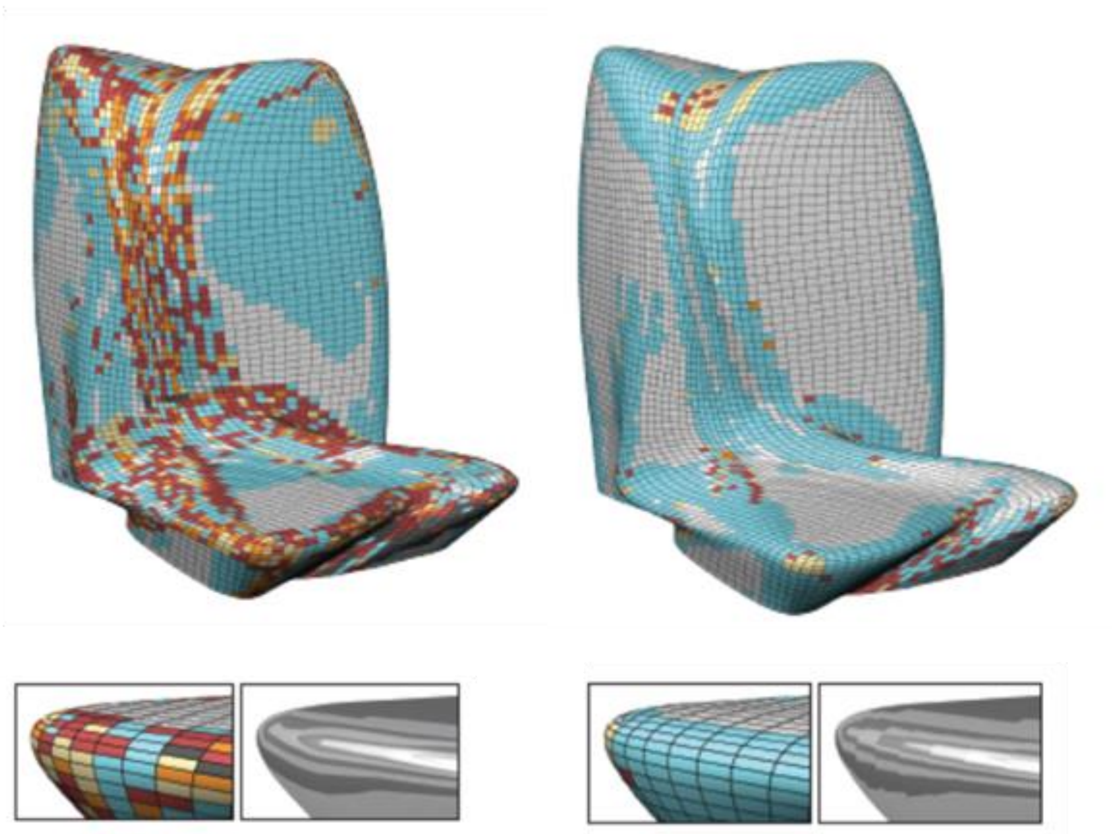


Figure 3.23: Interpretation examples of varying panelisation. National Holdings Headquarters Building, Abu Dhabi. (Stanford Graphics, 2015)

Although these images have limitations as they are virtual and do not depict the particular visual characteristics of the glass types, they do highlight the issue of the number of types that can be applied simultaneously to a single façade. The right hand images illustrated that through changing the panelisation, it is possible to reduce the number of bent glass types but this has an effect on the smoothness of the façade and visual consistency of the façade.

The image on the left achieved a smoother façade but required a greater range of glass types flat and bent and consequently adjacent panels may have different visual attributes. The right hand image used more of the same type, but compromised the smoothness as the modelled reflection is more facetted, which will also give an inconsistency. This emphasises the issue of how can a homogenous curved glass façade be achieved when a number of different glass types and bending methods are proposed for a total façade solution.

The study also illustrated how complex the panelisation categorisation can be and these may be bent in different ways with different glass types to achieve the geometry.

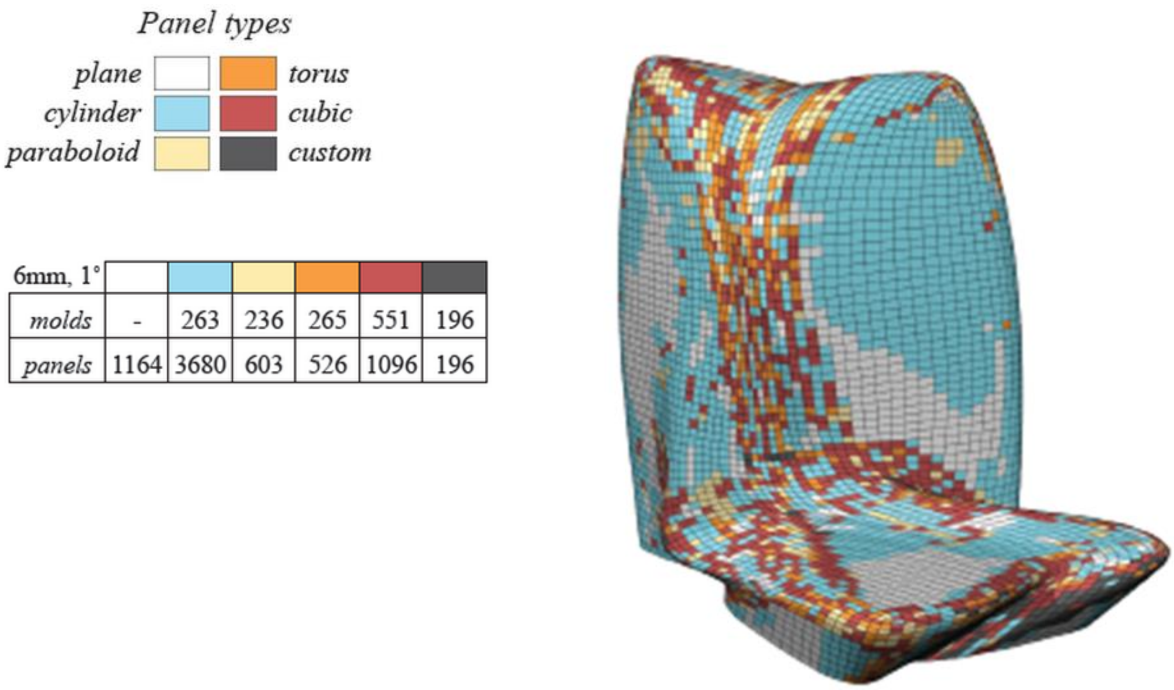


Figure 3.24: NHHQ panelisation interpretation and types identified. (Stanford graphics, 2015)

Using the geometry classifications above identified by the modeller the following potential glass build ups and bending methods possible were identified. The purpose was to illustrate how open the specification could be if based on panel geometry classification alone.

Table 3.1: Geometry definitions and potential bending types.

Key:

AN	annealed glass.
HS	heat strengthened glass.
FT	fully toughened glass.
mon	monolithic pane.
lam	laminated pane.
●	not feasible.

Geometry classifications identified in the study	**The possible bending type and glass substrate**				
	Flat	**Cold bent forced**	**Cold bent laminated**	**Hot bent radial**	**Hot bent slumped**
Plane/Flat	AN mono/lam HS mono/lam FT mono/lam	●	●	●	●

Geometry classifications identified in the study	**The possible bending type and glass substrate**				
	Flat	**Cold bent forced**	**Cold bent laminated**	**Hot bent radial**	**Hot bent slumped**
Single curved	•	HS mono/lam FT mono/lam	AN lam HS lam FT lam	HS mono/lam FT mono/lam	AN mono/lam
Double curved	•	•	•	•	AN mono/lam
Cylinder	•	•	AN lam HS lam FT lam	HS mono/lam FT mono/lam	AN mono/lam
Paraboloid	•	•	AN lam HS lam FT lam	•	AN mono/lam
Torus	•	•	•	HS mono/lam FT mono/lam	AN mono/lam
Cubic (considered as double curved)	•	•	•	•	AN mono/lam
Custom	•	•	•	•	AN mono/lam

This example highlighted that a large number of glass type/bending methods can achieve the curvature geometry of the façade glazing. This potential ambiguity highlights the need to understand the visual attributes for each type, so that the specification can be used to identify which key visual parameters are important for a particular project and achieve the best visual consistency based on the key project drivers of cost, quality and programme.

3.6.1 Effect of Fixing Methodology

The method of fixing the glass also has to be considered as different systems will provide support in different ways that will influence the visual characteristics. For example point fixing compared to a continuously fully supported fixing system. The latter provides more consistent visual quality due to the continuous support method. In particular for the cold bent forced method as acknowledged by N. Diller (Diller, N. *(pers.comm.)* 1st July 2015). This was considered for the case study and a fully supported solution proposed for the project as there was concern of potential pillowing of the glass between the point supports.

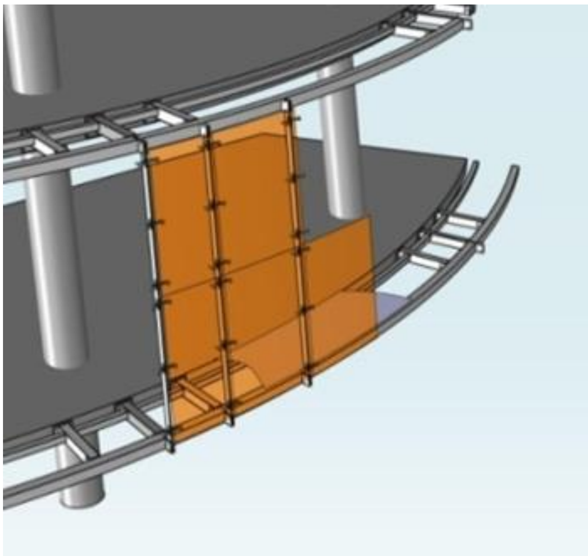


Figure 3.25: NHHQ fixing method – point fixed. (Ramboll, 2009)

Figure 3.26: NHHQ fixing method – continuously. (Ramboll, 2009)

3.6.2 Effect of Performance Requirements

The choice of glass type is influenced by performance requirements. For the case study 20% of the panels were identified as freeform bent to meet the geometry and would therefore be annealed glass. An example of performance limitation imposed on the bending types was due to the climate as the façade would be susceptible to thermal stress and this risk had to be assessed. The options were to repanelise to allow for toughened glass bent solutions, or carry out extensive thermal stress analysis to assess the risk.

Another example was that the inclined geometry of the façade would require post breakage failure safety measures both for the internal and external pane. The panes would need to be laminated. Additionally they might have to be tempered due to risk of thermal stress. This build-up of tempered double laminate has potential for visual distortion due to lensing effects.

3.6.3 Consequence of the Panelisation Categorisation

Potentially panels could be adjacent that are annealed or tempered and also laminated. The different visual attributes for these could be significantly different with roller wave, visual lensing and coating distortion effects between the panels for example.

The panelisation identified can render a specification open to interpretation and subsequently provide a visual consistency risk to the client. To understand how the finished building may look each of these types needs to be identified and its visual attributes known. The specification needs to be clear to identify to the façade contractor and glass processor what visual attributes are acceptable for the entirety of the façade.

3.7 Case Study 2: The Opus – Example of Rationalisation

This office building in Dubai was designed by Zaha Hadid Architects. Ramboll were the façade engineer for the project. A similar panelisation study was carried out for the categorisation of the panel types as for case study 1. These studies are not permitted for publication. However, this case study, illustrates a further stage of panelisation rationalisation carried out by a specialist façade contractor.

The project was reviewed with several specialist contractors for the tender. Part of the tender process was to analyse the panelisation and identify value engineering potential. The contractors identified the hot bent slump formed panels as a high cost and the risk of potential failure of annealed glass due to thermal stress. One contractor sought to minimise the application of the slump formed type through the re-panelisation of the façade to increase the number of forced cold bent panels. Figure 3.27 illustrates the original panelisation identified by the architect and which was analysed by the façade contractor. Figure 3.28 is the proposal by the façade contractor with the amended geometry panelisation and the subsequent impact on the overall form. By doing this, the façade contractor could offer a cost and programme saving to the client, which were key drivers for this particular project.

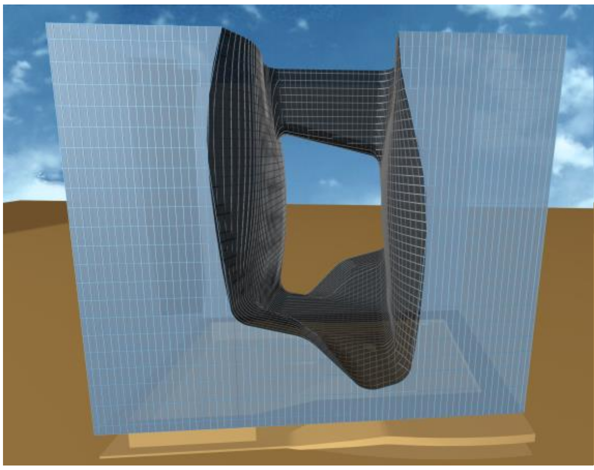


Figure 3.27: ZHA geometry and panelisation of the Opus. (Ramboll, 2009)

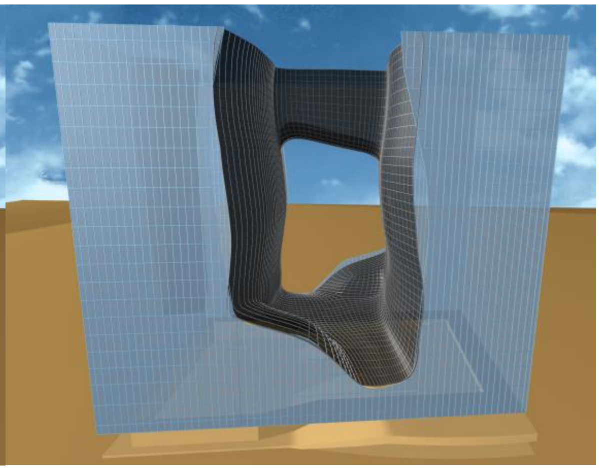


Figure 3.28: Façade Contractor proposed rationalisation of the panel geometry to minimise hot bent glass. (Ramboll, 2009)

Subsequently the project has been redesigned to be an office and hotel and is under construction. Unfortunately, there is no information available of the panelisation outcome for the final design illustrated below.

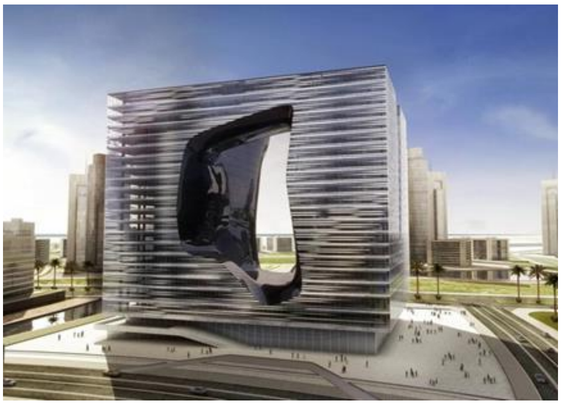


Figure 3.29: current image of the Opus office and hotel project. (Architect daily, 2015)

3.8 Case Study 3: Anon – Example of Importance of Visual Assessment Criteria

The purpose of this case study is to illustrate the importance of identifying the visual assessment criteria and benchmarking the acceptance quality. The façade engineer was Ramboll.

This project is confidential. It was a mixed use building with retail, office and residential units. The project included a mixture of curved glass both hot bent radial and also cold bent forced. The visual quality was a problem for the upper residential floors using the cold bent forced method. This method was proposed as it is cost effective and tempered glass was required for strength due to potential impact loads from the building maintenance unit (BMU).

Figure 3.30: Anon project – partial image of the upper storeys. (Ramboll, 2013)

It was identified that as the view became more oblique there was significant visual distortion.

Figure 3.31: Anon project – view perpendicular. (Ramboll, 2013)

Figure 3.32: Anon project – view becoming oblique. (Ramboll, 2013)

Figure 3.33: Anon project – view at extreme angle. (Ramboll, 2013)

Figure 3.34: Anon project – the phenomena was recurring. (Ramboll, 2013)

The level of distortion was unexpected and mitigation measures were introduced for the replacement panels. It was identified that the due to the use of tempered glass and lamination, the glass was subject to a multilayer lensing effect as both panes were laminated for the DGU.

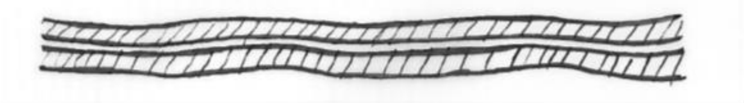


Figure 3.35: Waves in tempered laminated glass – matching.

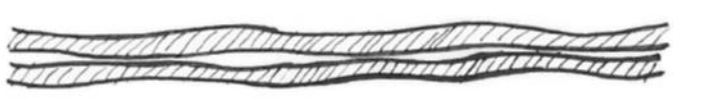


Figure 3.36: Waves in tempered laminated glass – mismatch creating lenses.

The mitigation measures adopted were to reduce the tolerance of the roller wave and to ensure each panel was viewed in its final position prior to leaving the factory.

Figure 3.37: Anon project – A typical pane found to have excessive roller wave distortion. (Ramboll, 2013)

Figure 3.38: Anon project – A typical pane found to be visually acceptable. (Ramboll, 2013)

This viewing criteria of inspecting the panel in its proposed position was not identified in the standards/guidance considered in the study. Generally viewing is advised with panels vertical and the observer perpendicular. Detail is summarised in table 2.7. This demonstrates the inadequacy of current standards/guidance for the specification of visual consistency of curved glass.

3.9 Summary of Visual Consistency Issues due to Panelisation

Key issues identified:

- Panelisation categorisation can encompass different glass bending methods and different glass types to meet the same geometry.
- Different glass and bending types have particular visual/optical defects and attributes.
- Annealed and tempered glasses may potentially fulfil the requirements and depending on how the final procurement of the panels is decided, then there is potential for these to be adjacent although they have different visual characteristics:
    - Annealed glass tends to have least visual distortion.
    - Tempered glass may have roller wave and inherent attributes such as anisotropy.
    - Laminated glass can have multi-layering lens effects especially if tempered.
    - Same coatings applied to flat and curved glass are not visually consistent particularly if tempered.
- The performance specification can provide the subcontractor with a number of options to achieve the geometry required.

- Clear visual assessment and acceptance criteria are needed in the specification.

3.10 The Way Forward

The issues identified illustrate the importance of establishing the key criteria and project drivers applicable to each unique project and ensure that the specification embraces the requirements. The impact of these criteria and drivers can be assessed in a road map/guide to inform the specification.

4 PRELIMINARY ROAD MAP FOR IMPROVING VISUAL CONSISTENCY OF CURVED GLASS FAÇADES

This dissertation has illustrated that there is potential for poor visual consistency of curved glass buildings. This section aimed to provide a methodology that could be used to assist the decision making process for choice of panelisation and improve the specification of curved glass façades by identifying the risks. This was considered by:

- Summarising the bending types – pros, cons and characteristics that were appraised during the study.
- Identifying decision making influences for glass types and panelisation.
- Using examples for a preliminary design roadmap for curved glass façades.

4.1 Design Considerations for Types of Bending – Pros, Cons and Attributes

The different glass types and methods of bending and their potential visual defects/attributes identified during this study are summarised as pros and cons in the table below and were used to support the preparation of the preliminary roadmap.

Table 4.1: Summary of key design and production parameters for curved glazed façades – pros and cons.

GEOMETRY	
Hot Bending	**Cold Bending**
PROS Better suited for radial or complex free form geometry.	***PROS*** Most appropriate solution for single point bent when 1 corner is forced. May be used for 2 point bending – larger radii.
CONS More visual/optical distortion if radially bent. Roller wave and roller pick up.	***CONS*** If bending using laminated method, some spring back may occur over time.
PRODUCTION	
Hot Bending	**Cold Bending**
PROS Radial hot bent uses tempering ovens that are also used for flat tempered glass. Process is fast.	***PROS*** Forced bent requires engineering capability, but not specialist glass equipment for manufacturing

CONS Slump formed requires specialist engineering experience for production. Special moulds are required. Radial bending has most wastage of all types. (Diller, N. *(pers.comm.)* 1st July 2015*)*.	***CONS*** Laminated cold bent requires engineering capability and autoclave for manufacturing.
APPEARANCE	
Hot Bending	**Cold Bending**
PROS Slump formed gives the best visual consistency (Figuerola, F. *(pers.comm)* 27th July 2015).and (Diller, N. *(pers.comm.)* 1st July 2015*)*.	***PROS*** Forced bent – minimal distortions – subject to those of flat glass. Laminated – minimal distortions due to bending process.
CONS Radial hot bent is subject to roller wave and anisotropy. Slump formed may be subject to warp distortion due to reflection and mould marks.	***CONS*** Over bending of forced cold bent will cause a ridge or dish to form Subject to roller wave if tempered glass used. Lensing affect if then laminated.
COATINGS	
Hot Bending	**Cold Bending**
	PROS Forced cold bent does not affect coatings. Laminated bent is unlikely to affect coatings – prototypes may be advised.
CONS Radial and slump formed bending will require testing of coatings. Coatings need to be temperable. Colour may be affected and not look the same as flat glass.	
STRENGTH	
Hot Bending	**Cold Bending**
PROS Radial formed can be tempered and laminated and therefore in either case is a safety glass	***PROS*** Forced cold bent is usually heat strengthened or fully toughened to accommodate the bending

Radial or slump formed glass does not does not undergo continuous stress.	stresses. Can be laminated as heat strengthened or monolithic fully toughened to be safety glass. Laminated cold bent can use tempered glass. It can also be achieved using annealed glass and therefore deemed a safety glass.
CONS Slump formed is annealed. It can be laminated to be a safety glass. Thermal stress can be an issue. Slump formed cannot be tempered. Can be chemically toughened although if monolithic is not classified a safety glass due to breakage pattern.	***CONS*** Forced bending causes continuous stress in the glass.
SUPPORT MECHANISM	
Hot Bending	**Cold Bending**
PROS Radial – can be fully supported or point fixed. Silicone bonding is possible for radial and slump formed.	***PROS*** Laminated cold bent can be fully supported or point fixed.
CONS Point fixing for radial formed, requires holes to be pre-drilled prior to tempering. Slump formed generally requires to be fully supported as annealed. Cannot be point fixed due to stresses. (unless chemically toughened, but then needs to be laminated if to be safety glass).	***CONS*** Forced bending - fully supported edge preferred as point fixing may lead to pillowing along the edge. Silicone bonding – will be subject to stresses. Mechanical fixing recommended. (Diller, N. *(pers.comm.)* 1st July 2015*).*
SITE CONSIDERATIONS – PREFABRICATION OR ON-SITE INSTALLATION	
Hot Bending	**Cold Bending**
PROS Radial and free form can be installed in an off-site prefabricated unitised systems. Radial and free form can be installed into stick system.	***PROS*** Forced bent and laminated can be installed in off-site prefabricated unitised systems.

	CONS Forced bent not practical for a site stick system.
COST	
Hot Bending	**Cold Bending**
PROS Radial formed is less expensive than slump formed. Cost of production of radial is not much more than flat tempered glass (Diller, N. *(pers.comm.)* 1st July 2015*).*	***PROS*** Forced bent is least expensive of the cold bending methods.
CONS Wastage of radial formed glass adds cost. Slump formed is the most expensive due to cost of the mould and production time. Mould may cost several thousand euros.	***CONS*** Laminated cold bent is more expensive than radial formed hot bent or forced cold bent methods.
PROGRAMME	
Hot Bending	**Cold Bending**
PROS Radial bending has similar production time as tempered flat glass as it is an automated process.	***PROS*** Forced bent can be an efficient process especially if the bending takes place on site.
CONS Slump formed takes the most time and this is protracted if there is lack of repetition as individual moulds have to be produced. Programme is influenced by need for prototype testing for hot bent radial and slump formed glass. Prototyping required if coatings are used	***CONS*** Programme is influenced by need for prototype testing for forced cold bent glass. Laminated bending is influenced by time required in the autoclave. If there is a lot of repetition then same jig set up can be used.

4.2 Influences on Choosing Panelisation and Glass Types

Each project will have different design, quality and programme drivers and these influence the bending method decision. The importance of these influences for glass types and panelisation was appraised using the survey. This considered the preferred methods of mitigating potential visual inconsistency.

Question 7 of the survey proposed mitigation measures for the visual inconsistency of bent glass:

If you were concerned about the possible visual distortion when using bent glass how would you rate your preference for each of the following possible mitigation measures. (Please give your level of preference for each of the items)

	Least preferred	Neutral	Most preferred	Total	Weighted Average
Re-panelise so all the glass is triangulated and flat	47.37% 27	38.60% 22	14.04% 8	57	1.67
Re-panelise so all the glass is curved by the same method	3.51% 2	31.58% 18	64.91% 37	57	2.61
Keep the panelisation similar but optimise to reduce number of different types	7.02% 4	42.11% 24	50.88% 29	57	2.44
Lower the glass reflectivity	8.93% 5	57.14% 32	33.93% 19	56	2.25
Etch or frit the glass	46.43% 26	44.64% 25	8.93% 5	56	1.63

Figure 4.1: Survey results Question 7.

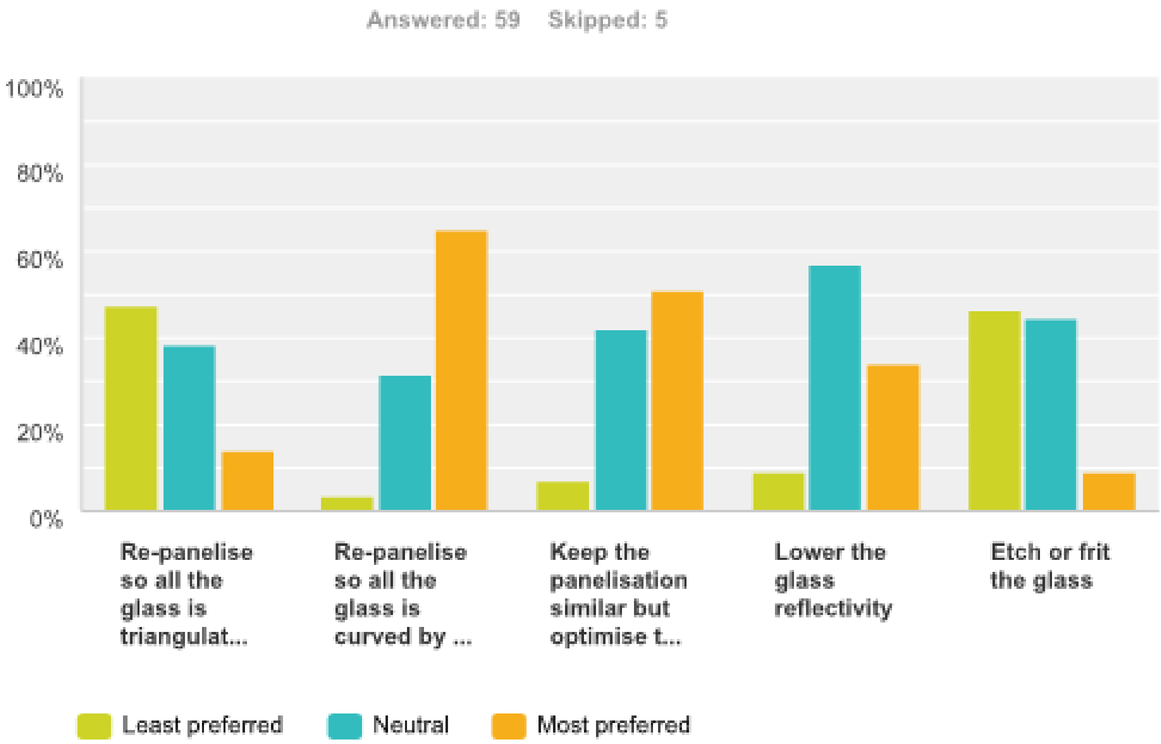


Figure 4.2: Graph results of survey Question 7.

Additional comments from participants provided some further suggestions for improvements. “Option 5; It would be preferential to apply a opaque interlayer as opposed to surface treatments to the glass. An Etch or Frit application to the glass surface will reduce the stress capacity of the glass, and in turn limit how much the etch/frit glass can be bent by compared to clear glass." (ANON., 15th June 2015) and "Consider the best worldwide suppliers of hot curved glass and see/obtain samples; if they can't satisfy the Architect's objectives, use facetted glass." (ANON., 14th June 2015).

The survey highlighted that it was preferred to review the panelisation in order to maximise the same bending method and next best option was to reduce the number of bending types through rationalisation/optimisation, although this may not provide the exact architectural outcome desired as illustrated in case study 2.

4.3 Design/Cost/Programme Drivers for Decision Making of Panelisation/Glass Types

The key project drivers were posed to the survey participants in order to establish the importance of cost, quality and programme project drivers.

Question 8 of the survey appraised the importance of these constraints.
For the following panelisation criteria for the design, specification and procurement of a project with bent glass please rate your level of importance to each of the criteria. (Please rate each of the items).

	Least important	Neutral	Most important	Total	Weighted Average
Panelisation should be most cost effective solution	**5.08%** 3	**49.15%** 29	**45.76%** 27	59	2.41
Panelisation should provide best visual consistency	**1.75%** 1	**22.81%** 13	**75.44%** 43	57	2.74
Panelisation should be optimised to speed programme	**22.81%** 13	**56.14%** 32	**21.05%** 12	57	1.98

Figure 4.3: Survey results Question 8.

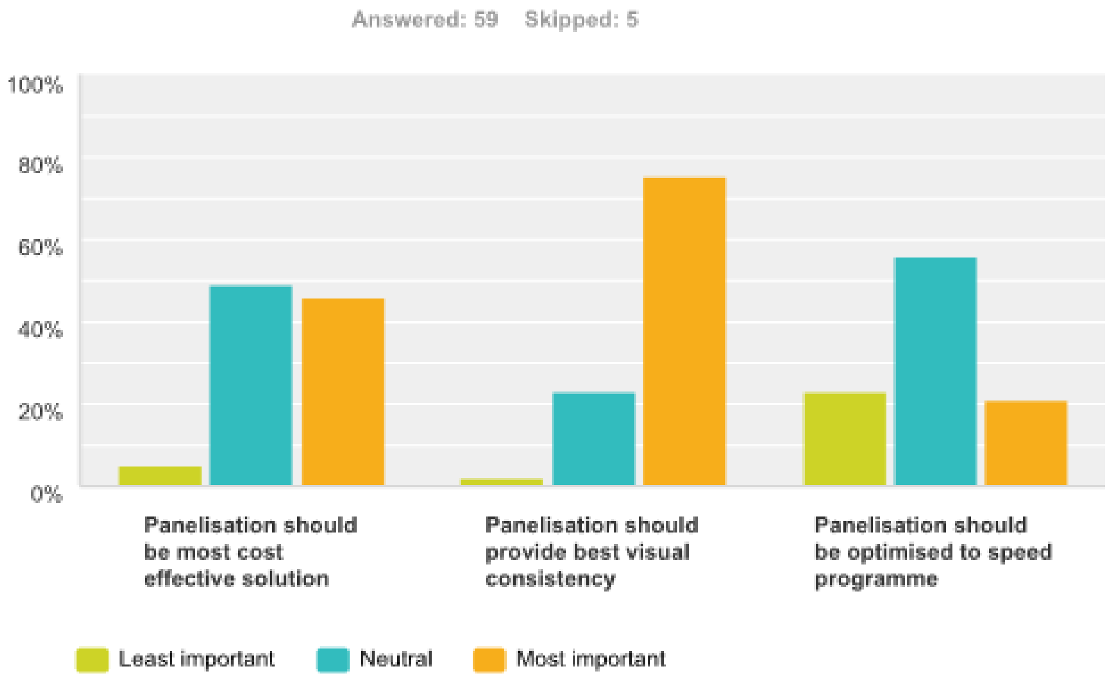


Figure 4.4: Graph results of survey Question 8.

The results highlighted how important the achievement of best visual consistency was to those participating. This supports the case for improved specification and production methods.

4.4 The Assessment Parameters Considered for the Preliminary Roadmap

The purpose of this section was to:

- Test preliminary decision making parameters for procuring a curved glass building that assist with the choice of glass types and bending methods. This required assessment of:
    - Key project drivers – which is the most important?
    - Panelisation – what is key parameter for categorisation?
    - Project performance – what parameters are project specific requirements?
- Develop a preliminary road map methodology that outlines the decision making processes and test using hypothetical examples.

4.5 Testing the Decision Making Parameters

4.5.1 Key Project Drivers

Identify the most important key driver for the project – visual consistency/quality, cost and programme.

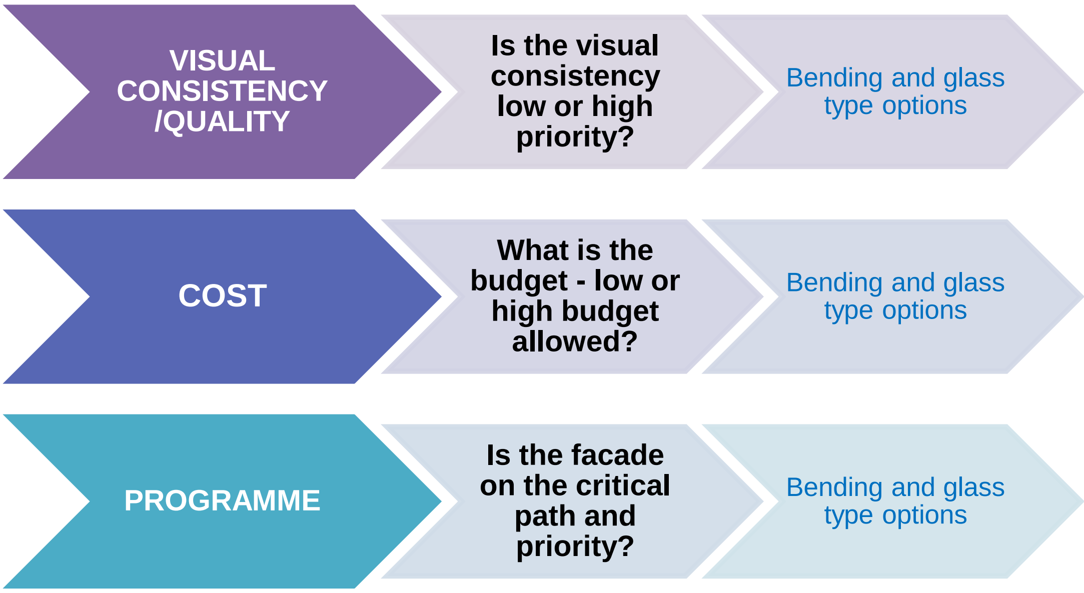


Figure 4.5: Identifying the key drivers.

The key drivers needed to be considered with the panelisation requirements and how they may impact on the decisions of the glass and bending types.

4.5.2 Key Parameters for Panelisation Categorisation

The following hypothetical examples were a basis for the design roadmap and illustrate the possible decision making routes for achieving a curved façade. To limit the iterations the project drivers of visual quality, cost and programme were tested against the key design parameters with most importance identified by the survey in Q.7. These were:

- Re-panelise so all the glass is curved by the same method.
    - Optimising single type bending.
- Keep the panelisation similar but optimise to reduce number of different types.
    - Rationalising bending types.
    - Considering types with similar visual attributes.

In order to rate the outcome of each example, the defects and attributes of the types were marked with negative or positive traits for visual quality/consistency.

Key:

negative trait for visual quality/consistency

positive trait for visual quality/consistency

Figure 4.6**:** Panelisation categorisation – single bending type with visual quality considered.

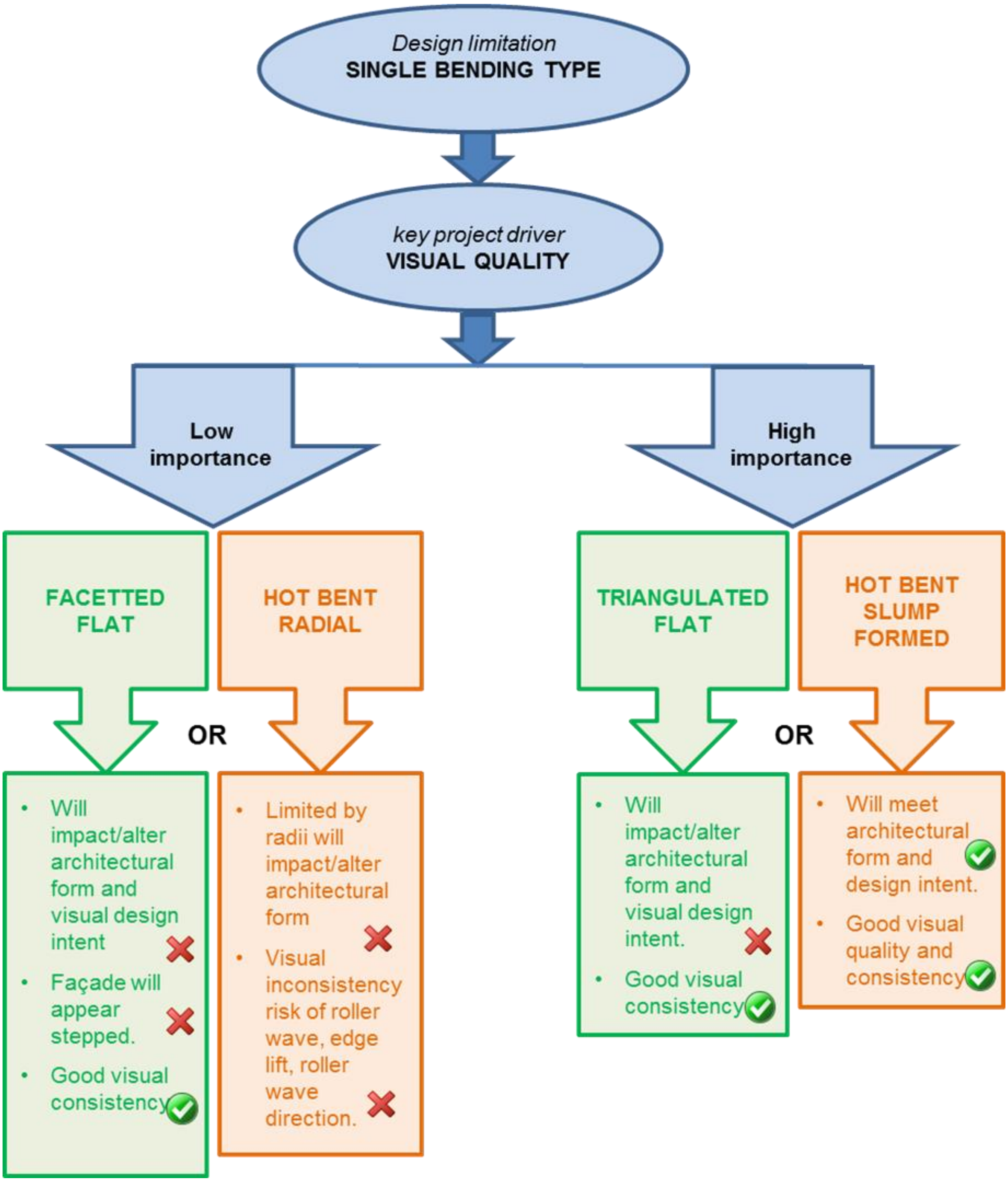


Figure 4.7**:** Panelisation categorisation – single bending type with cost considered.

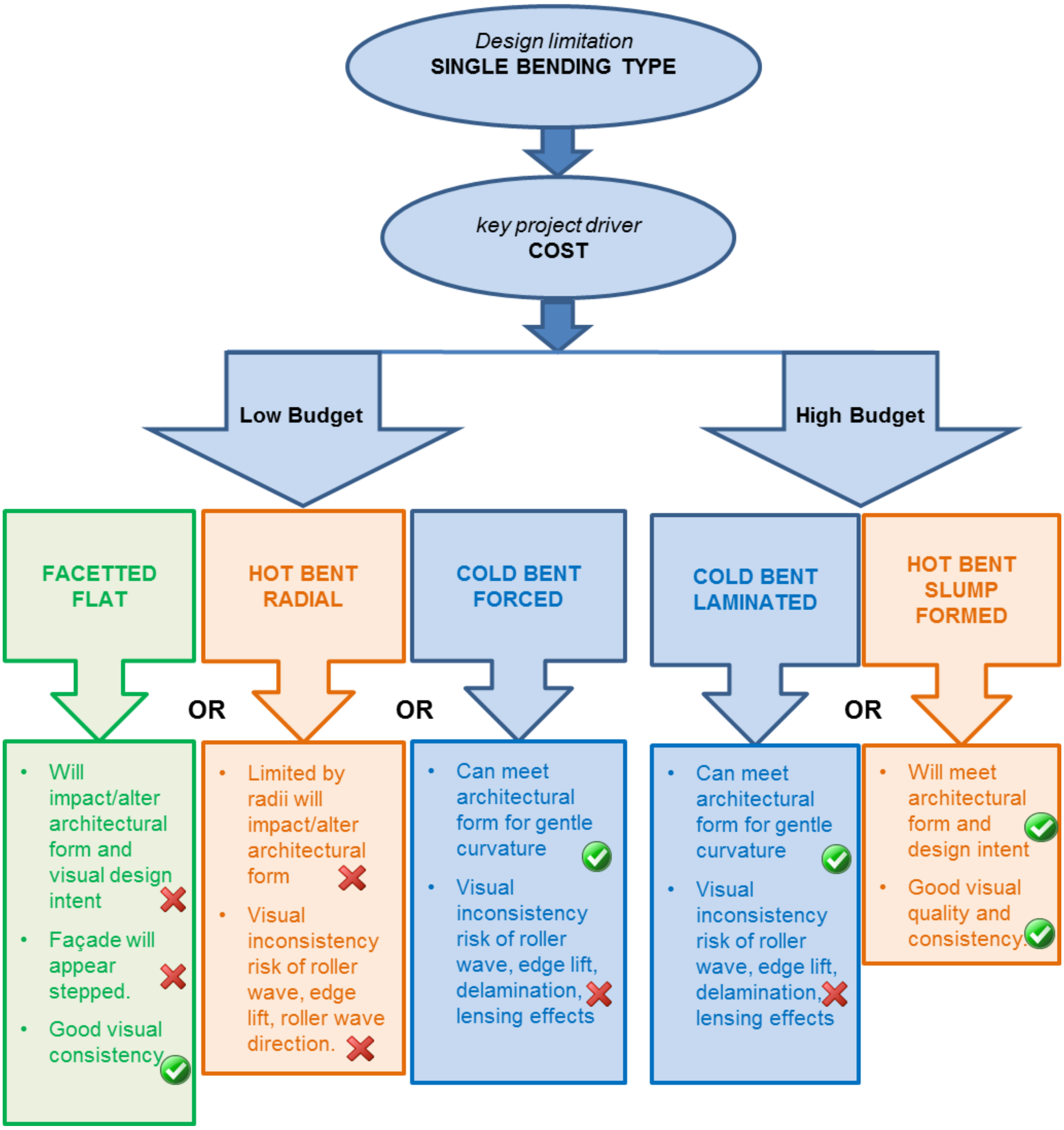


Figure 4.8**:** Panelisation categorisation – single bending type with programme considered.

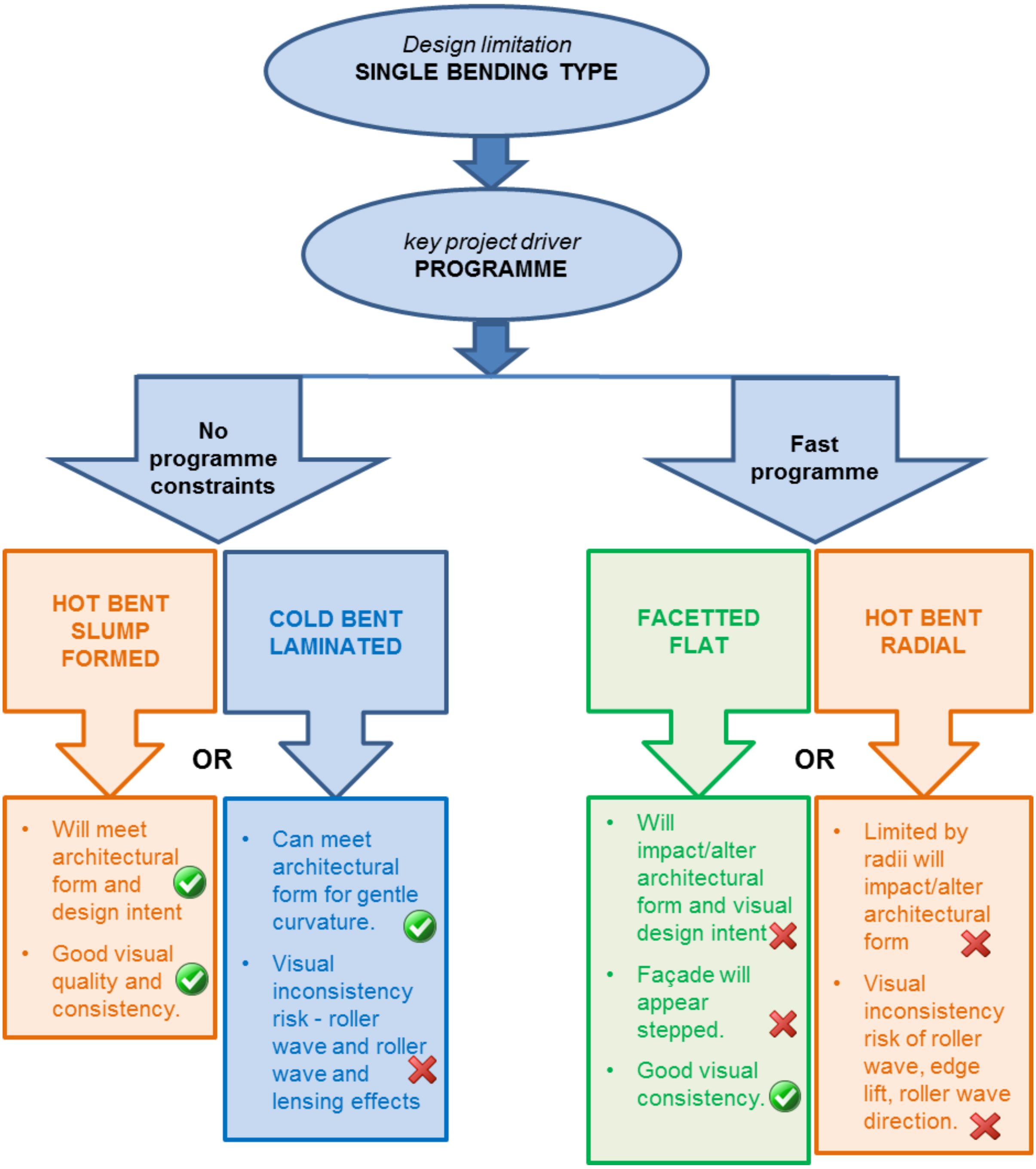


Figure 4.9**:** Panelisation categorisation – rationalise bending types for similar attributes with visual quality considered.

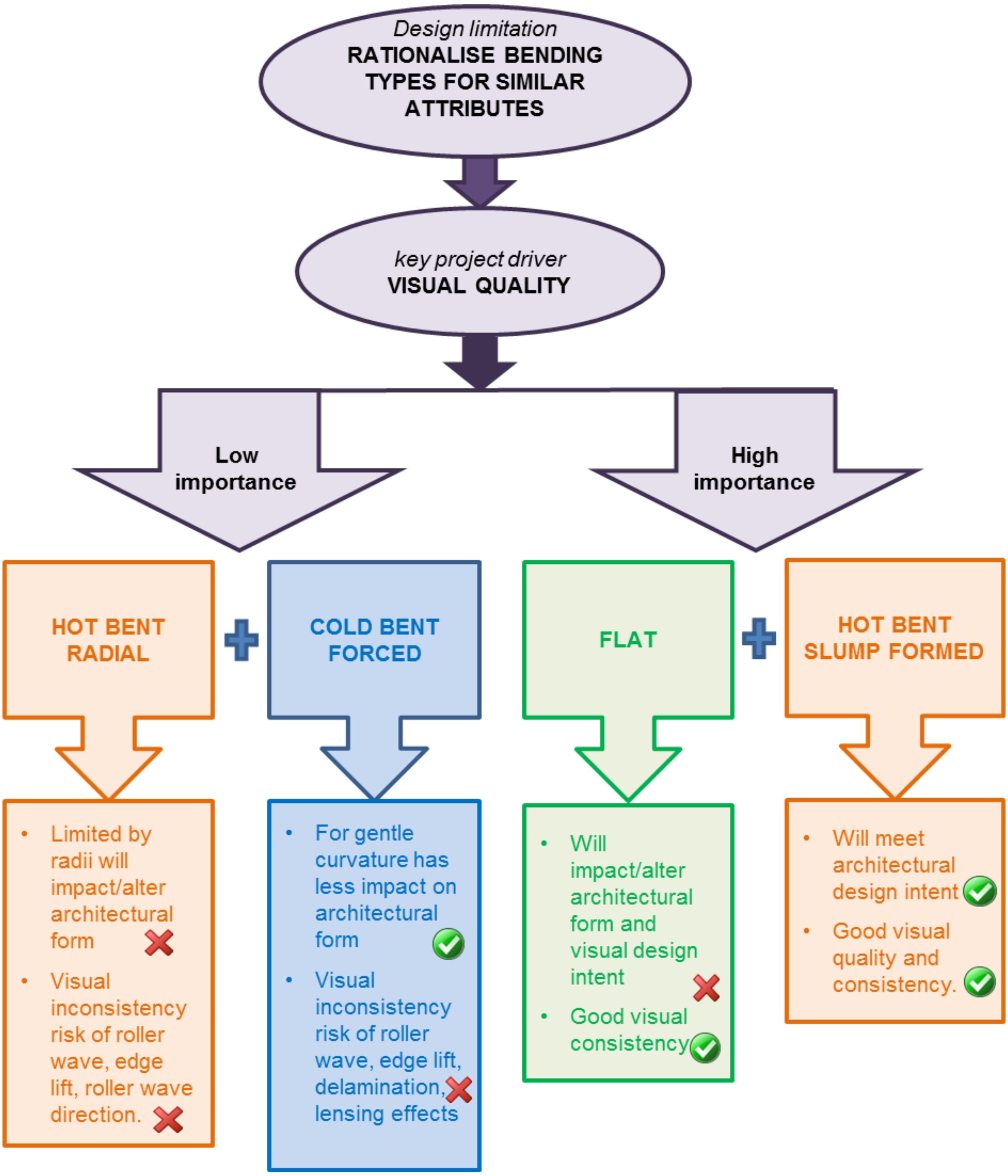


Figure 4.10: Panelisation categorisation – rationalise bending types for similar attributes with cost considered.

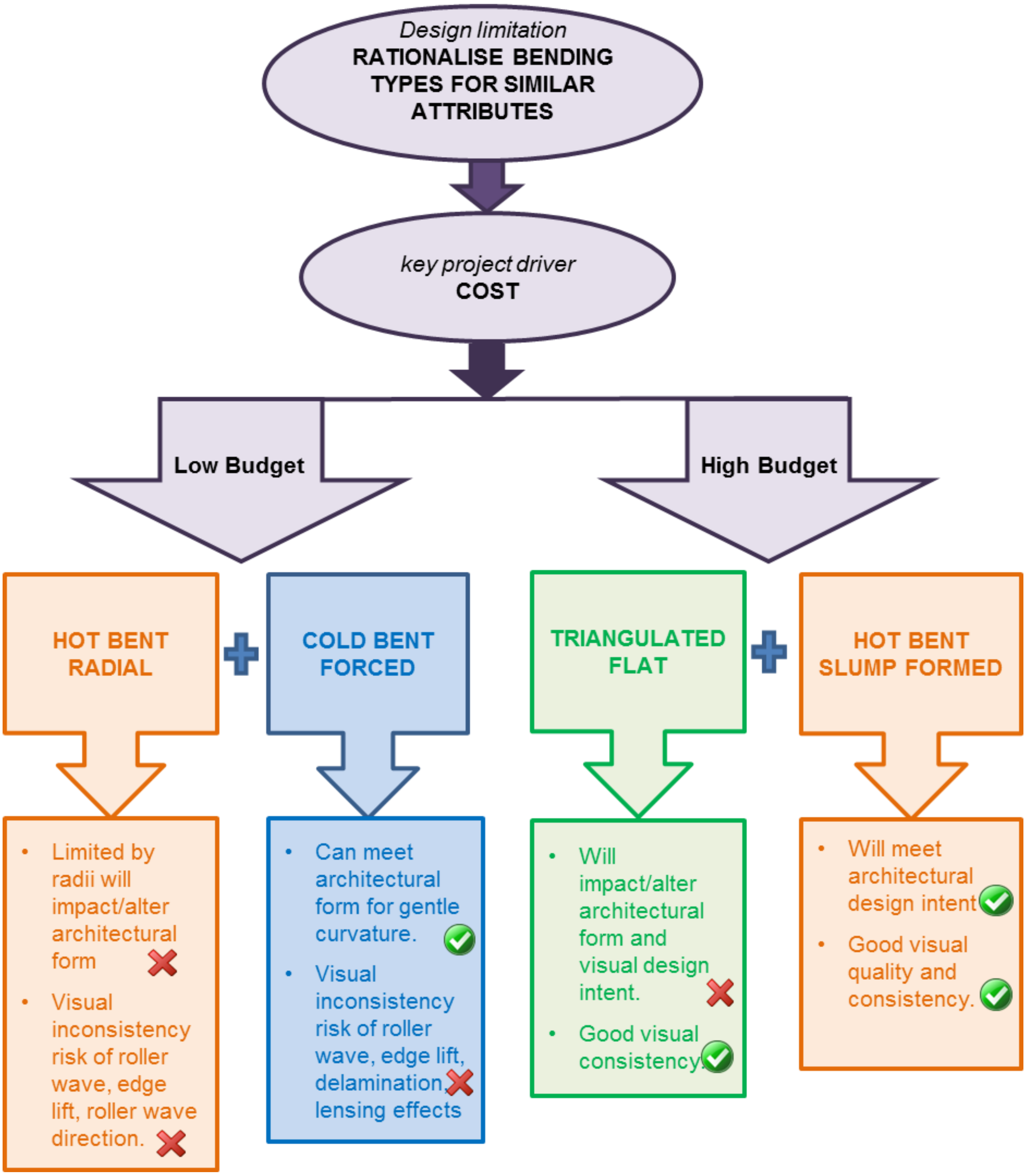
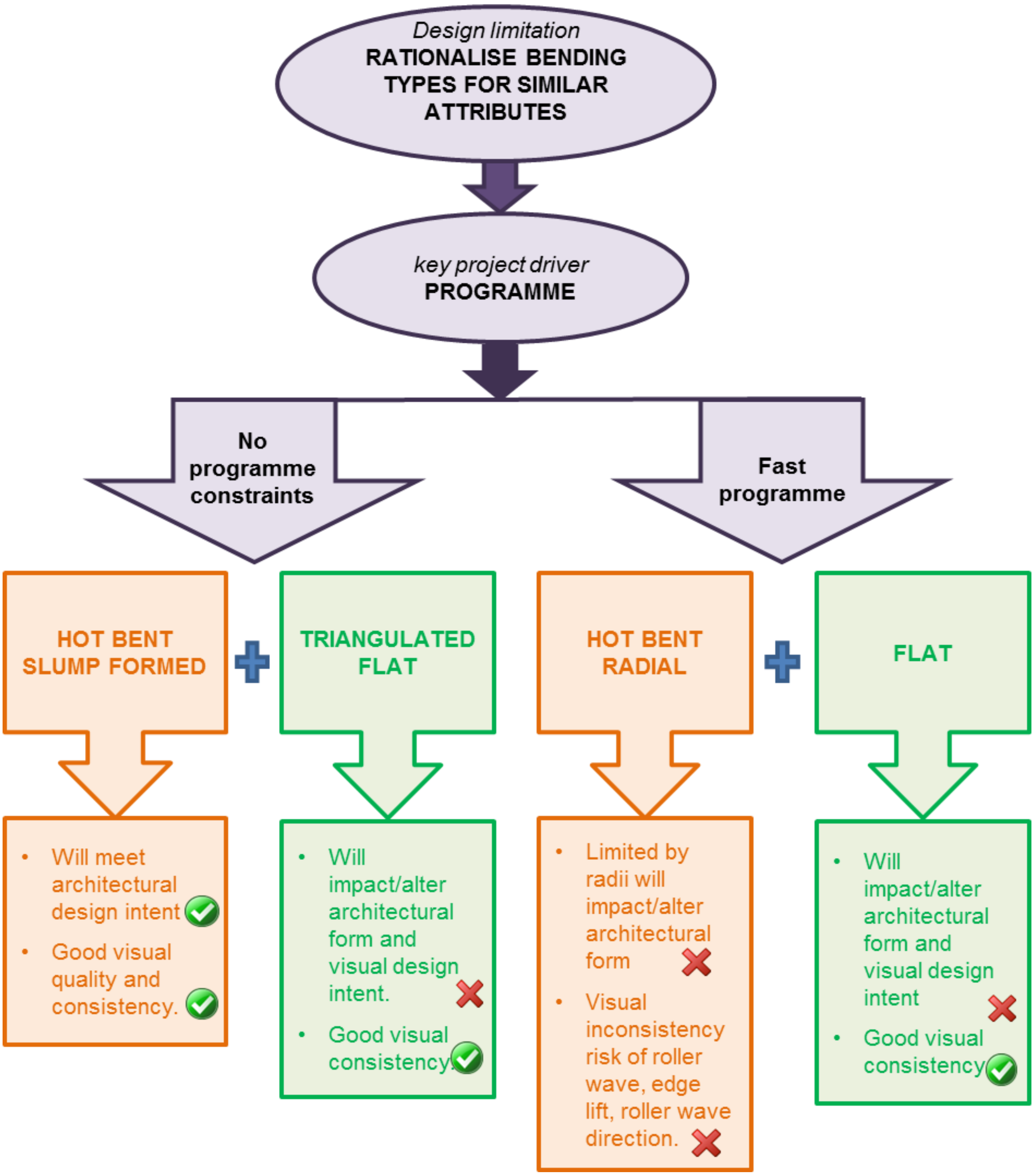


Figure 4.11: Panelisation categorisation – rationalise bending types for similar attributes with programme considered.



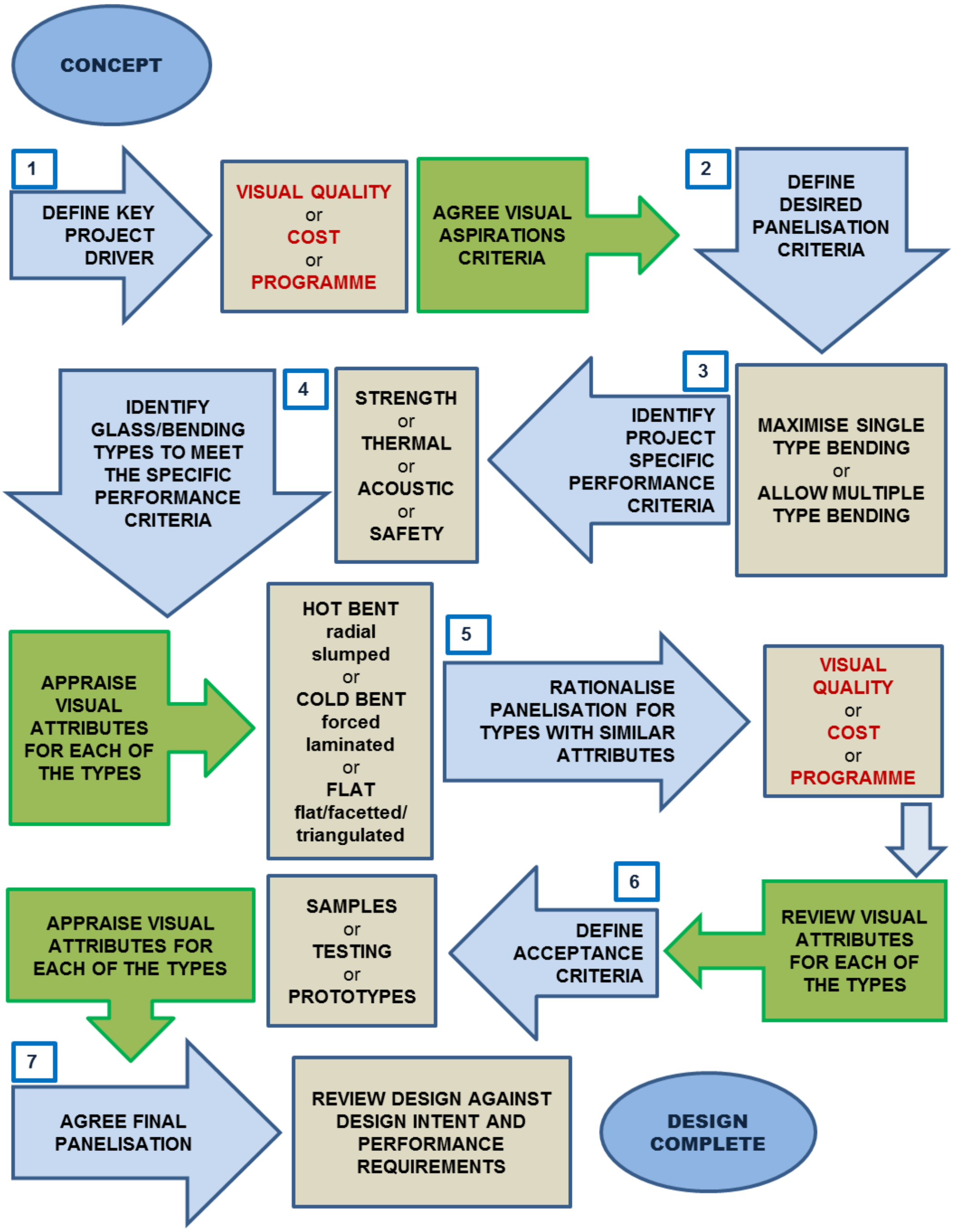
4.5.3 Summary of Panelisation Categorisation and Limitations

The examples illustrated that there are a large number of iterations that could be identified. Their limitation is that these have not been tested on tangible or current projects. However for the purposes of the study, these examples were used as a basis for developing the preliminary design roadmap.

4.6 Developing the Preliminary Design Roadmap for Improved Specification

The following preliminary road map was based on a typical design process flow and identified the key decision criteria that need to be considered during the stages.

Figure 4.12**:** Preliminary road map parameters.



4.6.1 Hypothetical Examples of the Preliminary Roadmap

For the purpose of this study hypothetical examples were used to test the preliminary roadmap. These used different project driver limitations to illustrate how the roadmap may be used as a guide for the choice of glass/bending types and highlight points during the process to appraise the visual requirements.

Figure 4.13: Roadmap example – visual quality is a key panelisation driver.

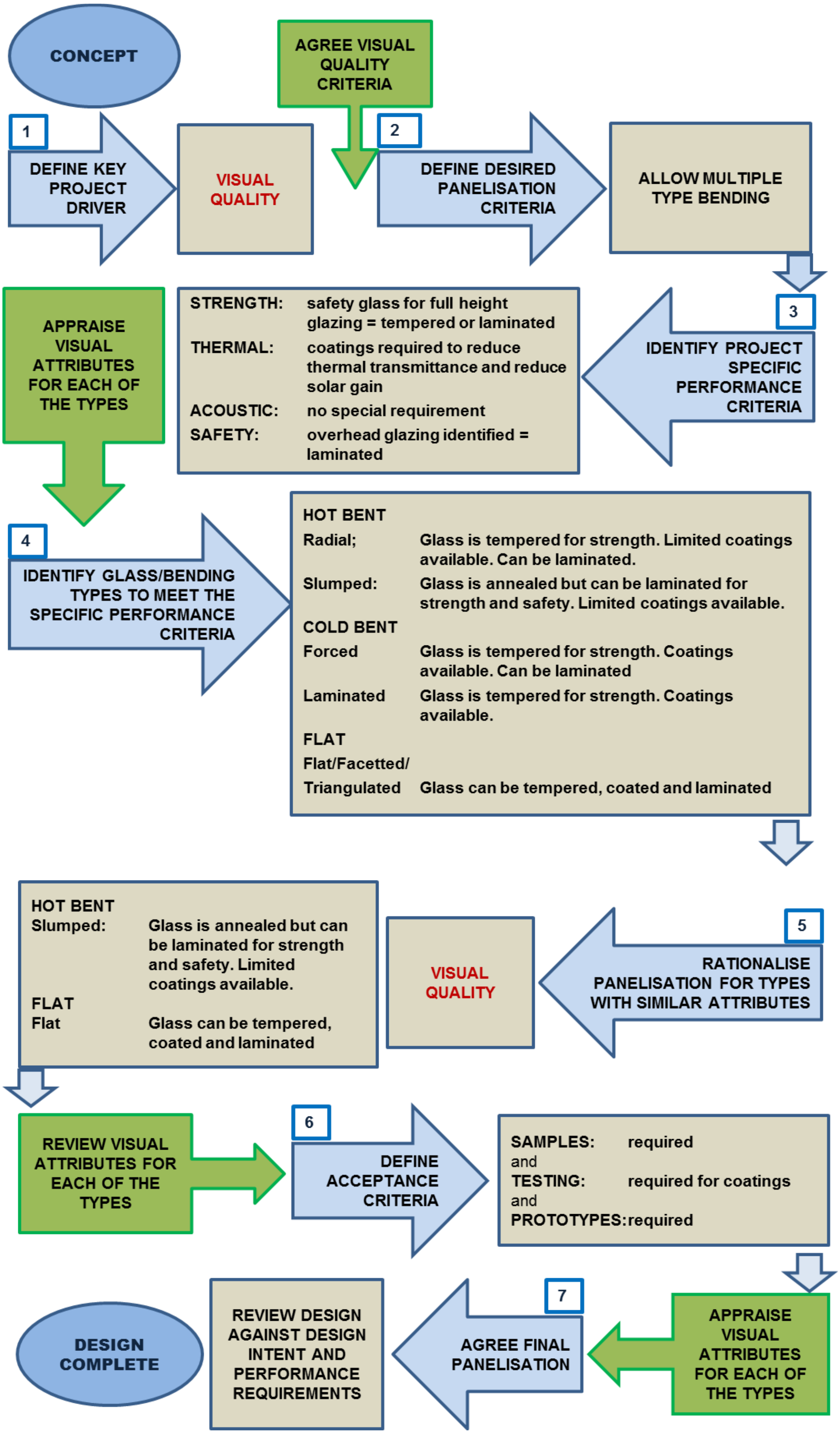


Figure 4.14: Roadmap example – limited budget is a key panelisation driver.

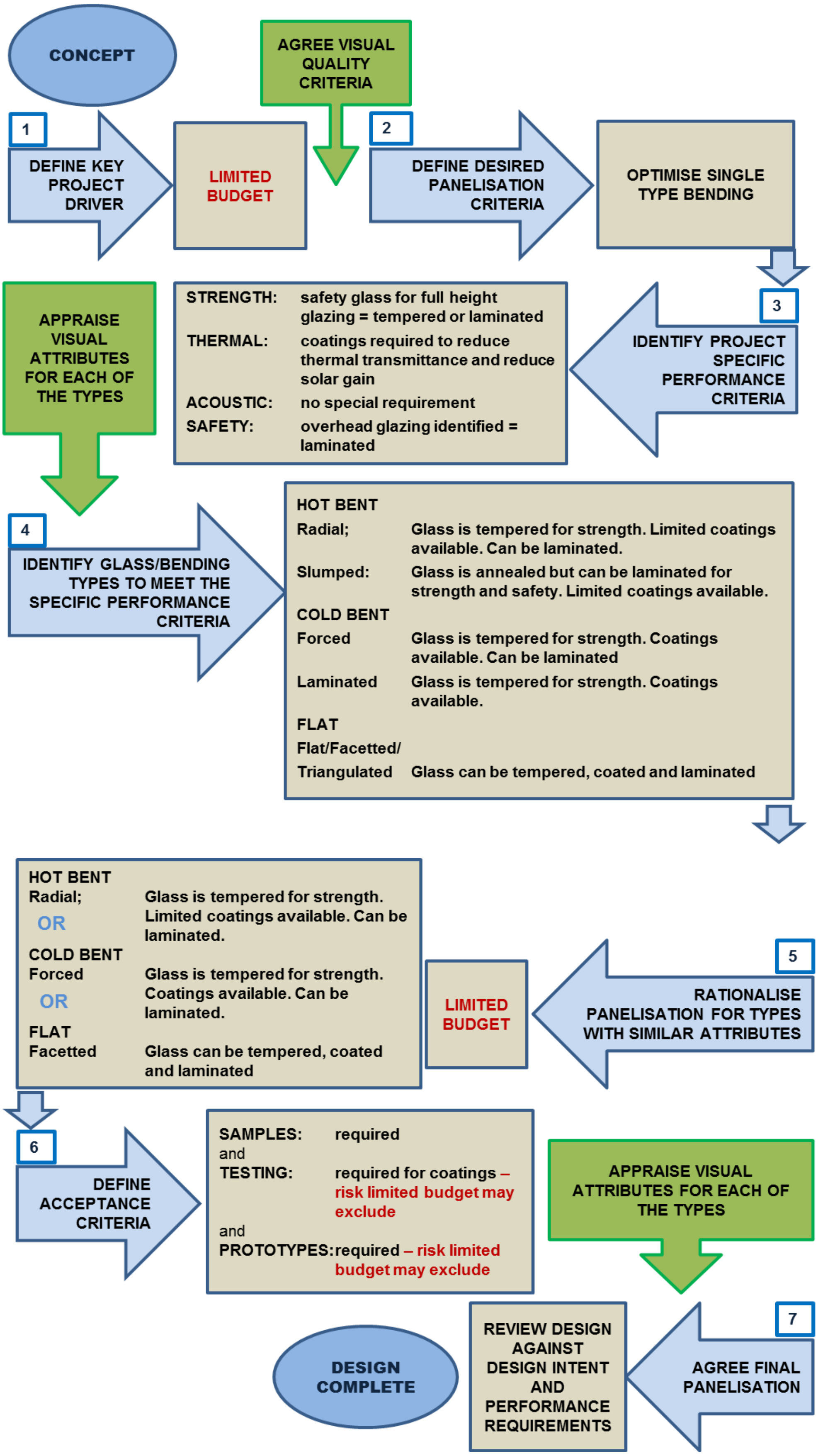
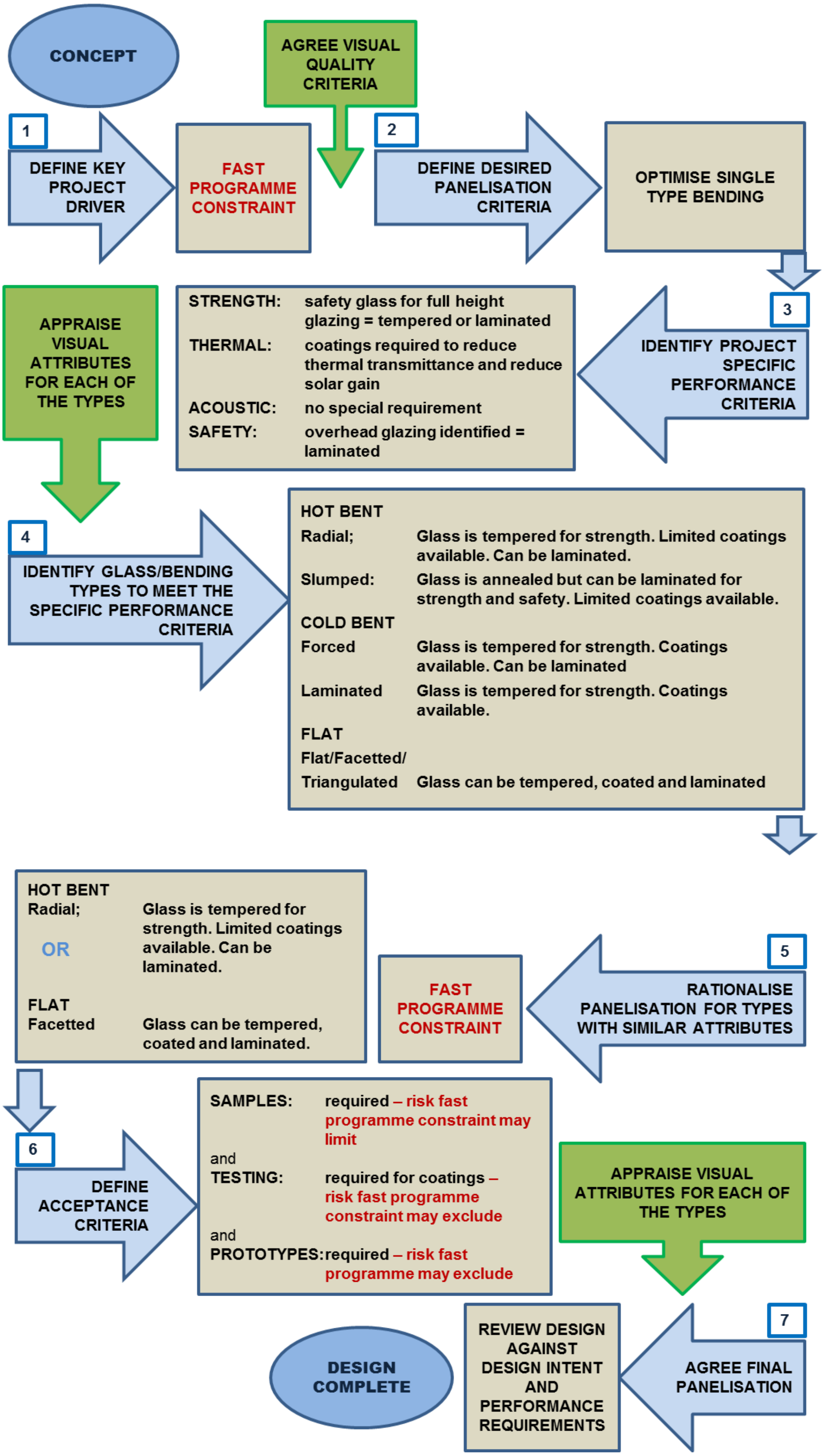


Figure 4.15**:** Roadmap example – fast programme constraint is a key panelisation driver.



4.7 Caveats and Limitations of the Preliminary Design Roadmap

The preliminary design road map illustrated the decision making process for key project drivers and how these will affect choices during the design process for a curved glazed façade. The examples identified that there could be different glass/bending types applied to meet the specific project requirements and this was dependent on the level of importance of key parameters/drivers.

However a limitation of the road map is that it has not been tested on current or tangible projects. It would need to be validated to be introduced as an acceptable methodology in the industry and it would also require support of recognised standards/guidance

This reaffirms the need for the identification of methods for improving specification for visual/optical quality of curved glass buildings.

5 OUTCOME OF THE STUDY AND FUTURE DEVELOPMENTS

The outcome of the study provided the following:

- Identified limitations that influenced the study.
- Appraised the key objectives met and whom they might benefit.

Future developments are considered by:

- Appraising the potential future improvements to curved glass specification and production based on the knowledge gained through the desk study, survey and industry feedback.

5.1.1 Limitations to the Study

The following were key limitation factors encountered during the study:

- The confidentiality of the design, glass, façade and construction industry.
- The number and diversity of the glass and façade standards/guidance available for review.
- The subjective nature of visual/optical quality and assessment.
- The lack of benchmarking for projects as each project is unique.

An obstacle in understanding the issues with glass production and bending methods was the censored nature of the industry, namely the confidentiality of the façade, glass and construction industry.

- Glass processors have patented and individual processes and methods which are not documented for scrutiny.
- Façade contractors are disinclined to share knowledge of their bespoke designs in case this information becomes beneficial to their competitors.
- Main contractors rarely share the real costs of the project so the impact of cost for different façade options is hard to evaluate.

There is a large amount of information available for specification for glass used in buildings. There are standards produced in various regions around the world. For the purpose of this study, the standards and guidance reviewed were limited to those used for UK and Europe. Even when limited, there were a great number to review.

A key parameter that limited the study is the subjective nature of visual assessment, which cannot be objectively measured. The standards have subjective acceptance criteria. BS EN 572-2 advises that using the zebra board method for assessing optical quality that the acceptance criteria is measured as “the angle α at which there is no disturbing distortion”. BS EN 12543-6:2011 states “Any visible defects that are disturbing shall be marked.” These criteria are not quantifiable measures.

A further limitation was that each project designed is unique and the design intent/aspirations and key project parameters – quality, cost and programme vary, so benchmarking was not possible to determine for the purpose of this study.

5.2 Objectives Summary and Who May Benefit

The objectives with the input from the desk study and survey aimed to provide greater understanding of specifying and producing curved glass façades. This knowledge gained in respect of the design and procurement process could benefit those involved. The key objectives considered and those parties that may potentially benefit are summarised below:

Table 5.1: Objectives outcome summary and potential beneficiaries.

Objective	Who may benefit	Outcome of the study and potential benefit	When they may benefit
Assessment of current standards/ guidance for the specification/ visual assessment of flat and bent glass. ***Study assessed:*** **Do they relate and assist or have omissions and conflict?**	Designers/ Consultants	**Identified:** specification conflicts and omissions – highlighted potential for improved specification and visual assessment criteria in documents. **Benefit:** Improve specification and less cause for dispute.	Design and specification stage.
	Glass processors/ Façade contractors	**Identified:** need for clearer specification and visual assessment criteria in documents. **Benefit:** clearer specification and less cause for dispute.	Specification compliance at tender and completion.
	Main contractor/ Client	**Identified:** need for clearer specification and visual assessment criteria in documents **Benefit:** less cause for dispute and cost uncertainty	Specification compliance at tender and completion.

Objective	Who may benefit	Outcome of the study and potential benefit	When they may benefit
Identified visual characteristics of different glass types and bending processes and their limitations for visual quality. ***Study assessed:*** **State of the art production and examples.**	Designers/ Consultants	**Identified:** The potential issues of glass processes and bending types and associated risks. **Benefit:** more practical specification and improved visual consistency.	Design and specification stage and completion.
	Clients	**Identified:** need to highlight impact on visual outcome of the project. **Benefit:** Inform client brief and cost plan.	Project brief and tender stage and completion.
Create 'preliminary design road map' ***Study developed and tested:*** **Roadmap based on knowledge gained and used hypothetical examples.**	Designers/ Consultants	**Identified:** Example methodology to assist decision making process during design development stages. **Benefit:** Better informed design and risks identified.	Design, specification and procurement stage
	Client/ Main Contractor	**Identified**: Stages that require input and design decisions. **Benefit**: Better informed of design decisions	Tender and completion stage.
	Glass processors/ Façade contractors	**Identified:** Stages that require input and procurement decisions. **Benefit:** Clearer visual requirements from design team	Specification compliance at completion stage.
Identify current issues/risks ***Study appraised:*** **Items of concern and potential for these to be**	Designers/ Consultants	**Identified:** Current specification and visual issue concerns. Potential specification parameters that could be improved. **Benefit:** Improved specification and enhanced visual quality/consistency of curved glass buildings.	Design, specification and procurement stage.

Objective	Who may benefit	Outcome of the study and potential benefit	When they may benefit
addressed in future.	Client	**Identified:** Visual issue concerns and potential improvements needed. **Benefit:** enhanced visual quality/consistency of curved glass and less cost uncertainty.	Design brief and completion stage.
	Main Contractor	**Identified:** Procurement and visual issue concerns. Potential improvements needed. **Benefit:** Less quality risk during procurement and more cost certainty.	Tender and completion stage.
	Glass processors/ Façade contractors	**Identified**: Key issues and risk items that give concern of visual inconsistency gives opportunity for R&D to improve quality. **Benefit:** Improved specification of visual requirements. Improved product quality and opportunity to increase curved glass production.	Specification compliance at completion stage.

5.3 Identifying the Key Specification Items Important for Visual Quality

Using the knowledge gained by the study and the feedback from the survey future improvements for the specification and production of curved glass buildings can be considered.

The survey provided feedback from the participants identifying the importance of key specification parameters that can influence the quality and attributes of hot and cold bent glass. These items for review were identified during initial consultation with consultants and industry.

Question 9 for hot bent glass:
HOT BENT GLASS - To optimise the visual quality of hot bent glass how would you rate the importance of each of the following items. (Please rate all items)

	Least important	(no label)	Neutral	(no label)	Most important	Do not know	Total	Weighted Average
Test sample all curved glass types to achieve benchmark samples	1.72% 1	1.72% 1	12.07% 7	12.07% 7	70.69% 41	1.72% 1	58	4.51
View samples in orientation for the project	1.72% 1	0.00% 0	12.07% 7	22.41% 13	60.34% 35	3.45% 2	58	4.45
Quality check all flat glass before it is curved.	11.86% 7	6.78% 4	47.46% 28	23.73% 14	8.47% 5	1.69% 1	59	3.10
Specify hard coatings instead of soft coatings for hot bent glass	3.39% 2	6.78% 4	33.90% 20	28.81% 17	15.25% 9	11.86% 7	59	3.52
Use a glass bending processor with tried and tested experience	1.69% 1	0.00% 0	6.78% 4	11.86% 7	79.66% 47	0.00% 0	59	4.68
Tighten roller wave values in the specification for hot bent monolithic / laminated glass	5.08% 3	8.47% 5	30.51% 18	27.12% 16	22.03% 13	6.78% 4	59	3.56

Figure 5.1: Survey results Question 9.

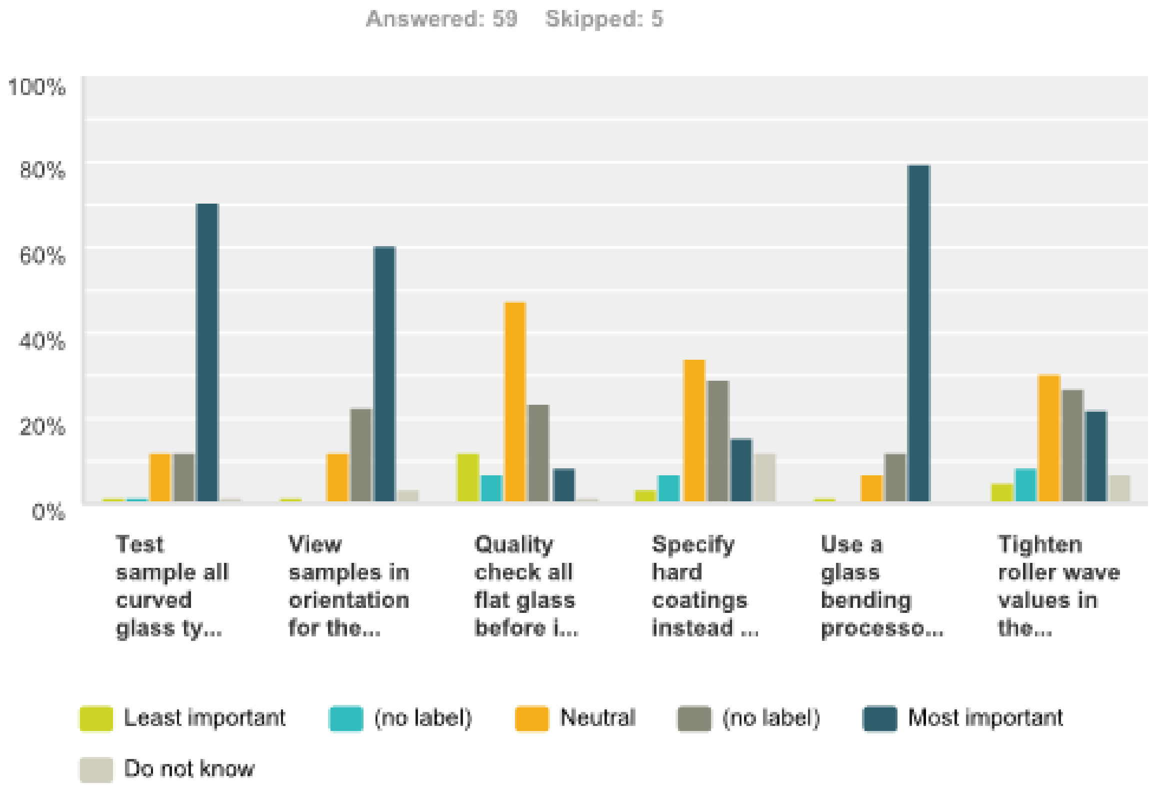


Figure 5.2: Graph results of survey Question 9.

Participants additional comments reaffirmed the complexity of the specification for coatings “Preferably avoid using any coatings at all! (so clear or body tinted glass only....if possible). With any hot bend glass, due to manufacture the variation in surface tension from glass to glass will be much more variable than in comparison to the variation observed with flat glass. If the hot bend glass also features a coating, then a much more pronounced variation in visible anistrophy from glass to glass should be expected! To avoid any potential wildly varying anistrophy effects, omit coatings altogether if possible!" (ANON., 15th June 2015).

The survey highlighted the importance given by the participants of sampling and using an experienced glass bending processor for the production of hot bent glass.

Question 10 for cold bent glass:

COLD BENT GLASS - To optimise the visual quality of cold bent glass how would you rate the importance of each of the following items. (Please rate all items)

	Least important	(no label)	Neutral	(no label)	Most important	Do not know	Total	Weighted Average
Test sample all curved glass types to achieve benchmark samples	0.00% 0	1.79% 1	14.29% 8	8.93% 5	60.71% 34	14.29% 8	56	4.50
View samples in orientation for the project	0.00% 0	0.00% 0	8.77% 5	21.05% 12	52.63% 30	17.54% 10	57	4.53
Quality check all flat glass before it is curved.	7.14% 4	1.79% 1	28.57% 16	32.14% 18	16.07% 9	14.29% 8	56	3.56
Specify hard coatings instead of soft coatings for cold bent glass	1.75% 1	10.53% 6	31.58% 18	22.81% 13	5.26% 3	28.07% 16	57	3.27
Use a glass bending processor / contractor with tried and tested experience	3.51% 2	1.75% 1	7.02% 4	19.30% 11	54.39% 31	14.04% 8	57	4.39
Tighten roller wave values in the specification for cold bent monolithic/laminated glass	7.02% 4	7.02% 4	22.81% 13	21.05% 12	21.05% 12	21.05% 12	57	3.53

Figure 5.3: Survey results Question 10.

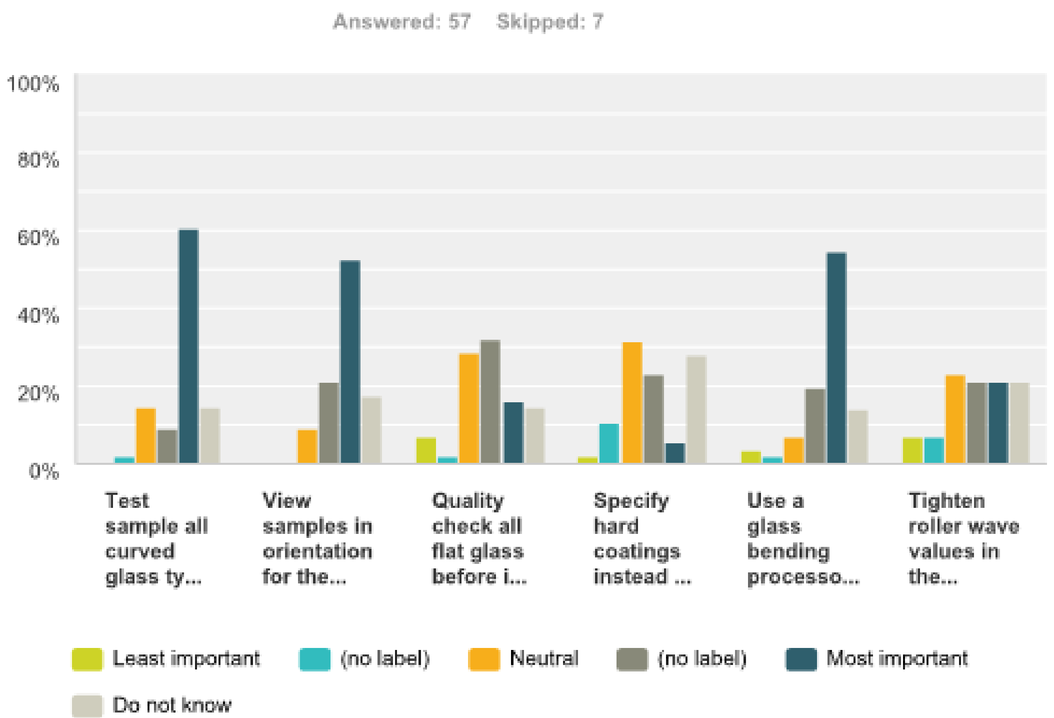


Figure 5.4: Graph results of survey Question 10.

Participants comments included the issue of life expectancy “My answers above assume that the cold bent glass is heat treated. The biggest issue with cold bent glass is the effect of cold bending on life expectancy.” (ANON., 14th July 2015). This is a key design parameter that will impact the specification and further research for this was indicated (Fildhuth, T et al. 2014) for the efficiency of the types of interlayers in respect of preventing springback over time. Potential improvements were also noted using new production methods, “for the cold bend laminated glass thin glass is used and hence it can be done on the new Lisec air-bed system (no roller wave)” (ANON., 15th June 2015).

The survey highlighted the importance given by the participants of sampling and using an experienced glass bending processor/contractor for the production of cold bent glass.

5.3.1 Survey Results Summary of Key Items for Optimising Visual Quality

The following table summarised the results of those items identified by the participants in question 9 and 10 as key criteria for optimising hot and cold bent glass. The figures shown are the sum of the percentages added above the neutral position. The figures are not weighted.

Table 5.2: Survey results summary of key criteria for optimising visual quality.

Note: Figures are rounded to the nearest whole number:

	GLASS TYPE	
KEY CRITERIA	**HOT bent glass** % agreed (above neutral)	**COLD bent glass** % agreed (above neutral).
Sampling to achieve a benchmark	83%	70%
Viewing the samples in the orientation for the project	83%	74%
Quality check of the flat glass before bending	32%	48%
Specify hard coatings instead of soft coatings	44%	28%
Use a processor with tried and tested experience	92%	74%
Tighten roller wave tolerances	49%	42%

These items assisted with the identification of potential clarifications/improvements for the future specification and procurement of curved glass buildings.

5.4 Proposals for Future Improvements for the Quality of Curved Glass Façades

Using the knowledge gained from the study and the feedback from the survey, potential improvements to the specification of and visual quality of curved glass buildings were identified: These are summarised as follows:

- Improve standards/guidance.
- Ensure sampling and viewing in finished position.
- Agree tolerances and acceptance criteria early in the design stage.
- Improve production methods of hot bent glass.
- Improve durability and colour consistency of temperable coatings.
- Investigate bending methods used by other industries.
- Research new materials such as thin glasses that are being developed.
- Consider mathematical approach to resolving inconsistency issues.

The survey provided feedback to potential improvements. Input for these items was given from initial early consultation with industry:

Question 11:

To improve the specification and production of bent glass please rate each of the following items for its level of importance to you. (please rate all items)

	Least important	(no label)	(no label)	(no label)	Most important	Do not know	Total	Weighted Average
Improve current standards for material specification	3.57% 2	7.14% 4	23.21% 13	33.93% 19	26.79% 15	5.36% 3	56	3.77
Provide further standards and guidance for the specification and visual quality of HOT bent glass	0.00% 0	0.00% 0	14.29% 8	42.86% 24	35.71% 20	7.14% 4	56	4.23
Provide further standards and guidance for the specification and visual quality of COLD bent glass	0.00% 0	0.00% 0	19.30% 11	29.82% 17	36.84% 21	14.04% 8	57	4.20
Agree tolerances early on in the design for the specification of bent glass	0.00% 0	0.00% 0	1.75% 1	28.07% 16	68.42% 39	1.75% 1	57	4.68
Develop improved methodology for visual acceptance criteria in the specification for bent glass	0.00% 0	1.75% 1	8.77% 5	31.58% 18	56.14% 32	1.75% 1	57	4.45
Reduce the external reflectance of HOT bent glass	0.00% 0	12.50% 7	46.43% 26	28.57% 16	5.36% 3	7.14% 4	56	3.29
Reduce the external reflectance of COLD bent glass	1.82% 1	12.73% 7	41.82% 23	23.64% 13	5.45% 3	14.55% 8	55	3.21
Improve production methods for HOT bent radial and conical glass	3.57% 2	1.79% 1	19.64% 11	39.29% 22	26.79% 15	8.93% 5	56	3.92
Develop production methods to improve tolerances in HOT bent formed glass	0.00% 0	3.51% 2	15.79% 9	45.61% 26	35.09% 20	0.00% 0	57	4.12
Develop production methods to improve tolerances in COLD bent formed glass	3.51% 2	5.26% 3	19.30% 11	40.35% 23	19.30% 11	12.28% 7	57	3.76
Develop alternative methods for HOT bent slump formed glass to allow thermal toughening	3.51% 2	3.51% 2	21.05% 12	38.60% 22	26.32% 15	7.02% 4	57	3.87
Develop more coatings that can be HOT bent and maintain visual consistency	1.79% 1	5.36% 3	8.93% 5	44.64% 25	39.29% 22	0.00% 0	56	4.14

Improve methods for producing HOT bent glass by investigating methods used in other industries such as the automotive industry	1.79% 1	7.14% 4	8.93% 5	41.07% 23	39.29% 22	1.79% 1	56	4.11
Investigate possibilities of bending using different glass materials such as thin sheet fused glass	5.36% 3	7.14% 4	28.57% 16	37.50% 21	5.36% 3	16.07% 9	56	3.36

Figure 5.5: Survey results Question 11.

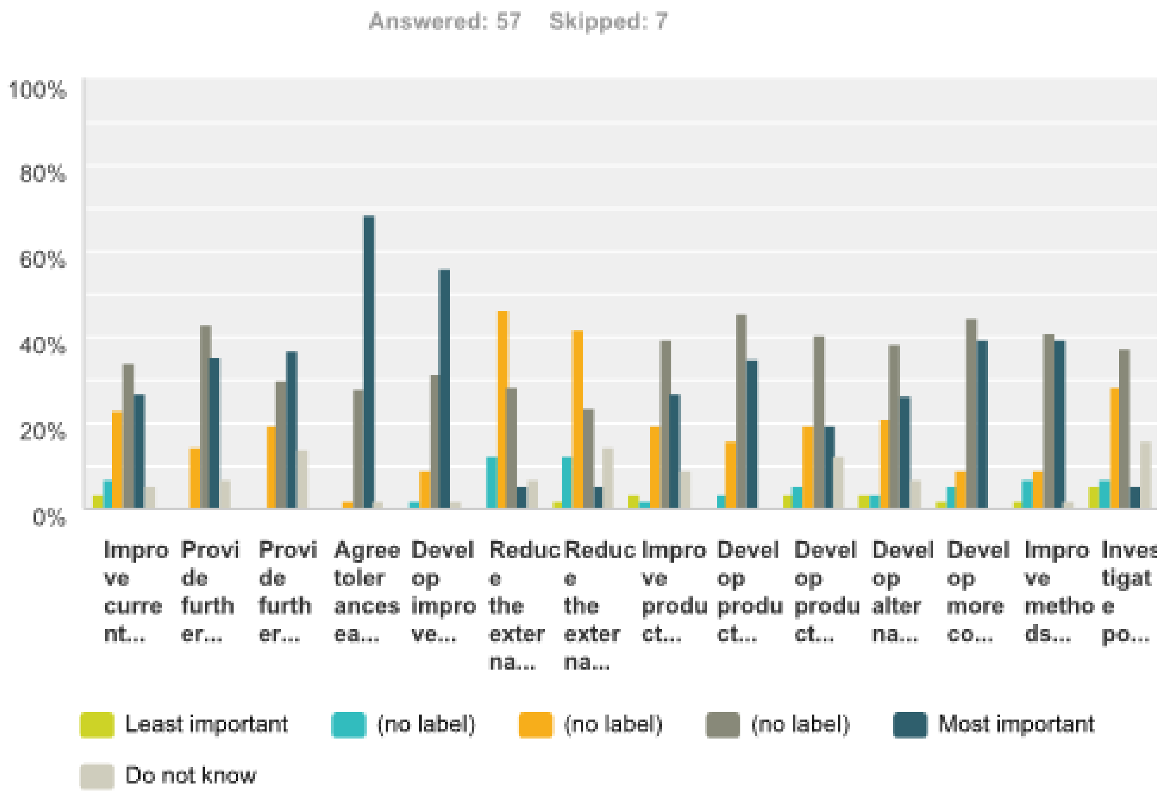


Figure 5.6: Graph results of survey Question 11.

The additional comments from participants included potential innovations in production. “Tempering Ovens where the glass goes through on a perforate conveyor belt as opposed to a series of rollers, or goes through vertically as opposed to horizontally could be further investigated as a way of reducing distortion.” (ANON., 15th June 2015).

The table below summarised the survey results. The figures are simplified into the % below the mid neutral position, those that were neutral and those above the mid neutral position. These figures are not weighted:

Table 5.3: Survey results summary of key criteria for improving specification and production of curved glass buildings.

Note: Figures are rounded to the nearest whole number:

ITEM	RESULTS		
	% below the mid neutral position. (item considered of lesser importance.)	% at the mid neutral position (item not considered of lesser or higher importance)	% above the mid neutral position. (item considered of higher importance.)
Improve current standards for material specification	11%	23%	61%
Provide further standards and guidance for the specification and visual quality of HOT bent glass	0%	14%	79%
Provide further standards and guidance for the specification and visual quality of COLD bent glass	0%	19%	67%
Agree tolerances early on in the design for the specification of bent glass	0%	2%	96%
Develop improved methodology for visual acceptance criteria in the specification for bent glass	2%	9%	88%
Reduce the external reflectance of HOT bent glass	13%	46%	34%
Reduce the external reflectance of COLD bent glass	15%	42%	29%
Improve production methods for HOT bent radial and conical glass	5%	20%	66%
Develop production methods to improve tolerances in HOT bent formed glass	4%	16%	81%
Develop production methods to improve tolerances in COLD bent formed glass	9%	19%	60%
Develop alternative methods for HOT bent slump formed glass to allow thermal toughening	7%	21%	65%

ITEM	RESULTS		
	% below the mid neutral position. (item considered of lesser importance.)	% at the mid neutral position (item not considered of lesser or higher importance)	% above the mid neutral position. (item considered of higher importance.)
Develop more coatings that can be HOT bent and maintain visual consistency	7%	9%	84%
Improve methods for producing HOT bent glass by investigating methods used in other industries such as the automotive industry	9%	9%	80%
Investigate possibilities of bending using different glass materials such as thin sheet fused glass	13%	29%	43%

5.5 Items for the Future Improvement of the Quality of Curved Glass Buildings.

This section provides further information for the proposed items identified for improvement and how they might be implemented.

5.5.1 Improve Standards/Guidance.

The study identified inconsistencies and omissions in the standards and guidance for the specification and visual assessment of curved glass buildings. Potential improvements:

- An update of the standards and guidance to resolve inconsistencies.
- Assess bent glass production in order to inform bent glass standards.
- Provide guidance for use of different glass types simultaneously for curved glass buildings.

5.5.2 Ensure Sampling and Viewing in Finished Position

The survey participants and case study 3 highlighted the need for sampling and for viewing samples in the finished position. This could be implemented:

- For designers and specifiers – include in the specification.
- Standards and guidance when updated to include requirement.
- Processors include in their quality plan.

5.5.3 Agree Tolerances and Acceptance Criteria Early in the Design Stage

This was identified as a key visual quality parameter by the survey participants and reaffirmed when discussing with a glass processor (Figuerola, F. *(pers.comm.)* 27th July 2015) and specialist façade contractor (Arbós, F. *(pers. comm.)* 28th July 2015). Potential improvements:

- An update of the standards and guidance to include consistent tolerances.
- Remove subjective reference in current standards. “Disturbing” visual defects as noted in BS EN 12543-6:2011 are not measurable.
- Standards to advise of practical viewing criteria for different bent glass types.
- Develop methods to assess visual quality that are measurable and objective.

5.5.4 Consider Reflection Criteria for Curved Glass

The study identified that reflection effects have an impact on the visual appearance of the curved glass and high reflection will highlight distortions present.

Figure 5.7: Slump formed samples with and without frit.

The fritted sample displays less reflection than the clear sample. Image taken at Cricursa July 2015.

This was reaffirmed by a specialist façade contractor (Arbós, F. *(pers. comm.)* 28th July 2015). Potential investigations:

- Consider effect of frit/finishes to glass surface to reduce the reflection.
- Review and develop anti-reflective temperable coatings to reduce reflection.

5.5.4.1 Improve Production Methods of Hot Bent Glass

The study identified that hot bent radial glass compared to other methods tends to have more visual distortion due to the processes it undergoes. This was reaffirmed by a specialist façade contractor (Diller, N. *(pers.comm.)* 1st July 2015) and façade designer/supplier (Hoenicke, G. *(pers.comm.)* 22 April 2015). Potential improvements to the process:

- Improve current radial process to reduce roller wave.
- Develop new methods for tempering hot bent glass for the slumping method.
- Develop the state of the art air cushion system that allows the tempering of thin glass without touching rollers to be used for curved glass application. This process improves visual quality “Roller waves cannot be created as the surfaces of the glass sheets are not being touched in the LiSEC tempering process.” (LiSEC, 2015)

5.5.4.2 Improve Durability and Colour Consistency of Temperable Coatings

The study and survey confirmed that there is an issue with colour consistency of temperable glass coatings for curved glass buildings.

The following examples illustrated the issue of colour inconsistency of hard coatings.

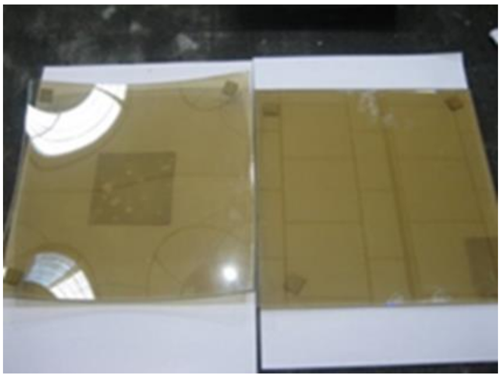


Figure 5.8: Slump formed and flat glass sample – coating air side. (Ramboll 2009)

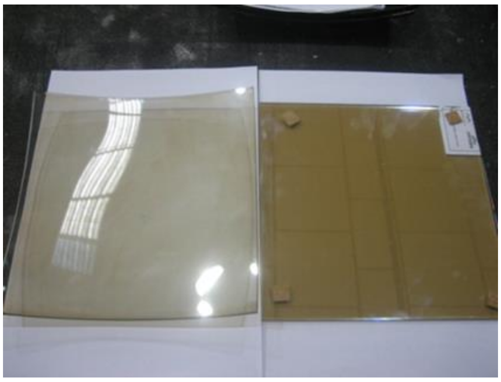


Figure 5.9: Slump formed and flat glass sample – coating mould side and discoloured (Ramboll 2009)

Figure 5.10: Slump formed and flat glass sample – coating air side but distorted. (Ramboll 2009)

This illustrated that the behaviour of coatings is unpredictable and sampling and testing is vital. Soft coatings are further limited as they cannot be in contact with the rollers or moulds.

Coatings are increasingly providing more of a challenge as there is requirement to increase their performance. This was reaffirmed by a specialist glass processor (Tarrus, J. *(pers.comm.)* 27th July 2015). Potential improvements:

- Test and develop new coatings that are temperable.
- Glass suppliers/processors processors could provide sample swatch/examples of current coatings in use so visual differences are illustrated.

5.5.5 Investigate Bending Methods Used By Other Industries

The survey reaffirmed that the building industry should investigate bending methods used by other industries. Potential investigations:

- Consider the automotive industry processes and if these can be adapted for cost effective implementation in the façade industry.
- Review marine glass manufacture for implementation in the building industry.

5.5.6 Research New Materials Such As Thin Glasses That Are Being Developed.

The feedback from the survey reaffirmed that new products should be investigated. Potential investigations:

- Thin glass is being developed. Several papers have been presented to the façade industry and identified that, “The application of thin glass requires further research and development.” (SPISS, H. 2015) and “The application of thin glass has the potential to improve the overall perception of glass and the glass industry.” (SPISS, H. 2015).

5.5.7 Mathematical Approach to Resolving the Issue of Visual Inconsistency.

“Mathematics leads design” (Arbós, F. *(pers.comm.)* 28th July 2015).

- The increased of use of software and 3d analysis was reaffirmed during the visit to Bellapart. The use of mathematical equations as a key design tool was emphasised and that architecture can be translated into a mathematical form (Arbós, F. *(pers.comm.)* 28th July 2015).
- Mathematics is a key design tool that could be further investigated, using the limitations of algorithms to optimise visual consistency.

5.6 Progressing Future Improvements.

The study and the findings of the survey have identified potential proposals that could improve the specification, visual assessment criteria and final quality of curved glazed façades.

These proposals would benefit from input from all parties involved in the design and procurement process: designers/specifiers; consultants; suppliers/manufacturers; façade and main contractors and clients.

In order to progress the propsals further extensive research, development and funding by the industry would be required. However, the benefits to projects of improved specification and quality with reduced procurement risk and fewer disputes during the process would be of assistance to all parties involved.

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Schüco International – façade supplier. Meeting at MFT office 22nd April 2015.
Seele – specialist façade contractor with experience of hot and cold bent projects.

(Diller, N. *(pers.comm.)* 1st July 2015).
DILLER, N. Managing Director, Seele, Gutenbergstraße 19, 86368 Gersthofen, Germany. (formerly Managing Director of Sedak)
Seele – specialist façade contractor with experience of hot and cold bent projects.
Sedak – specialist glass processor producing hot bent and cold bent glass.

Factory visit to Cricursa – specialist glass processor producing hot bent glass.
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7 APPENDICES

7.1 APPENDIX A – SURVEY AND RESPONSES

The following is a copy of the pilot survey with initial questions followed by the results for each question and additional comments provided by the participants.

QUESTION 1:

Question format for Q 1.

Experience of bent glass

1. Please indicate awareness / type of experience with the following types of bent glass (please tick all those that apply)

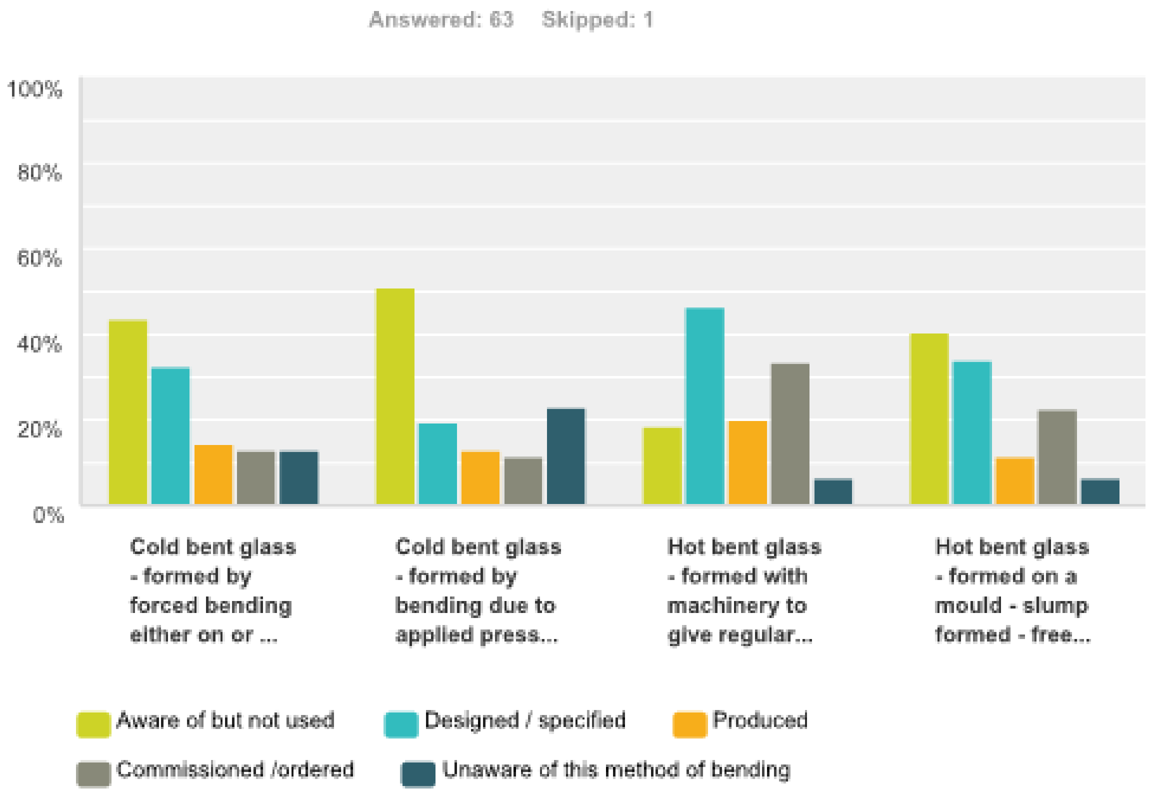
	Aware of but not used	Designed / specified	Produced	Commissioned /ordered	Unaware of this method of bending
Cold bent glass - formed by forced bending either on or off site and restrained by a support member					
Cold bent glass - formed by bending due to applied pressure and then laminated in an autoclave					
Hot bent glass - formed with machinery to give regular geometry as a cylinder / radial / conical					
Hot bent glass - formed on a mould - slump formed - free form / organic geometry					

Other (please specify)

Responses for Q 1.

	Aware of but not used	Designed / specified	Produced	Commissioned /ordered	Unaware of this method of bending	Total Respondents
Cold bent glass - formed by forced bending either on or off site and restrained by a support member	**43.55%** 27	**32.26%** 20	**14.52%** 9	**12.90%** 8	**12.90%** 8	62
Cold bent glass - formed by bending due to applied pressure and then laminated in an autoclave	**50.82%** 31	**19.67%** 12	**13.11%** 8	**11.48%** 7	**22.95%** 14	61
Hot bent glass - formed with machinery to give regular geometry as a cylinder / radial / conical	**18.33%** 11	**46.67%** 28	**20.00%** 12	**33.33%** 20	**6.67%** 4	60
Hot bent glass - formed on a mould - slump formed - free form / organic geometry	**40.32%** 25	**33.87%** 21	**11.29%** 7	**22.58%** 14	**6.45%** 4	62

Graphic analysis for Q 1.



Additional comments from participants Q 1.

Other (please specify)	Date
by process, also the channel glass belongs to bend glass, but is not featured in this research, I assume.	6/15/2015 6:23 AM
I have been involved in projects involving (a) (c) & (d) above but I have not been responsible for the design/specification or commissioning/ordering.	6/14/2015 4:32 PM

QUESTION 2:

Question format for Q 2.

Adequacy of standards / guidance

3. Do you think there are adequate standards and guidance for the specification and visual assessment of bent glass?

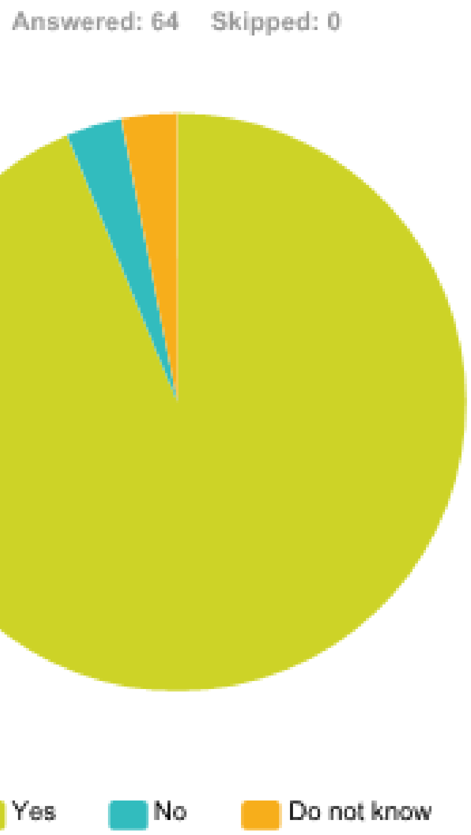
- Yes
- No
- Don't know

Other (please specify)

Responses for Q 2.

Answer Choices	Responses	
Yes	**93.75%**	60
No	**3.13%**	2
Do not know	**3.13%**	2
Total		**64**

Graphic analysis for Q 2.



Additional comments from participants Q 2.

Other (please specify)	Date
There are no responses.	

QUESTION 3:

Question format for Q 3.

Standards / guidance used

4. Have you used any of the following standards/guidance for the specification and visual acceptance criteria for bent glass? (Please tick all that apply)

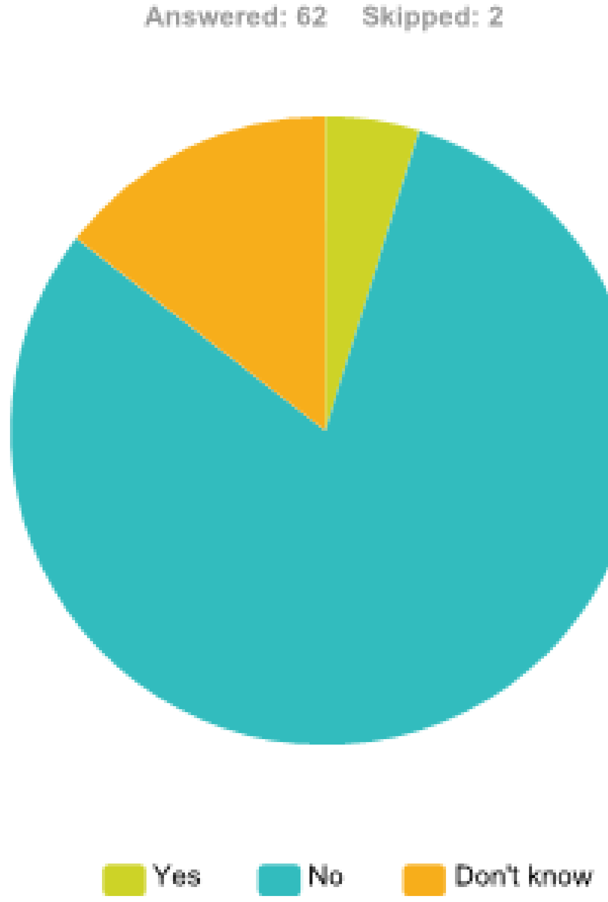
- BS EN Standards for basic soda lime silicate glass - standards for flat / processed glass
- BS EN Standards for insulating glass units
- ASTM C1464 Standard Specification for Bent Glass: 2011
- BS ISO 11485 Glass in Building - Curved glass
- GGF Manual Section 4 Curved Glass: 2011
- BF-Bulletin 009/2011 Guidelines for thermally-curved glass in the building industry
- CWCT TN 35
- Hadamar 06/09 Guidelines to Assess the Visible Quality of Glass in Buildings
- None

Other (please specify)

Responses for Q 3.

Answer Choices	Responses	
Yes	**4.84%**	3
No	**80.65%**	50
Don't know	**14.52%**	9
Total		**62**

Graphic analysis for Q 3.



Additional comments from participants Q 3.

Other (please specify)	Date
Some standards and guidelines are available however more clarity and reconciliation required	6/15/2015 9:25 AM
are there any for the visual assessment?	6/15/2015 6:25 AM
I don't consider that Standards are adequate for any type of glass	6/14/2015 4:34 PM

QUESTION 4:

Question format for Q 4.

Standards / guidance used

4. Have you used any of the following standards/guidance for the specification and visual acceptance criteria for bent glass? (Please tick all that apply)

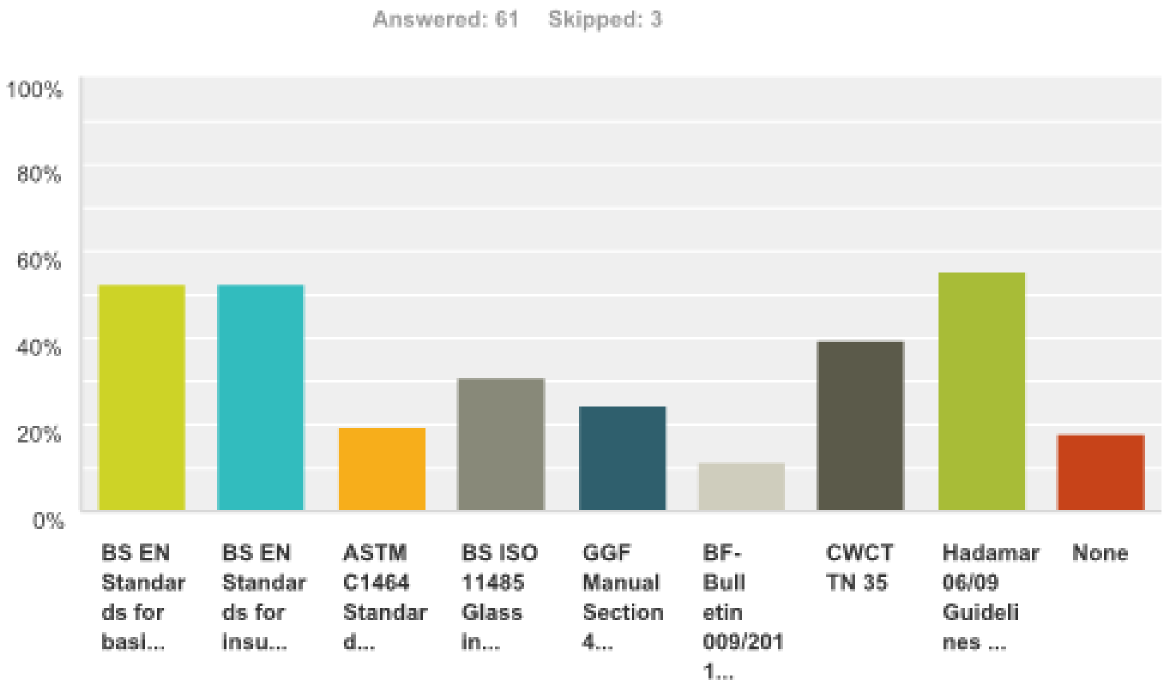
- [ ] BS EN Standards for basic soda lime silicate glass - standards for flat / processed glass
- [ ] BS EN Standards for insulating glass units
- [ ] ASTM C1464 Standard Specification for Bent Glass: 2011
- [ ] BS ISO 11485 Glass in Building - Curved glass
- [ ] GGF Manual Section 4 Curved Glass: 2011
- [ ] BF-Bulletin 009/2011 Guidelines for thermally-curved glass in the building industry
- [ ] CWCT TN 35
- [ ] Hadamar 06/09 Guidelines to Assess the Visible Quality of Glass in Buildings
- [ ] None

Other (please specify)

Responses for Q 4.

Answer Choices	Responses	
BS EN Standards for basic soda lime silicate glass - standards for flat / processed glass	**52.46%**	32
BS EN Standards for insulating glass units	**52.46%**	32
ASTM C1464 Standard Specification for Bent Glass: 2011	**19.67%**	12
BS ISO 11485 Glass in Building - Curved glass	**31.15%**	19
GGF Manual Section 4 Curved Glass: 2011	**24.59%**	15
BF-Bulletin 009/2011 Guidelines for thermally-curved glass in the building industry	**11.48%**	7
CWCT TN 35	**39.34%**	24
Hadamar 06/09 Guidelines to Assess the Visible Quality of Glass in Buildings	**55.74%**	34
None	**18.03%**	11
Total Respondents: 61		

Graphic analysis for Q 4.



Additional comments from participants Q 4.

Other (please specify)	Date
Have previously specified criteria according Hadamar, but with distance according to BF-Bulletin 009. GGF Section 4 is incomplete. BS ISO 11485 and ASTM offer very limited guidance.	7/23/2015 5:00 PM
And client specified upfront agreed criteria	6/15/2015 3:23 PM
German Guidlines for thermally-curved glass in the building industry	6/15/2015 9:27 AM
Specific samples/tests shall be carried out with the supplyer	6/15/2015 9:00 AM
I approach things differently - I advise Clients to use certain curved glass processors that provide the best quality available.	6/14/2015 4:36 PM

QUESTION 5:

Question format for Q 5.

HOT BENT GLASS - issues

5. HOT BENT GLASS. Have you experienced poor visual quality of curved glass used in buildings due to any of the following for hot bent glass? (Please tick all that apply)

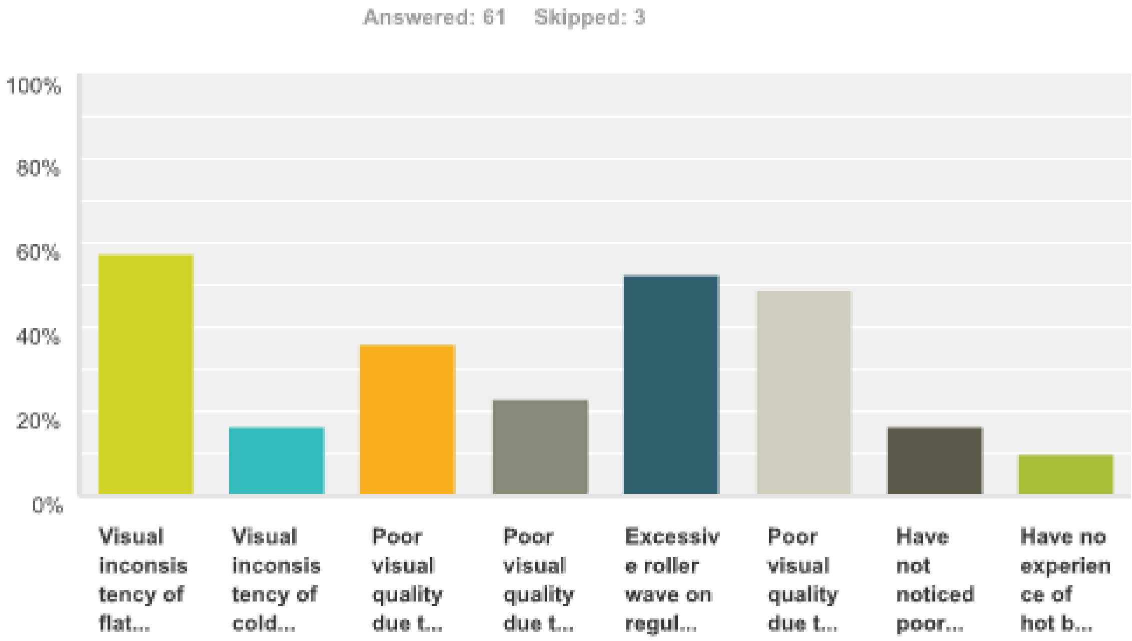
- Visual inconsistency of flat glass adjacent to hot bent glass
- Visual inconsistency of cold bent glass adjacent to hot bent glass
- Poor visual quality due to soft coatings on hot bent glass
- Poor visual quality due to hard coatings on hot bent glass
- Excessive roller wave on regular radial/conical formed hot bent glass
- Poor visual quality due to distortion in laminated hot bent glass
- Have not noticed poor visual quality in hot bent glass
- Have no experience of hot bent glass

Other (please specify)

Responses for Q 5.

Answer Choices	Responses	
Visual inconsistency of flat glass adjacent to hot bent glass	**57.38%**	35
Visual inconsistency of cold bent glass adjacent to hot bent glass	**16.39%**	10
Poor visual quality due to soft coatings on hot bent glass	**36.07%**	22
Poor visual quality due to hard coatings on hot bent glass	**22.95%**	14
Excessive roller wave on regular radial/conical formed hot bent glass	**52.46%**	32
Poor visual quality due to distortion in laminated hot bent glass	**49.18%**	30
Have not noticed poor visual quality in hot bent glass	**16.39%**	10
Have no experience of hot bent glass	**9.84%**	6
Total Respondents: 61		

Graphic analysis for Q 5.



Additional comments from participants Q 5.

Other (please specify)	Date
Visible block lines that make the form	6/15/2015 5:31 PM
The bend radius has a big influence on the final appearance of the glass and on the coating selection	6/15/2015 9:06 AM
Certain curved glass processors consistently produce hot curved glass with better visual regularity than others. Food for thought !	6/14/2015 4:39 PM
I thought but I might be wrong that you can't hot bend glass with soft coatings as the coatings melt and run to the curve also when you hot bend hard coatings the coatings change colour slightly which is one reason why coated bent glass looks different to flat glass. Because of this the last time I used hot bent glass I just used a low e coating so it wouldn't look too different to the adjacent flat glass	6/13/2015 12:45 PM
Air bubbles in resin laminate	6/13/2015 12:11 PM

QUESTION 6:

Question format for Q 6.

COLD BENT GLASS - issues

6. COLD BENT GLASS. Have you experienced poor visual quality of curved glass used in buildings due to any of the following for cold bent glass? (Please tick all that apply)

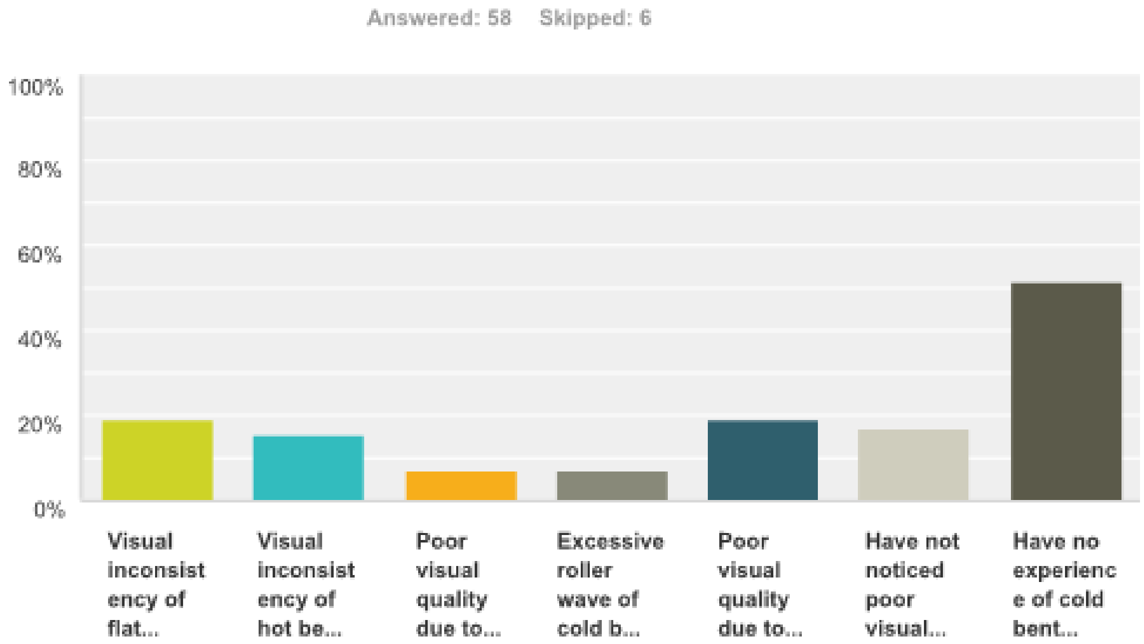
- ☐ Visual inconsistency of flat glass adjacent to cold bent glass
- ☐ Visual inconsistency of hot bent glass adjacent to cold bent glass
- ☐ Poor visual quality due to coatings on cold bent glass
- ☐ Excessive roller wave of cold bent tempered glass
- ☐ Poor visual quality due to distortion in laminated cold bent glass
- ☐ Have not noticed poor visual quality in cold bent glass used on a project
- ☐ Have no experience of cold bent glass

Other (please specify)

Responses for Q 6.

Answer Choices	Responses	
Visual inconsistency of flat glass adjacent to cold bent glass	**18.97%**	11
Visual inconsistency of hot bent glass adjacent to cold bent glass	**15.52%**	9
Poor visual quality due to coatings on cold bent glass	**6.90%**	4
Excessive roller wave of cold bent tempered glass	**6.90%**	4
Poor visual quality due to distortion in laminated cold bent glass	**18.97%**	11
Have not noticed poor visual quality in cold bent glass used on a project	**17.24%**	10
Have no experience of cold bent glass	**51.72%**	30
Total Respondents: 58		

Graphic analysis for Q 6.



Additional comments from participants Q 6.

Other (please specify)	Date
The appearance is highly dependent of how much the glass is cold bent	6/15/2015 9:12 AM
Have yet to have a project with cold bent glass completed.	6/14/2015 4:39 PM

QUESTION 7:

Question format for Q 7.

Mitigation of visual inconsistencies

7. If you were concerned about the possible visual distortion when using bent glass how would you rate your preference for each of the following possible mitigation measures. (Please give your level of preference for each of the items)

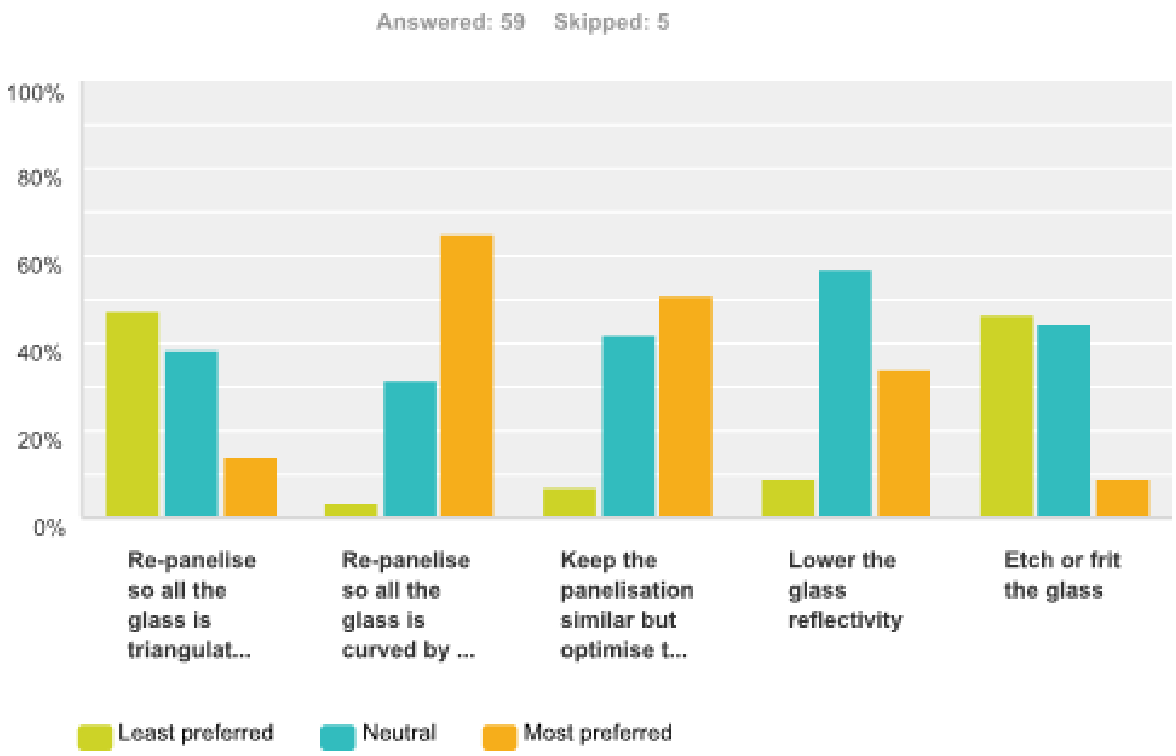
	Least preferred	Neutral	Most preferred
Re-panelise so all the glass is triangulated and flat	○	○	○
Re-panelise so all the glass is curved by the same method	○	○	○
Keep the panelisation similar but optimise to reduce number of different types	○	○	○
Lower the glass reflectivity	○	○	○
Etch or frit the glass	○	○	○

Other (please specify)

Responses for Q 7.

	Least preferred	Neutral	Most preferred	Total	Weighted Average
Re-panelise so all the glass is triangulated and flat	**47.37%** 27	**38.60%** 22	**14.04%** 8	57	1.67
Re-panelise so all the glass is curved by the same method	**3.51%** 2	**31.58%** 18	**64.91%** 37	57	2.61
Keep the panelisation similar but optimise to reduce number of different types	**7.02%** 4	**42.11%** 24	**50.88%** 29	57	2.44
Lower the glass reflectivity	**8.93%** 5	**57.14%** 32	**33.93%** 19	56	2.25
Etch or frit the glass	**46.43%** 26	**44.64%** 25	**8.93%** 5	56	1.63

Graphic analysis for Q 7.



Additional comments from participants Q 7.

Other (please specify)	Date
Specify the use of annealed glass and form on mould to minimise optical distortions	7/23/2015 5:00 PM
Remove the bent and facet glass panels	6/15/2015 8:44 AM
Option 5; It would be preferential to apply a opaque interlayer as opposed to surface treatments to the glass. An Etch or Frit application to the glass surface will reduce the stress capacity of the glass, and in turn limit how much the etch/frit glass can be bent by compared to clear glass.	6/15/2015 2:30 AM
Consider the best worldwide suppliers of hot curved glass and see/obtain samples; if they can't satisfy the Architect's objectives, use facetted glass.	6/14/2015 4:42 PM

QUESTION 8:

Question format for Q 8.

Panelisation criteria

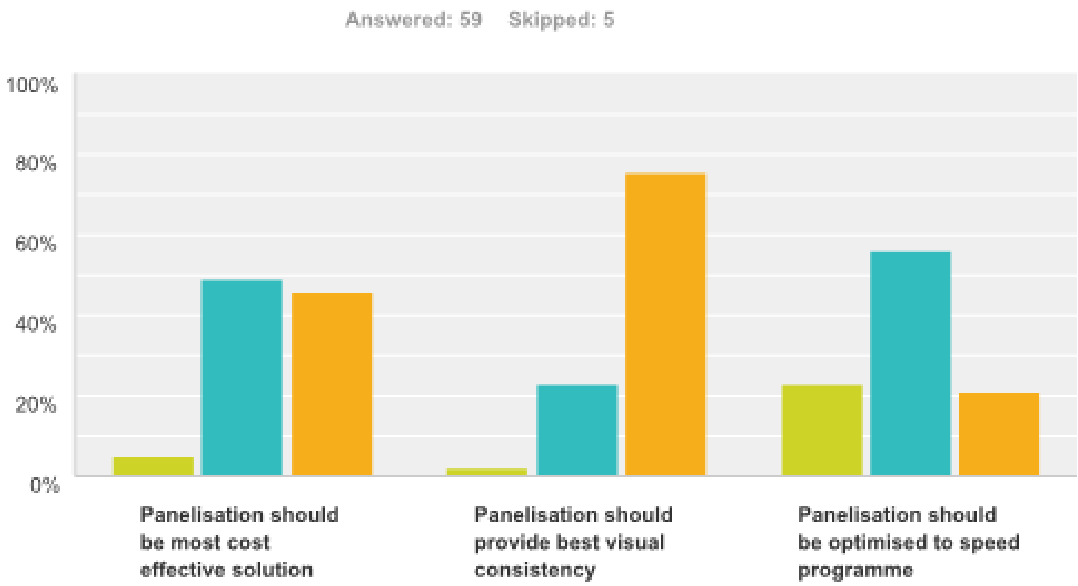
8. For the following panelisation criteria for the design, specification and procurement of a project with bent glass please rate your level of importance to each of the criteria. (Please rate each of the items)

	Least important	Neutral	Most important
Panelisation should be most cost effective solution	○	○	○
Panelisation should provide best visual consistency	○	○	○
Panelisation should be optimised to speed programme	○	○	○

Responses for Q 8.

	Least important	Neutral	Most important	Total	Weighted Average
Panelisation should be most cost effective solution	**5.08%** 3	**49.15%** 29	**45.76%** 27	59	2.41
Panelisation should provide best visual consistency	**1.75%** 1	**22.81%** 13	**75.44%** 43	57	2.74
Panelisation should be optimised to speed programme	**22.81%** 13	**56.14%** 32	**21.05%** 12	57	1.98

Graphic analysis for Q 8.



QUESTION 9:

Question format for Q 9.

HOT BENT GLASS - Optimising visual quality

9. HOT BENT GLASS - To optimise the visual quality of hot bent glass how would you rate the importance of each of the following items. (Please rate all items)

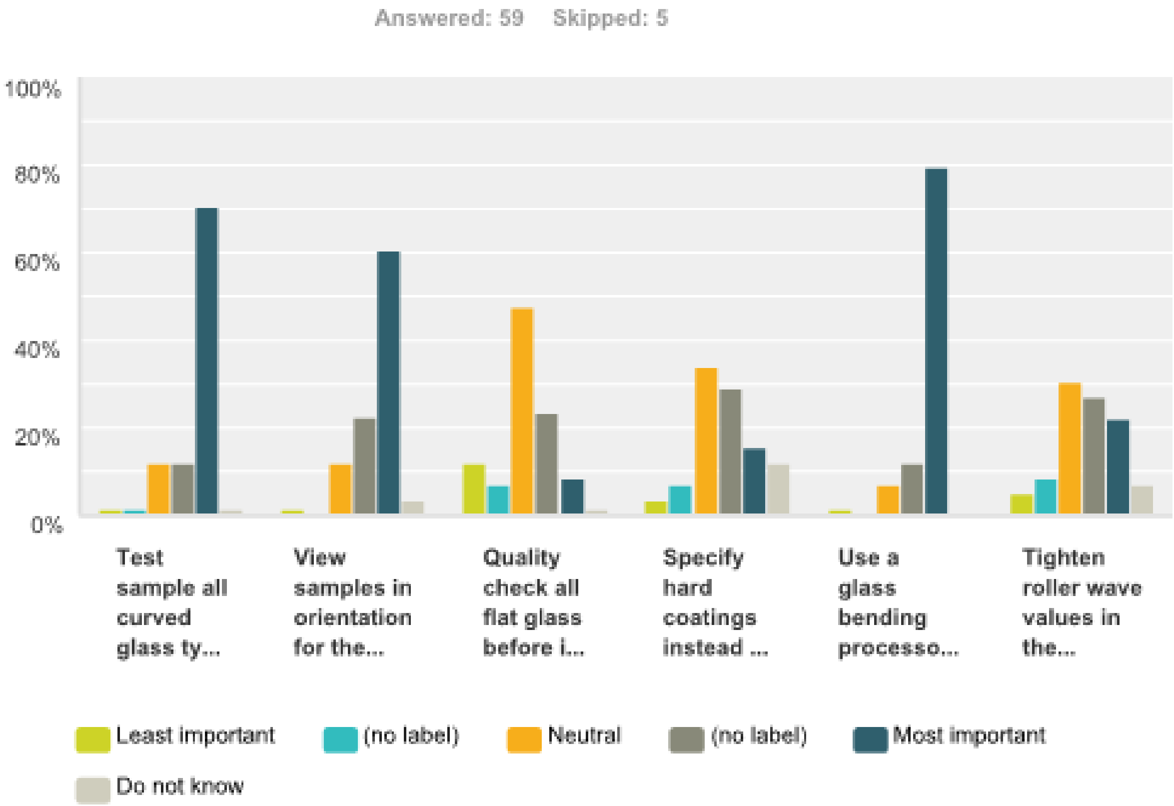
	Least important		Neutral		Most important	Do not know
Test sample all curved glass types to achieve benchmark samples						
View samples in orientation for the project						
Quality check all flat glass before it is curved.						
Specify hard coatings instead of soft coatings for hot bent glass						
Use a glass bending processor with tried and tested experience						
Tighten roller wave values in the specification for hot bent monolithic / laminated glass						

Other (please specify)

Responses for Q 9.

	Least important	(no label)	Neutral	(no label)	Most important	Do not know	Total	Weighted Average
Test sample all curved glass types to achieve benchmark samples	**1.72%** 1	**1.72%** 1	**12.07%** 7	**12.07%** 7	**70.69%** 41	**1.72%** 1	58	4.51
View samples in orientation for the project	**1.72%** 1	**0.00%** 0	**12.07%** 7	**22.41%** 13	**60.34%** 35	**3.45%** 2	58	4.45
Quality check all flat glass before it is curved.	**11.86%** 7	**6.78%** 4	**47.46%** 28	**23.73%** 14	**8.47%** 5	**1.69%** 1	59	3.10
Specify hard coatings instead of soft coatings for hot bent glass	**3.39%** 2	**6.78%** 4	**33.90%** 20	**28.81%** 17	**15.25%** 9	**11.86%** 7	59	3.52
Use a glass bending processor with tried and tested experience	**1.69%** 1	**0.00%** 0	**6.78%** 4	**11.86%** 7	**79.66%** 47	**0.00%** 0	59	4.68
Tighten roller wave values in the specification for hot bent monolithic / laminated glass	**5.08%** 3	**8.47%** 5	**30.51%** 18	**27.12%** 16	**22.03%** 13	**6.78%** 4	59	3.56

Graphic analysis for Q 9.



Additional comments from participants Q 9.

Other (please specify)	Date
Roller wave is very difficult to measure on bent glass. As such we would also recommend avoiding processes where rollers are used (heat strengthened and tempered) where possible.	7/23/2015 5:00 PM
The bend radius influences a lot the final appearance of the glass	6/15/2015 9:12 AM
spacing/ Size of roller s depending on machiene and hence this is directly related to teh max size of glass panel than can be curved....	6/15/2015 8:18 AM
Hot bend glass - if visual quality and consistency is the priority; 1. Use a configuration of annealed glass only. 2. If a configuration of annealed or annealed laminate is inadequate, use chemical tempering methods as opposed to oven tempering. 3. Preferably avoid using any coatings at all! (so clear or body tinted glass only....if possible). With any hot bend glass, due to manufacture the variation in surface tension from glass to glass will be much more variable than in comparison to the variation observed with flat glass. If the hot bend glass also features a coating, then a much more pronounced variation in visible anistrophy from glass to glass should be expected! To avoid any potential wildly varying anistrophy effects, omit coatings altogether if possible!	6/15/2015 3:22 AM
See earlier answers: the most important factor is the glass processor used.	6/14/2015 4:44 PM

QUESTION 10:

Question format for Q 10.

COLD BENT GLASS - Optimising visual quality

10. COLD BENT GLASS - To optimise the visual quality of cold bent glass how would you rate the importance of each of the following items. (Please rate all items)

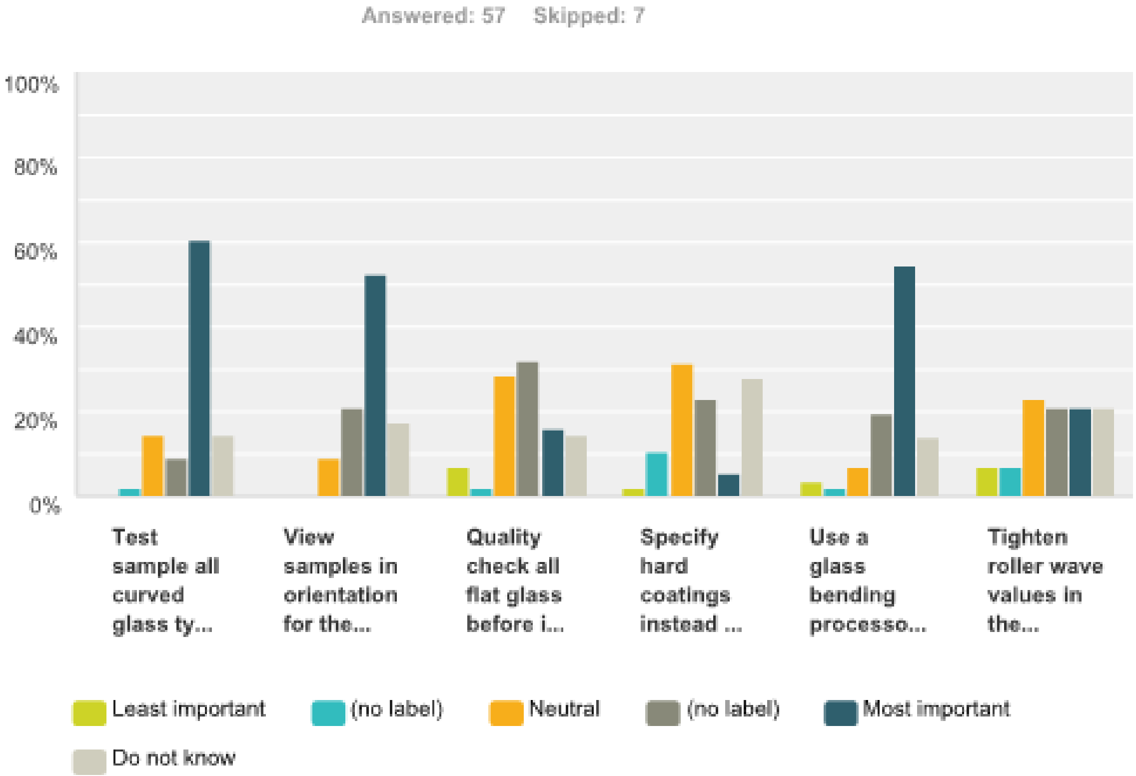
	Least important		Neutral		Most important	Do not know
Test sample all curved glass types to achieve benchmark samples	○	○	○	○	○	○
View samples in orientation for the project	○	○	○	○	○	○
Quality check all flat glass before it is curved.	○	○	○	○	○	○
Specify hard coatings instead of soft coatings for cold bent glass	○	○	○	○	○	○
Use a glass bending processor / contractor with tried and tested experience	○	○	○	○	○	○
Tighten roller wave values in the specification for cold bent monolithic/laminated glass	○	○	○	○	○	○

Other (please specify)

Responses for Q 10.

	Least important	(no label)	Neutral	(no label)	Most important	Do not know	Total	Weighted Average
Test sample all curved glass types to achieve benchmark samples	**0.00%** 0	**1.79%** 1	**14.29%** 8	**8.93%** 5	**60.71%** 34	**14.29%** 8	56	4.50
View samples in orientation for the project	**0.00%** 0	**0.00%** 0	**8.77%** 5	**21.05%** 12	**52.63%** 30	**17.54%** 10	57	4.53
Quality check all flat glass before it is curved.	**7.14%** 4	**1.79%** 1	**28.57%** 16	**32.14%** 18	**16.07%** 9	**14.29%** 8	56	3.56
Specify hard coatings instead of soft coatings for cold bent glass	**1.75%** 1	**10.53%** 6	**31.58%** 18	**22.81%** 13	**5.26%** 3	**28.07%** 16	57	3.27
Use a glass bending processor / contractor with tried and tested experience	**3.51%** 2	**1.75%** 1	**7.02%** 4	**19.30%** 11	**54.39%** 31	**14.04%** 8	57	4.39
Tighten roller wave values in the specification for cold bent monolithic/laminated glass	**7.02%** 4	**7.02%** 4	**22.81%** 13	**21.05%** 12	**21.05%** 12	**21.05%** 12	57	3.53

Graphic analysis for Q 10.



Additional comments from participants Q 10.

Other (please specify)	Date
for the cold bend laminated glass thin glass is used and hence it can be done on the new Lisec air-bed system (no roller wave)	6/15/2015 8:20 AM
Bend it as least as possible!	6/15/2015 3:22 AM
My answers above assume that the cold bent glass is heat treated. The biggest issue with cold bent glass is the effect of cold bending on life expectancy.	6/14/2015 4:47 PM

QUESTION 11:

Question format for Q 11.

Improving specification

11. To improve the specification and production of bent glass please rate each of the following items for its level of importance to you. (please rate all items)

	Least important				Most important	Do not know
Improve current standards for material specification	○	○	○	○	○	○
Provide further standards and guidance for the specification and visual quality of HOT bent glass	○	○	○	○	○	○
Provide further standards and guidance for the specification and visual quality of COLD bent glass	○	○	○	○	○	○
Agree tolerances early on in the design for the specification of bent glass	○	○	○	○	○	○
Develop improved methodology for visual acceptance criteria in the specification for bent glass	○	○	○	○	○	○
Reduce the external reflectance of HOT bent glass	○	○	○	○	○	○
Reduce the external reflectance of COLD bent glass	○	○	○	○	○	○
Improve production methods for HOT bent radial and conical glass	○	○	○	○	○	○
Develop production methods to improve tolerances in HOT bent formed glass	○	○	○	○	○	○
Develop production methods to improve tolerances in COLD bent formed glass	○	○	○	○	○	○

	Least important				Most important	Do not know
Develop alternative methods for HOT bent slump formed glass to allow thermal toughening						
Develop more coatings that can be HOT bent and maintain visual consistency						
Improve methods for producing HOT bent glass by investigating methods used in other industries such as the automotive industry						
Investigate possibilities of bending using different glass materials such as thin sheet fused glass						

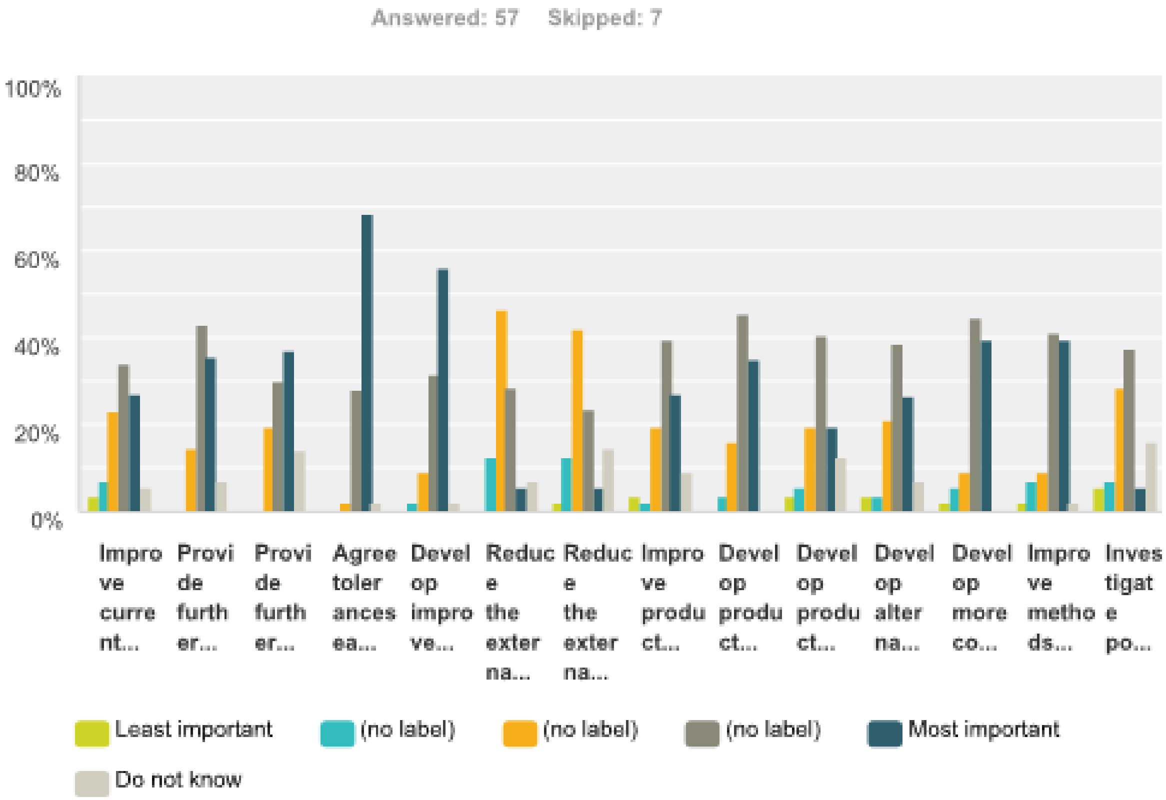
Other (please specify)

Responses for Q 11.

	Least important	(no label)	(no label)	(no label)	Most important	Do not know	Total	Weighted Average
Improve current standards for material specification	**3.57%** 2	**7.14%** 4	**23.21%** 13	**33.93%** 19	**26.79%** 15	**5.36%** 3	56	3.77
Provide further standards and guidance for the specification and visual quality of HOT bent glass	**0.00%** 0	**0.00%** 0	**14.29%** 8	**42.86%** 24	**35.71%** 20	**7.14%** 4	56	4.23
Provide further standards and guidance for the specification and visual quality of COLD bent glass	**0.00%** 0	**0.00%** 0	**19.30%** 11	**29.82%** 17	**36.84%** 21	**14.04%** 8	57	4.20
Agree tolerances early on in the design for the specification of bent glass	**0.00%** 0	**0.00%** 0	**1.75%** 1	**28.07%** 16	**68.42%** 39	**1.75%** 1	57	4.68
Develop improved methodology for visual acceptance criteria in the specification for bent glass	**0.00%** 0	**1.75%** 1	**8.77%** 5	**31.58%** 18	**56.14%** 32	**1.75%** 1	57	4.45

	Least important	(no label)	(no label)	(no label)	Most important	Do not know	Total	Weighted Average
Reduce the external reflectance of HOT bent glass	**0.00%** 0	**12.50%** 7	**46.43%** 26	**28.57%** 16	**5.36%** 3	**7.14%** 4	56	3.29
Reduce the external reflectance of COLD bent glass	**1.82%** 1	**12.73%** 7	**41.82%** 23	**23.64%** 13	**5.45%** 3	**14.55%** 8	55	3.21
Improve production methods for HOT bent radial and conical glass	**3.57%** 2	**1.79%** 1	**19.64%** 11	**39.29%** 22	**26.79%** 15	**8.93%** 5	56	3.92
Develop production methods to improve tolerances in HOT bent formed glass	**0.00%** 0	**3.51%** 2	**15.79%** 9	**45.61%** 26	**35.09%** 20	**0.00%** 0	57	4.12
Develop production methods to improve tolerances in COLD bent formed glass	**3.51%** 2	**5.26%** 3	**19.30%** 11	**40.35%** 23	**19.30%** 11	**12.28%** 7	57	3.76
Develop alternative methods for HOT bent slump formed glass to allow thermal toughening	**3.51%** 2	**3.51%** 2	**21.05%** 12	**38.60%** 22	**26.32%** 15	**7.02%** 4	57	3.87
Develop more coatings that can be HOT bent and maintain visual consistency	**1.79%** 1	**5.36%** 3	**8.93%** 5	**44.64%** 25	**39.29%** 22	**0.00%** 0	56	4.14
Improve methods for producing HOT bent glass by investigating methods used in other industries such as the automotive industry	**1.79%** 1	**7.14%** 4	**8.93%** 5	**41.07%** 23	**39.29%** 22	**1.79%** 1	56	4.11
Investigate possibilities of bending using different glass materials such as thin sheet fused glass	**5.36%** 3	**7.14%** 4	**28.57%** 16	**37.50%** 21	**5.36%** 3	**16.07%** 9	56	3.36

Graphic analysis for Q 11.



Additional comments from participants Q 11.

Other (please specify)	Date
the bend glass in general is a local area of a entire project and henci it will have to live with teh reflectance of the 'typical' area. reducing the reflectance in the ME is even more importnat due to the distortion due to pillowing on the standard panel, therefore I wouldn't related solely to the bend glass.	6/15/2015 8:26 AM
Tempering Ovens where the glass goes through on a perforate conveyor belt as opposed to a series of rollers, or goes through vertically as opposed to horizontally could be further investigated as a way of reducing distortion.	6/15/2015 3:22 AM

8 APPENDIX B – DETAILED STANDARDS/GUIDANCE REVIEW

A detailed review of the following standards was carried out. This was in order to appraise the information available in respect of the visual defects/attributes and visual assessment for curved glass buildings. Where applicable, figures/tables from the documents were included to illustrate the limitation of information available and examples of inconsistencies and omissions.

The review included flat and curved glass standards/guidance as follows:

BS EN 572-1:2012. Glass in building – basic soda lime silicate glass products. Part 1: Definitions and general physical and mechanical properties. BSI Standards Publication.

BS EN 572-2:2012 Glass in building – basic soda lime silicate glass products. Part 2: Float glass. BSI Standards Publication.

BS EN 12150-1:2000 Glass in building – Thermally toughened soda lime silicate safety glass. Part 1: Definitions and classification. BSI Standards Publication.

BS EN 14179-1:2005 Glass in building – Heat soaked thermally toughened soda lime silicate safety glass. Part 1: Definitions and classification. BSI Standards Publication.

BS EN 12543-1:2011 Glass in building – Laminated glass and laminated safety glass. Part 1: DEFINITIONS AND DESCRIPTION OF COMPONENT PARTS (ISO 12543-1:2011) BSI Standards Publication.

BS EN 12543-6:2011 Glass in building – Laminated glass and laminated safety glass. Part 6: Appearance. BSI Standards Publication.

BS EN 1096-1:2012 Glass in Building – Coated glass Part 1: Definitions and classification. BSI Standards Publication.

BS EN 1279-1:2004 Glass in Building – Insulating glass units Part 1: generalities, dimensional tolerances and rules for the system description. BSI Standards Publication.

BS ISO 11485-1: 2011 – Glass in building. Curved glass. Part 1. Terminology and definitions. BSI Standards Publication.

BS ISO 11485-2:2011 – Glass in building. Curved glass. Part 2: Quality requirements. BSI Standards Publication.

BS ISO 11485 3 2014 Glass in building. Curved glass. Part 3. Requirements for curved tempered and curved laminated safety glass. BSI Standards Publication.

ASTM C1464-06:2011. Standard Specification for Bent Glass: C1464 – 06 (Reapproved 2011).

Guidelines for thermally-curved glass in the building industry – BF Bulletin 009 / 2011.

Curved glass Part 1:2011 Generalities – Definitions, Terminology, Properties and Basis of Measurement and Test. GGF.

Curved glass Part 2:2011 Curved annealed glass. GGF.

Curved glass Part 3:2011 Curved thermally treated glasses. GGF.

HADAMAR 2009 Guideline to Assess the Visible Quality of Glass in Buildings.

CWCT Technical Note No 35 Assessing the appearance of glass.

8.1 Flat Glass Standards

Annealed Glass

BS EN 572-1:2012. Glass in building – basic soda lime silicate glass products. Part 1: Definitions and general physical and mechanical properties. BSI Standards Publication.

The standard covers all soda lime silicate products and advises that for fault descriptions and quality limits for each particular type that the relevant Part is to be consulted.
Clause 6.5.1 Optical, highlights that the optical quality faults are generally due to "distortion of the surface and lack of homogeneity" and these should use visual observation methods for evaluation.
Clause 6.5.2 Appearance, states "The visual quality can be affected by the presence of spot faults (bubbles, stones, etc.) linear/extended faults (scuff marks, scratches, lines, deposits, impressions, etc.) pattern faults and wire faults.
Spot faults are evaluated by specifying numbers and dimensions.
Linear/extended faults are evaluated by visual observation.
Pattern faults are evaluated by measuring deviation."

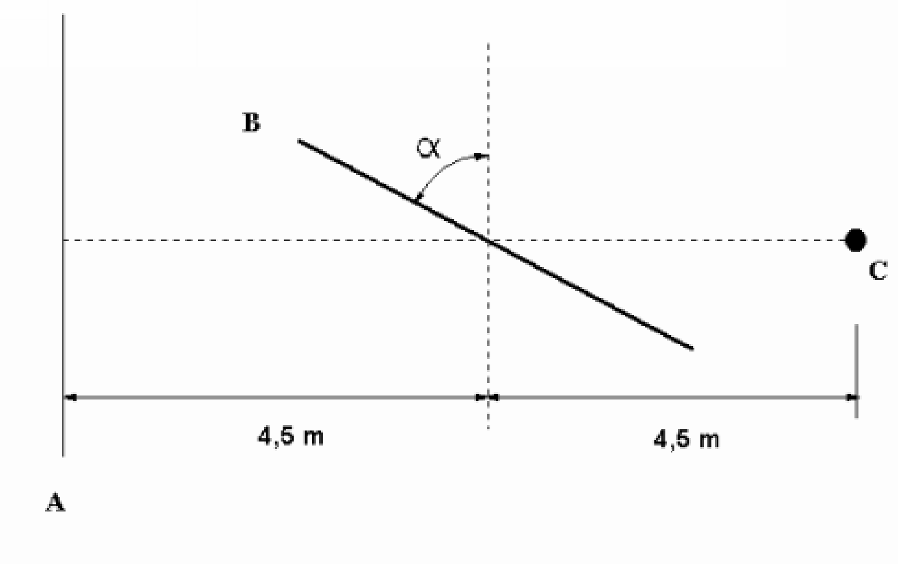
This standard relates to flat transparent float glass and makes no reference to curved glass. However it is relevant to the base material used for the production of curved glass – such as slump formed or cold bent annealed glass. It is also the basis for tempered, laminated, coated glass and for glass used for an insulated glass unit.

BS EN 572-2:2012 Glass in building – basic soda lime silicate glass products. Part 2: Float glass. BSI Standards Publication.

The standard further defines the acceptance criteria for the faults in the glass.
Section 5 covers optical and visual faults.

Optical Faults

Clause 5.2.1 provides the methodology for using a zebra board for observing the glass for optical quality. The glass piece 3210mm wide x 300-500mm is supported to allow rotation around a vertical axis and viewed against the vertical zebra board which is 9m from the observer with the glass piece at 4.5m from the board. The glass is rotated until an angle α is found where the lines on the screen are no longer distorted and the angle is recorded.



Key

A screen

B glass sample

C observer

Figure 2 — Plan view showing set up of zebra test

Figure B.1: Excerpt from BS EN 572-2:2012

The glass section is divided into 4 along the 3210mm width and the zones for distortion are measured in *d* and *D*.

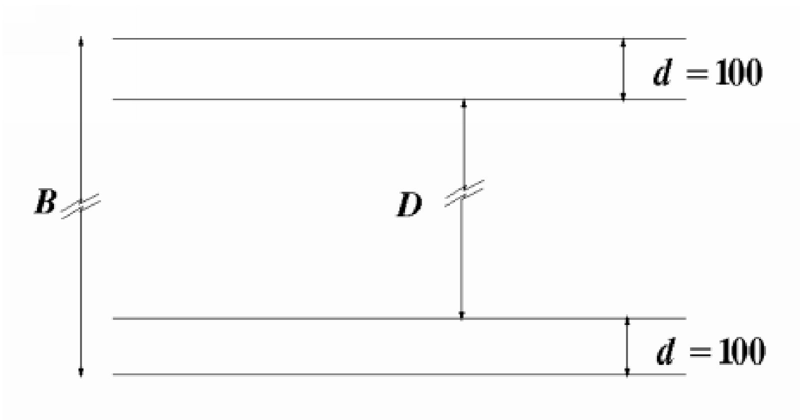


Figure 3 — Zones for the measurement of optical distortion

Figure B.2: Excerpt from BS EN 572-2 figure 3

The acceptance criteria are such that the “the angle α at which there is no disturbing distortion shall not be less than the appropriate critical viewing angle given in Table 4.” The definition of disturbing however is a subjective criterion.

Table 4 — Critical viewing angles

Nominal glass thickness mm	Angle α in zone D degrees	Angle α in zone d degrees
2	45	40
3 and greater	50	45

Figure B.3: Excerpt from BS EN 572-2 figure 3

Visual Faults – Spot Faults

The glass is held vertically and illuminated and the spot fault (including halo which is area around the nucleus of the spot fault) is measured with a distortion gauge or with calipers. The distortion gauge has black spots from 0.6mm to 9.0mm on a plastic transparent sheet:

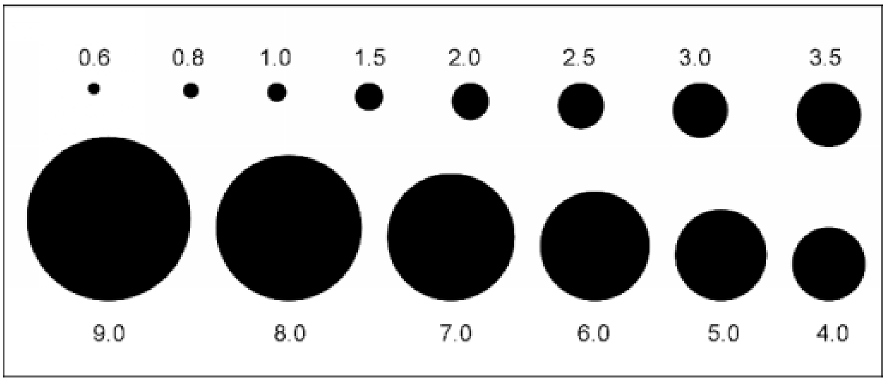


Figure A.2 — Example of distortion gauge with printed black spots

Figure B.4: Excerpt from BS EN 572-2 Figure A.2 – with example of distortion gauge.

Clause 5.2.2.1 table 3 provides the limitations for spot faults.

Table 3 — Categories of spot faults

Dimensions in millimetres

Category	Dimension of spot fault
A	> 0,6 and ≤ 1,5
B	> 1,5 and ≤ 3,0
C	> 3,0 and ≤ 9,0
D	> 9,0

Figure B.5: Excerpt from BS EN 572-2 Table 3

The acceptance criterion given for jumbo glass is in table 5:

Table 5 — Acceptance levels for spot faults in jumbo sizes

Category of fault	Average per pane	Maximum in any pane
A	any number	any number
B	3	5
C	0,6	1
D	0,05	1, but faults that cause breakage are not allowed
NOTE The word "average" is intended to indicate a cumulative average over at least 20 tons of glass.		

Figure B.6: Excerpt from BS EN 572-2 Table 5

and for split sizes in table 6:

Table 6 — Acceptance levels for spot faults in split sizes

Category of fault	Average per 20 m^2	Maximum in any pane
A	any number	any number
B	3	2
C	0,6	1
D	0,05	1, but faults that cause breakage are not allowed
NOTE The word "average" is intended to indicate a cumulative average over at least 20 t of glass.		

Figure B.7: Excerpt from BS EN 572-2 Table 5

For glass sizes above these, the acceptance criteria are to be agreed with the manufacturer.

Visual Faults – Linear/extended Faults

For visual observation of linear/extended faults it states that the glass should be observed from a distance of 2m in lighting conditions emulating diffuse light in front of a matt black screen. The acceptance levels are related to at least 20 tons of glass and allowable number is average of 0.05 faults for $20m^2$ of glass.

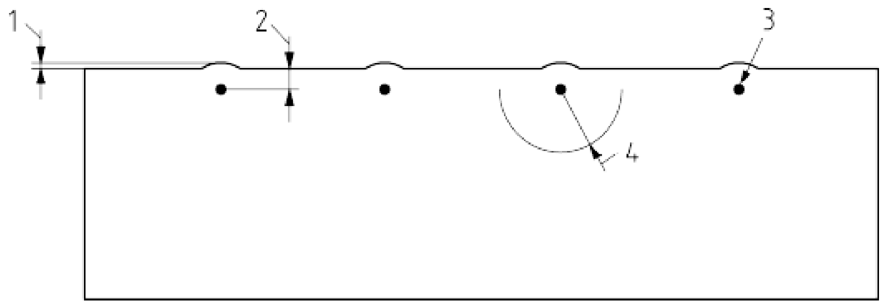
This standard relates to flat transparent float glass and makes no reference to curved glass. However it is relevant to the base material used for the production of curved glass – such as slump formed or cold bent annealed glass. It is also the basis for tempered, laminated, coated glass and for glass used for an insulated glass unit.

A further standard is currently in Draft form. Draft BS ISO 16293-2 Glass in Building – basic soda lime silicate products part 2: Float glass. Compared to BS 572-2, this draft indicates some of the acceptance criteria for tolerances may be relaxed. For visual quality it indicates to better quantify measurement of spot faults based on per m^2. However, as this is still draft, this study will reference BS 572-2 for optical and visual quality assessment.

Heat Strengthened Glass

BS EN 1863-1:2011 Glass in building – Heat strengthened soda lime silicate glass. Part 1: Definitions and classification. BSI Standards Publication.

In respect of visual quality, 6.2.4 provides limiting criteria for vertical heat strengthening: tong marks no more than 20mm in from the edge



Key

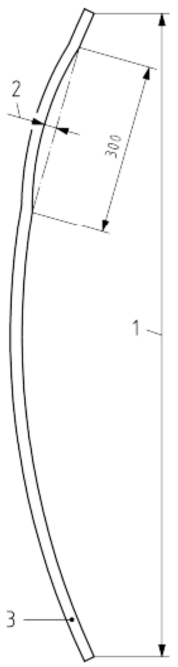
1 deformation
2 up to 20 mm
3 tong mark
4 100 mm radius maximum area of optical distortion

Figure 2 — Tong mark deformation

Figure B.8: Excerpt from BS EN 1863-1 Figure 2 – Tong mark deformation

The standard states, “By the very nature of the heat strengthening process, it is not possible to obtain a product as flat as annealed glass.” Section 6.3.1 advises allowance for local distortion should be made. This is measured as illustrated in Figure B.9 and B.10.

Dimension in millimetres



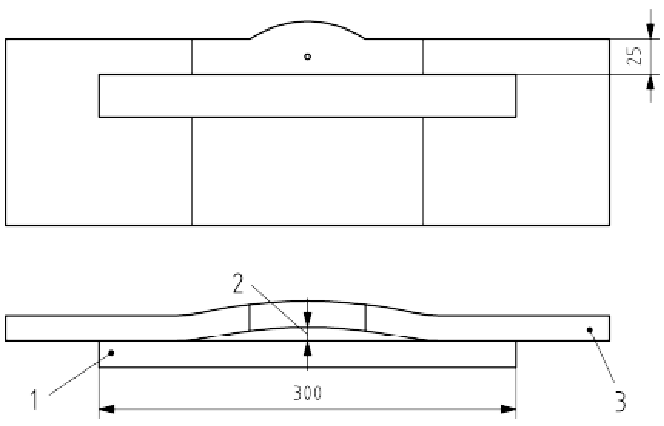
Key

1 *B*, or *H*, the side on which the tong marks occur
2 local distortion
3 heat strengthened glass

Figure 6 — Representation of local distortion

Figure B.9: Excerpt from BS EN 1863-1 Figure 6 – Representation of local deformation

Dimension in millimetres



Key

1 straight edge
2 local distortion
3 heat strengthened glass

Figure 10 — Measurement of local distortion

Figure B.10: Excerpt from BS EN 1863-1 Figure 10 – Measurement of local deformation

The limitations for these effects are provided in section 6.3.7

Table 6 — Maximum values of overall bow and local distortion for vertically heat strengthened glass

Glass Type	Maximum value for distortion	
	Overall bow mm/m	Local distortion mm/300 mm
All [a]	5,0	1,0

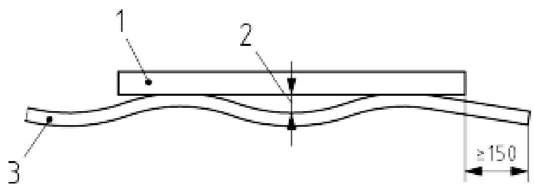
a For enamelled glass which is not covered over the whole surface the manufacturer should be consulted.

Figure B.11: Excerpt from BS EN 1863-1 Table 6 – Maximum values of overall bow and local distortion for vertically heat strengthened glass

More relevant for heat strengthened glass is the horizontal process. The measurement criteria and limitations for the distortions due to roller wave, overall bow and edge lift are provided.

Roller wave measurement in section 6.3.3.4 states the glass to be measured at right angles to the roller wave, to exclude the 150mm zone to the glass edge and that the glass is to be laid flat to reduce any overall bow in the panel.

Dimension in millimetres



Key

1 straight edge
2 roller wave distortion
3 heat strengthened glass

Figure 8 — Measurement of roller wave distortion

Figure B.12: Excerpt from BS EN 1863-1 Figure 8 – Measurement of roller wave distortion.

Section 6.3.6 then provides the limitations allowable for these effects.

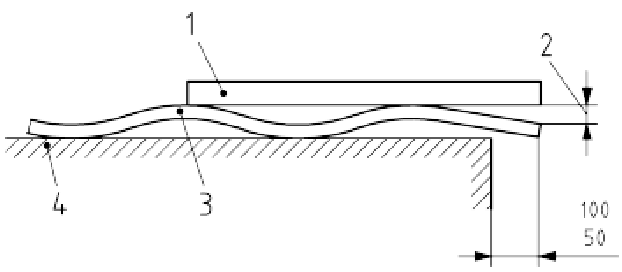
Table 4 — Maximum values of overall bow and roller wave distortion for horizontally heat strengthened glass

Glass Type	Maximum value for distortion	
	Overall bow mm/m	Roller Wave mm
Uncoated float glass in accordance with EN 572-1 and EN 572-2	3,0	0,3
Others [a]	4,0	0,5
Dependant upon the wave length of the roller wave an appropriate length of gauge has to be used.		
a For enamelled glass which is not covered over the whole surface the manufacturer should be consulted.		

Figure B.13: Excerpt from BS EN 1863-1 Table 4 Maximum values of overall bow and roller wave distortion for horizontally heat strengthened glass

For edge lift measurement in section 6.3.4, the glass is placed flat with the edge overhanging by 50-100mm.

Dimensions in millimetres



Key

1 straight edge
2 edge lift
3 heat strengthened glass
4 flat support

Figure 9 — Measurement of edge lift

Figure B.14: Excerpt from BS EN 1863-1 Figure 9 – Measurement of edge lift

Table 5 — Maximum values for edge lift for horizontal heat strengthening

Type of glass	Thickness of glass mm	Maximum values mm
Uncoated float glass in accordance with EN 572-1 and EN 572-2	3	0,5
	4 to 5	0,4
	6 to 12	0,3
Others [a]	all	0,5
Dependant upon the wave length of the roller wave an appropriate length of gauge has to be used.		
a For enamelled glass which is not covered over the whole surface the manufacturer should be consulted.		

Figure B.15: Excerpt from BS EN 1863-1 Table 5 Maximum values for edge lift for horizontally heat strengthened glass

The standard identifies optical distortion and describes the effects in section 9. In 9.1, It describes tong marks as a result of vertical toughening and roller wave as a result of horizontal toughening and also roller pick up for glass over 8mm using the horizontal process. Clause 9.2 describes anisotropy and states that it is a visible effect and not a defect. The standard does not provide observation criteria.

This standard relates to flat transparent heat strengthened glass. It make a single reference in terms and definitions to curvature in clause 3.1 “ curved heat strengthened soda lime silicate glass heat strengthened soda lime silicate glass which has been deliberately given a specific profile during manufacture.”

Fully Toughened Glass

BS EN 12150-1:2000 Glass in building – Thermally toughened soda lime silicate safety glass. Part 1: Definitions and classification. BSI Standards Publication.

This standard is similar to BS EN 1863 - 1:2011 for overall bow and vertical toughening visual criteria and acknowledges that fully toughened glass will not be as flat as annealed glass. However, it does not include measurement and limitations of roller wave or edge lift.

The standard identifies optical distortion and describes the effects in section 9. In 9.1, It describes tong marks as a result of vertical toughening and ‘roller wave’ as a distortion in the surface as a result of horizontal toughening and also ‘roller pick-up’ for glass over 8mm using the horizontal process. 9.2 describes anisotropy and states that it is a visible effect and not a defect. It does not provide observation criteria.

This standard relates to flat transparent thermally toughened soda lime silicate safety glass. It makes reference to curvature in Annex B (informative).

"Curved thermally toughened soda lime silicate safety glass
Curved (in the UK also called bent) thermally toughened soda lime silicate glass has been deliberately given a specific profile during the course of manufacture. It is not included in this standard since there is insufficient data available to standardize the product. However, the information given in this standard on thickness, edge work and fragmentation is also applicable to curved thermally toughened soda lime silicate glass."

BS EN 14179-1:2005 Glass in building – Heat soaked thermally toughened soda lime silicate safety glass. Part 1: Definitions and classification. BSI Standards Publication.

The standard identifies optical distortion and describes the effects in section 1. In 11.1, It describes tong marks as a result of vertical toughening and 'roller wave' as a distortion in the surface as a result of horizontal toughening and also 'roller pick-up' for glass over 8mm using the horizontal process. Clause 11.2 describes anisotropy and states that it is a visible effect and not a defect. It does not provide observation criteria.

This standard relates to flat transparent heat soaked thermally toughened soda lime silicate safety glass. It makes reference to curvature in Annex B (informative)
"Curved heat soaked thermally toughened soda lime silicate safety glass
Curved (in the UK also called bent) heat soaked thermally toughened soda lime silicate glass has been deliberately given a specific profile during the course of manufacture. It is not included in this European Standard since there is insufficient data available to standardise the product. However, the information given in this European Standard on thickness, edge work and fragmentation is also applicable to curved heat soaked thermally toughened soda lime silicate glass.

The information on the heat soak process cycle is also applicable. However, extreme care should be taken to ensure that the curved shape does not interfere with the airflow."

Laminated Glass

BS EN 12543-1:2011 Glass in building – Laminated glass and laminated safety glass. Part 1: Definitions and description of component parts (ISO 12543-1:2011) BSI Standards Publication.

This standard relates to flat transparent laminated glass and laminated safety glass. It makes a single reference in definitions and description of component parts to curvature in clause 2.9 "**curved laminated glass"** laminated glass in which the constituent glass panes and plastic glazing sheet material have been deliberately shaped by forming or bending prior to laminating"

This would therefore imply that it was not applicable to forced cold bending in an autoclave.

BS EN 12543-6:2011 Glass in building – Laminated glass and laminated safety glass. Part 6: Appearance. BSI Standards Publication.

This standard identifies the optical defect and fault criteria for flat transparent laminated glass and laminated safety glass. It makes no reference to curved glass.

It advises that observation should be from a distance of 2m and the observer should be perpendicular to the glass. Section 4 states "Any visible defects that are disturbing shall be marked." This is a subjective criterion. Defects are identified. Spot defects – including bubbles, foreign bodies and opaque spots. Linear defects – including scratches or grazes and foreign bodies. Other defects including vents, interlayer defects of creasing, shrinkage and streaking. The acceptance criteria does not allow any vents which are cracks which run into the glass from an edge, no interlayer defects – creases and streaks are allowed in the vision area. Spot defects over 3mm are not allowed. Acceptance criteria are summarised

Table 1 — Permissible spot defects in the vision area

Size of defect d mm		$0{,}5 < d \leq 1{,}0$	$1{,}0 < d \leq 3{,}0$			
Size of pane A m^2		for all sizes	$A \leq 1$	$1 < A \leq 2$	$2 < A \leq 8$	$A > 8$
Number or density of permissible defects	2 panes	no limitation; however, no accumulation of defects	1	2	$1/m^2$	$1{,}2/m^2$
	3 panes		2	3	$1{,}5/m^2$	$1{,}8/m^2$
	4 panes		3	4	$2/m^2$	$2{,}4/m^2$
	≥5 panes		4	5	$2{,}5/m^2$	$3/m^2$
NOTE An accumulation of defects occurs if four or more defects are at a distance of <200 mm from each other. This distance is reduced to 180 mm for laminated glass consisting of three panes, to 150 mm for laminated glass consisting of four panes and to 100 mm for laminated glass consisting of five or more panes.						

The number of permissible defects in Table 1 shall be increased by one for each individual interlayer which is thicker than 2 mm.

Figure B.16: Excerpt from BS EN ISO 12543-6:2011. Table 1 – Permissible spot defects in the vision area.

The acceptance criteria for linear defects are given.

Table 2 — Number of permissible defects in the vision area

Area of pane m^2	Number of permissible defects >30 mm in length[a]
≤5	not allowed
5 to 8	1
>8	2

[a] Linear defects less than 30 mm in length are allowed.

Figure B.17: Excerpt from BS EN ISO 12543-6:2011. Table 2 – number of permissible defects in the vision area.

Coated Glass

BS EN 1096-1:2012 Glass in Building – Coated glass Part 1: Definitions and classification. BSI Standards Publication.

Section 8 includes appearance defects. These may be due to the glass substrate and these are covered by the appropriate substrate standard or they may be due to the coating.

The standard advises a minimum 3m distance to observe the coated glass either in the factory or on site and illuminated with an artificial sky or by daylight without direct sunlight. It also advises of the maximum angle for the examination not to exceed 30 degrees and the examination should not exceed 20 seconds. Clause 8.2 refers to uniformity defects and stains and uses the criteria of failure as visually disturbing, which is a subjective criterion.

Table 1 in section 8.4 summarises the acceptance criteria

Table 1 — Acceptance criteria for coated glass defects

DEFECT TYPES	ACCEPTANCE CRITERIA		
	PANE/PANE	INDIVIDUAL PANE	
UNIFORMITY/STAIN	Allowed as long as not visually disturbing	Allowed as long as not visually disturbing	
		MAIN AREA	EDGE AREA
PUNCTUAL	Not applicable		
Spots/Pinholes; > 3 mm		Not allowed	Not allowed
> 2 mm and ≤ 3 mm		Allowed if not more than 1/m^2	Allowed if not more than 1/m^2
Clusters;		Not allowed	Allowed as long as not in area of through vision
Scratches;			
> 75 mm		Not allowed	Allowed as long as they are separated by > 50 mm
≤ 75 mm		Allowed as long as local density is not visually disturbing	Allowed as long as local density is not visually disturbing

Figure B.18: Excerpt from BS EN 1096-1:2012. Table 1 – Acceptance criteria for coated glass defects.

This standard makes no reference to curved glass

Insulating glass units

BS EN 1279-1:2004 Glass in Building – Insulating glass units Part 1: generalities, dimensional tolerances and rules for the system description. BSI Standards Publication.

This standard makes a reference to curvature in section 4.6
“Curved insulating glass units
Units with a bending radius greater than 1 metre comply with this standard without having to undergo the additional tests on curved test pieces.
Units with a bending radius equal or less than 1 metre comply with this standard if in addition curved test pieces with the same or similar smaller bending radius meet the moisture penetration requirements of EN 1279–2. The test specimens should be curved with the curving axis parallel with the longest side.”

This standard reverts to the European Standards for the optical and quality criteria for the glass making up the unit. In addition it identifies defects that may be noted in the insulated glass unit in Annex C (informative). Those particular to insulated glass units are noted in C.1 Interference colouration which include Brewster’s fringes when lines are identified due to the decomposition of the light spectrum, and are considered as inherent to the unit and not a failure. Newton rings occur when the glass is nearly touching or is touching and is a failure. Other optical effects include pillowing which is due to temperature and barometric pressure variations. Other effects may be external condensation and also colour of the glass due to the thicker make-up of the glass in the unit.

8.2 Bent Glass Standards

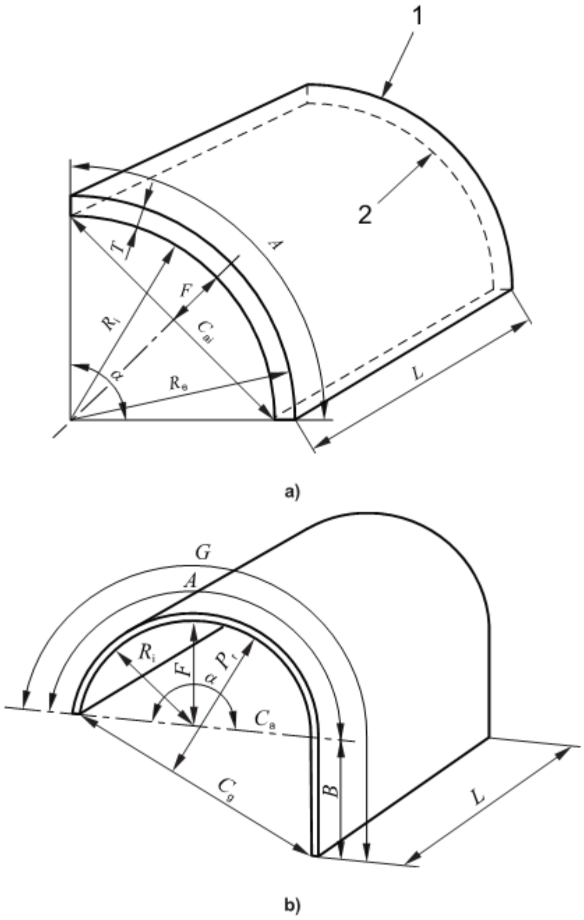
The following bent glass standards are those identified as more commonly considered within UK and Europe in reference to specification of curved glass.

BS ISO 11485-1: 2011 – Glass in building. Curved glass. Part 1. Terminology and definitions. BSI Standards Publication.

This standard provides a description of the terminology for curved glass. This standard is for hot bent glass types.
Clause 2.1 defines
“curved glass
bent glass (US)
sheet of annealed glass curved by a heating process”

Reference within the document for concave is the hollow of the glass and convex is the bulge of the glass.
This includes the types of curved glass: annealed; tempered; heat soaked tempered; heat strengthened; laminated; insulating glass unit.
The standard describes the measurement terminology for the different geometries. It also introduces additional deviation criteria compared to flat glass – 2.37, edge straightness deviation warp and 2.38 twist deviation.
In respect of visual quality, it references:
2.39 optical distortion; due to the bending processes
2.40 displacement in laminated glass or IGUs.
2.41 cold crack
2.42 pock marks
2.43 ring marks
2.44 tong marks

It provides detailed information on terms and dimensions for curvature and this is illustrated.



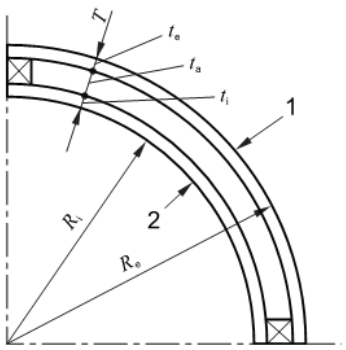
Key

1 bulge outer face (convex)

2 hollow inner face (concave)

Figure 1 — Examples of terms and dimensions

Figure B.19: Excerpt from BS ISO 11485-1:2011. Figure 1 – Examples of terms and dimensions.



Key

1 convex part

2 concave part

Figure 2 — Thicknesses and radius of an insulating glass

Figure B.20: Excerpt from BS ISO 11485-1:2011. Figure 2 – Thicknesses and radius of an insulating glass.

Key (noted) from BS ISO 11485-1:2011

□□= **Angle –** angular measurement of a segment of a curve in degrees

R_i = **inner radius** – radius of concave face

R_e = **outer radius** – radius of convex face

A = **arc** – length of the curved portion. An arc is described as either interior arc (A_i) or exterior arc (A_e).

C_a = **chord of the arc** – line segment that connects end points of an arc. A chord is described as either an interior chord (C_{ai}) or an exterior chord (C_{ae}). The interior chord (C_{ai}) corresponds to the interior arc (A_i) and the exterior chord (C_{ae}) corresponds to the exterior arc (A_e).

F = **rise depth** – segment between the middle of the arc of the circle and the middle of the chord that subtends the arc

G = **girth –** distance around the concave or convex surface measured perpendicular to the height including any flats

C_g = **chord of the girth –** line segment that connects end points of a girth

P_r = **depth –** maximal distance between the upper part of the girth (G) and the corresponding chord (C_d)

L = **length –** dimension of the straight edge of the curved glass

B = **flat –** flat segments forming a part of curved glass

T = **thickness** – nominal thickness of the final product. In a curved insulating glass, the thickness is the sum of the thicknesses of the inner glass (T_i), the gas space (T_a) and the outer glass (T_e).

This standard is useful in providing a means to identify dimensioning and geometry.

The Bibliography refers to:

[1] ISO 11485-2, Glass in building – Curved glass – Part 2: Quality requirements (Part 3: Requirements for curved tempered and curved laminated safety glass is not mentioned as this was published in 2014)

[2] ISO 12543 (all parts), Glass in building – laminated glass and laminated safety glass.

[3] ASTM C1464-06, Standard Specification for Bent Glass

BS ISO 11485-2:2011 – Glass in building. Curved glass. Part 2: Quality requirements. BSI Standards Publication.

This standard gives detailed information for quality requirements. It notes some key tolerance criteria. This has an impact on the visual quality as if these are exceeded; they may be seen as distortion due to the reflectivity of the glass. The standard provides test methodology for the measurement of the tolerances. The accuracy of these measurements may be difficult to achieve depending on the geometry. Clause 4.1 explains tolerances. However, it refers to ISO 16293 (all parts) which are still in draft. It does note that “minor changes to glass thickness may occur due to stretching during forming and/or shaping.”

Tolerances on the shape are given:

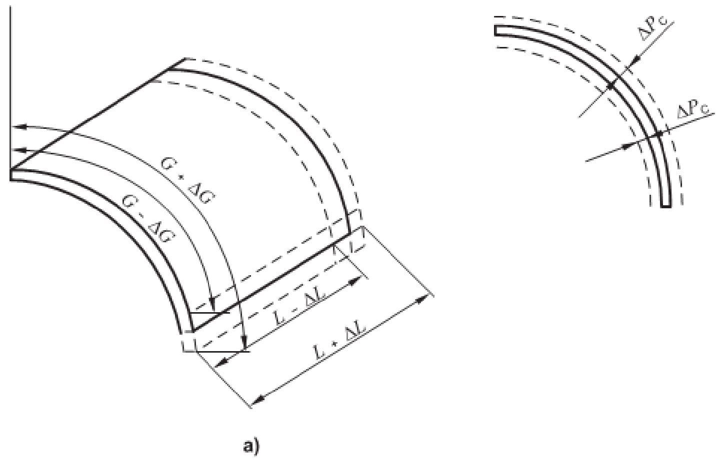


Figure 1 — Tolerances on shape accuracy, girth and length

Figure B.21: Excerpt from BS ISO 11485-2:2011. Figure 1 – Tolerances on shape accuracy, girth and length.

The standard advises in section 5.1 that the sample is measured for shape accuracy “using a gauge or 1:1 scale template.” This is not illustrated. The limitations are provided.

Table 2 — Tolerances on the shape accuracy, girth and length

	Tolerance	
	Thickness < 10 mm	**Thickness ≥ 10 mm**
ΔP_C [a]	2/3 T	1/2 T
ΔG	± 2 mm/m	± 3 mm/m
ΔL	± 2 mm/m	± 3 mm/m

[a] Measured perpendicularly to the glass.

Figure B.22: Excerpt from BS ISO 11485-2:2011. Table 2 – Tolerances on the shape accuracy, girth and length.

Key (noted) from BS ISO 11485-2:2011

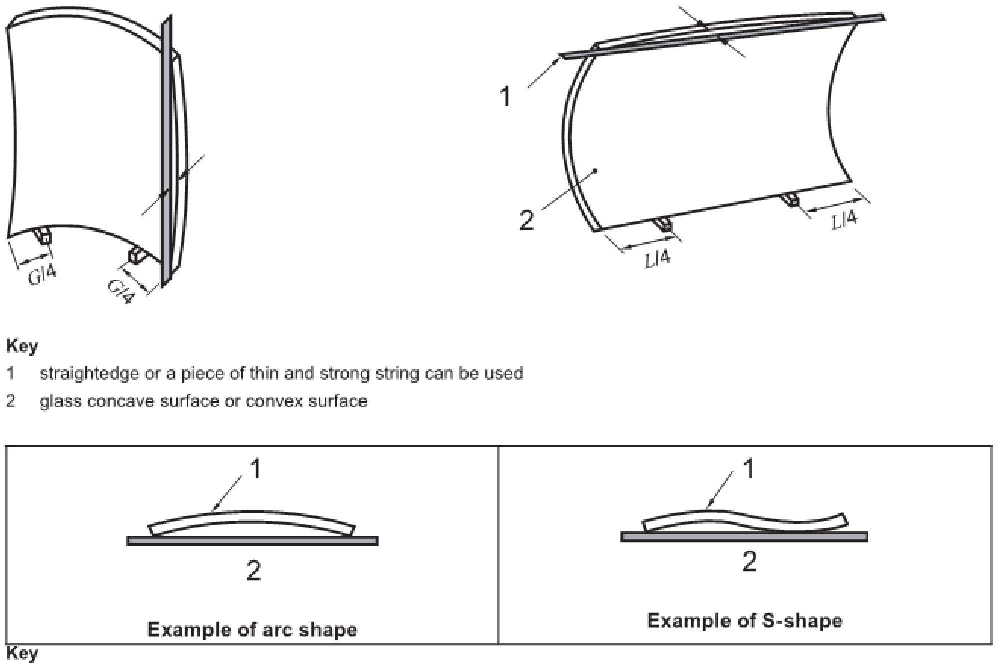
$\otimes P_C$ = tolerance on the shape accuracy;

$\otimes G$= is the tolerance on the overall girth

$\otimes L$= is the tolerance on length.

T = nominal thickness of the final product when the curved glass type is curved annealed glass, curved tempered glass, curved tempered heat-soaked glass or curved laminated glass, or the thickness of the glass components when assembled into a curved insulating glass.

Section 4.3 encompasses edge straightness deviation, noted as $\otimes R_B$. Method of measurement is advised in section 5.2 using a ruler with 0.1mm intervals and illustrated.



Key

1 glass edge

2 ruler

Figure 8 — Measurement of edge straightness deviation

Figure B.23: Excerpt from BS ISO 11485-2:2011. Figure 8 – Measurement of edge straightness deviation.

This is limited to " $\otimes R_B \leq 3$ mm/m or 2 mm, whichever is greater." It is also illustrated as follows:

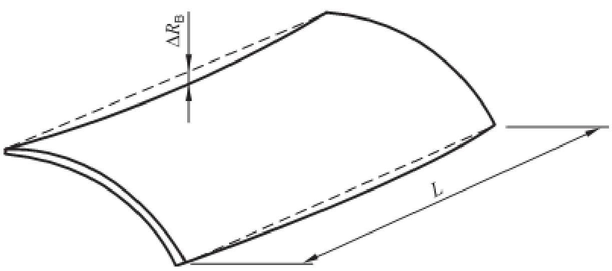


Figure 2 — Example of edge straightness deviation

Figure B.24: Excerpt from BS ISO 11485-2:2011. Figure 2 – Example of edge straightness deviation.

Maximum cross curve deviation is limited not to exceed 4mm.

Maximum twist deviation noted as *V* is measured as illustrated below.

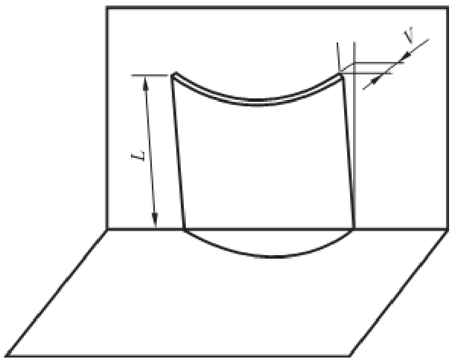


Figure 3 — Twist deviation

Figure B.25: Excerpt from BS ISO 11485-2:2011. Figure 3 – Twist deviation.

This is limited in Table 3

Table 3 — Maximum tolerances for twist deviation

Length (mm)	**Twist deviation** (mm)
$L \leq 1\,200$	$V < 4$
$1\,200 < L \leq 1\,500$	$V < 5$
$1\,500 < L \leq 2\,000$	$V < 6$
$2\,000 < L \leq 2\,400$	$V < 7$
$L > 2\,400$	$V < 8$

Figure B.26: Excerpt from BS ISO 11485-2:2011. Table 3 – Maximum tolerances for twist deviation.

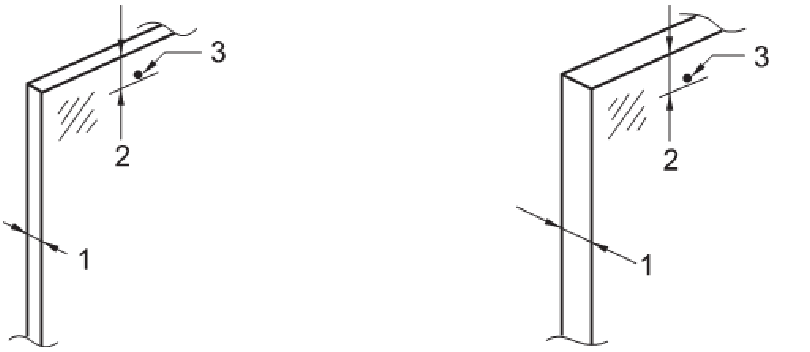
The section 4.6 on appearance advises that test method 5.5 be used which states inspection of the glass be in the vertical position and be from 3m distance in daylight without direct sunlight. Defects to be measured with a ruler with 0.5mm intervals.

The acceptance criteria are provided in table 4.

Table 4 — Appearance acceptability

Type of defect	Acceptability
cracking (cold crack)	None
chipping	Covered edge: No chipping of a width or length more than the nominal thickness of the glass. Exposed edge: No chipping that hinders serviceability.
tong marks	In cases where the nominal thickness of glass is 6 mm or less, tong marks shall only be allowed within 8 mm of the glass edge, as shown in Figure 4. In cases where the nominal thickness is over 6 mm, tong marks shall be allowed within the thickness of the glass + 2,0 mm, as shown in Figure 4.
pock marks	Pock marks shall not exceed 2,0 mm in diameter.
ring marks	In cases where the finished glass will be installed into a frame that conceals the edge(s), ring marks can be present inboard of the edge(s). In cases where the glass edge(s) are exposed in their final installation, ring marks inboard of the glass edge(s) are acceptable to the extent of glass thickness + 2,0 mm from the edge, only at the discretion of the concerned parties.

Figure B.27: Excerpt from BS ISO 11485-2:2011. Table 4 – Appearance acceptability



Key
1 nominal thickness 6 mm or less
2 8 mm max.
3 tong marks

Key
1 nominal thickness over 6 mm
2 nominal thickness + 2 mm max.
3 tong marks

Figure 4 — Tong marks

Figure B.28: Excerpt from BS ISO 11485-2:2011. Tong marks for curved glass

It is more stringent than BS EN 1863-1:2011 and BS 12150-1:2000 for tong marks which allows these within 20mm. If curved glass made from flat glass has tong marks within the allowable tolerances, these may exceed those stated in the curved glass standard. Clause 4.7 illustrates the maximum displacement for curved laminated glass. This is less stringent than flat laminated for panes with a dimension greater than 4000mm. The flat glass standard BS EN ISO 12543-5:2011 allows maximum 6mm if L or H are greater than 4000mm. The curved glass standard BS ISO 11485-2:2011 gives a general figure of 2mm/m for glass with *L* or *G* greater than 1000mm.

Clause 4.8 provides guidance on dimensional tolerances of curved insulating glass. The clause refers to ISO 16293 (all parts) – however, these are not yet published, so a comparison can be made with the flat insulating glass units BS EN 1279-1:2004. The curved glass standard is less onerous than the flat glass. It allows “The tolerance on the total thickness shall equal the sum of the tolerances on the components (see applicable standards) increased by 3mm.”

A tolerance on shape accuracy is provided which is an additional requirement compared to flat insulating glass units and is illustrated:

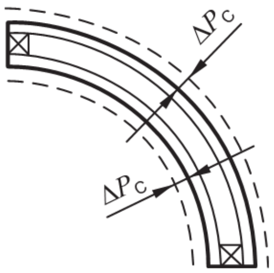


Figure 6 — Shape accuracy

Figure B.29: Excerpt from BS ISO 11485-2:2011. Figure 6 – Shape accuracy

This provides guidance on the tolerance of shape accuracy as:

“$\Delta P\mathrm{C} = \Delta P\mathrm{C1} + \Delta P\mathrm{C2} + 2\,\mathrm{mm}$

where

$\Delta P\mathrm{C1}$ is the tolerance on the curvature of the first component of the curved insulating glass;

$+\Delta P\mathrm{C2}$ is the tolerance on the curvature of the second component of the curved insulating glass with

$\Delta P\mathrm{C1}$ and $\Delta P\mathrm{C2}$ in accordance with limits given in Table 2.

NOTE The thickness deviation of curved insulating glass is partly the consequence of the tolerance on shape accuracy.”

Clause 4.8.3 provides guidance on the maximum edge displacement of curved insulating glass. This is not provided in the flat glass standard BS EN 1279-1:2004.

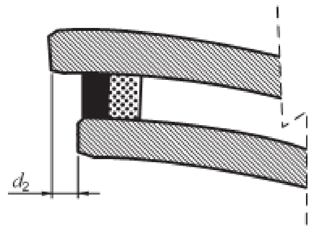


Figure 7 — Displacement for curved insulating glass

Figure B.30: Excerpt from BS ISO 11485-2:2011. Figure 7 – Displacement for curving insulating glass

Table 6 — Maximum displacement of curved insulating glass

L or G	**Maximum displacement**
L or $G \leq$ 1 000 mm	$d_2 \leq$ 3 mm
L or $G >$ 1 000 mm	$d_2 \leq$ 3 mm/m

Figure B.31: Excerpt from BS ISO 11485-2:2011. Table 6 – Maximum displacement for curving insulating glass.

Section 5 provides guidance for test methods – generally the measurement of the deviations for curved glass. There is – no equivalent in BS EN 1279-1:2004 for flat IGUs.

Overall this standard provides guidance for tolerances and dimensioning that will impact the quality of the final panels. However, it is limited in giving guidance on visual quality.

BS ISO 11485 3 2014 Glass in building. Curved glass. Part 3. Requirements for curved tempered and curved laminated safety glass. BSI Standards Publication

This standard provides criteria for the curved tempered and laminated safety glass.

There is limited information on laminated curved safety glass in section 4.2 which also refers to ISO 11485-1. It also states that laminated curved glass can be formed from annealed, heat strengthened and tempered glass (also chemically toughened – not covered in this study).

Section 5 provides fragmentation test guidance. The comparison with the flat glass standard BS EN 12150-1-2000 for minimum values from the particle, identifies that BS ISO 11485-3: 2014 for glass with nominal thickness of 3mm is more stringent with a value of 270 compared to 135 for flat glass for the equivalent test are. Above 3mm values are equivalent.

Clause 6.2 states that the mechanical strength measurement for curved glass has no standardised methodology of evaluation of measurement.

Clause 8.1 states that the impact performance for accidental human impact for curved tempered safety glass does not have an ISO standard for testing and therefore advises that national standards be applied until a standard is agreed.

This makes no reference to visual assessment.

ASTM C1464-06:2011. Standard Specification for Bent Glass: C1464 – 06 (Reapproved 2011).

This standard has limitations for shape tolerances – height, girth, shape accuracy. It also limits size of pock marks and ring marks. It does not note number of allowable defects, but refers back to the flat and laminated glass standards for blemishes. It does have limits for crossbend and twist deviation. In respect of diagrams and methodology, it is less detailed than BS ISO 11485-1:2011 and 11485-2: 2011. For the purposes of this study, the associated ASTMs are not reviewed and therefore this standard has limited value in the assessment of visual quality.

8.3 Bent Glass Guidance

Guidelines for thermally-curved glass in the building industry – BF Bulletin 009 / 2011.

This German guidance document was produced by Bundesverband Flaschglas e. V. The participating firms include many of the European glass processors. This collaboration took place as industry had identified a lack of guidelines for the thermally curved glass.

The guidelines explain that the intention is to give designers, planners and contractor some direction in the use, specification and panelisation of thermally curved glass from the design stage through to construction including transportation and installation. It also states the intention to provide guidance for the visual assessment. It does advise that the glass manufacturer should be contacted regarding queries that are beyond the guidelines.

Section 3 provides a summary of the manufacture of hot bent glass both roller formed tempered and slumped annealed. This section also raises the overall performance of the glass needs to be considered, coatings, the base glass specification and the experience of the bending processors are paramount to the success.

It points out that for more complex geometry, the panels are likely to be annealed slumped formed. If these are then needed to form laminates for safety it is highlighted that these may have lower tolerances than plies made from tempered curved glass as the annealed slumping is formed by individual panes.

The guidelines do refer to Construction Regulations in Section 4. It generally advises on the process for meeting German requirements and reference is made to TRVL and TRAV Although these are German based, it does note that thermally curved glass is a “non-regulated building product.” This section also points out that for curved glass the TRLV requirements for permissible bending stress or the advice for dimensioning of curved units cannot be met. It also states that the TRAV impact resistance proofs in Table 2 cannot be met.

The guidance summarises the glass products that may be used for curved glass. With a lack of curved glass standards, this section specifically states that the flat glass standards are used as a base and these are supplemented with information relevant to curved glass. As a European document, the referred standards are based on The European Product Standard EN and the German DIN standards. There are also some references to certain Annexes relating to curved glass. The following are some of the key points noted:

Curved annealed glass – this refers only to EN 572-2 and gives no further information on effect of curvature on the product.

Curved thermally toughened safety glass – refers to EN 12150-1 and references back to Annex B of the standard “Curved thermally-toughened soda lime silicate safety glass is a glass to which a fixed shape has been given in the course of the production process. It does not form part of the object of the present Product Standard, since the available data are not sufficient for standardisation. Notwithstanding this fact, the information contained in the present Product Standard relative to thicknesses, edgework and fracture patterns can also be applied to curved thermally-toughened soda lime silicate safety glass.”

Curved heat-strengthened glass – refers to EN 1863 and references back to Annex B of the standard “Curved heat-strengthened soda lime glass is a glass to which a fixed shape has been given in the course of the production process. It does not form part of the object of the present Product Standard, since the available data are not sufficient for standardization. Notwithstanding this fact, the information contained in the present Product Standard relative to thicknesses, edgework and fracture patterns can also be applied to curved heat-strengthened soda lime glass.“

Curved laminated glass and laminated safety glass – refers to EN 14449 and notes that this is for flat glass only. It does not refer to EN ISO 12543: Glass in building – laminated glass and laminated safety glass.

Curved insulating glass units – refers to EN 1279 and states that this is applicable to curved units although with certain limits. It quotes EN 1279 "Units with a bend radius of > 1000 mm are in compliance with the present Product Standard without having undergone the additional tests for curved test specimens. Units with a bend radius of 1000 mm or less are in compliance with this Product Standard where the further condition is fulfilled that curved test specimens with the same or with a smaller bend radius satisfy the requirements in respect of water-vapour diffusion set by EN 1279-2. The test specimens should be curved with the bending axis parallel to their longest side."

Section 7.1 covers safety and in summary states that the curved glass should use flat glass testing where this is possible to carry over. Safety requirements required by authorities are to be applied to curved glass also.

Section 8.0 refers to visual quality. It references that the 2 Guideline to Assess the Visible Quality of Glass in Buildings" is used. This is commonly known as Hadamar 2009. It provides the measuring criteria as using diffuse daylight and viewing the glass from 3m distance from the inside and using an angle that would be used for the room. This is subjective.

It does state that the reflectance of curved glass that makes it visually different to flat glass. Also the following criteria influence: coatings, reflectance of the base glass, the curvature, tangential transitions and glass thicknesses. The visual quality section is limited to 3 paragraphs. It does recommend that sample panes are made to understand the optical and visual effects.

Similarly to BS ISO 11485-2 and ASTM C1464-06:2011 it provides guidance on dimensioning and tolerances.

It illustrates twist deviations which are limited to +/-3mm per metre (straight edge)

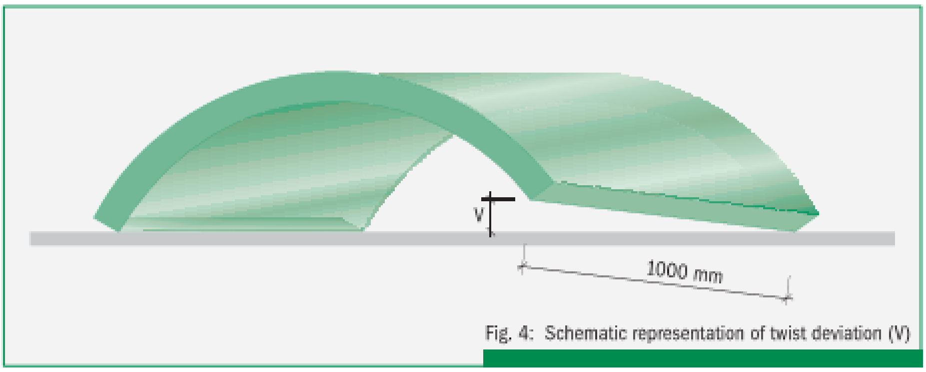


Figure B.32: Excerpt from BF 009 2011 Fig2: twist deviation

Shape accuracy is limited to not exceeding 3mm in or out offset.

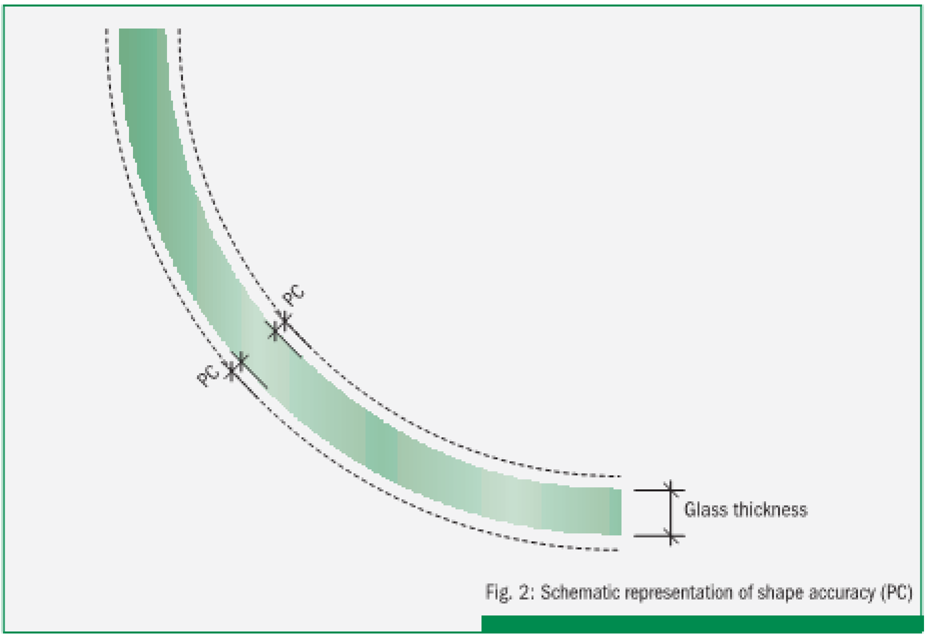


Figure B.33: Excerpt from BF 009 2011 Fig2: shape accuracy

It states that it is not possible to use the product standards to tempered glass for local bow and that this is dependent on geometry, glass thickness and size and is to be discussed with the manufacturer.

It states that climatic pressures due to bending can be greater than for flat IGUs and this can put a greater stress on the edge seal.

Page 15 – following states: *12.3 Instructions in respect of design and construction matters*

'On account of its high degree of stiffness the tolerances of curved glass (see Ch. 9) must definitely be taken into account already at the time of its design and construction ……..In

addition, storage which does not take care to avoid forcing and straining may lead to impairment of the glass's visual quality.'

It also advises that for to achieve the desired end product that precise measurements are required by the manufacturer from the designer and these are the arc, bend radius, rise (inner or outer) and the angle as well as the dimensions of the straight edge and number of panels This is illustrated:

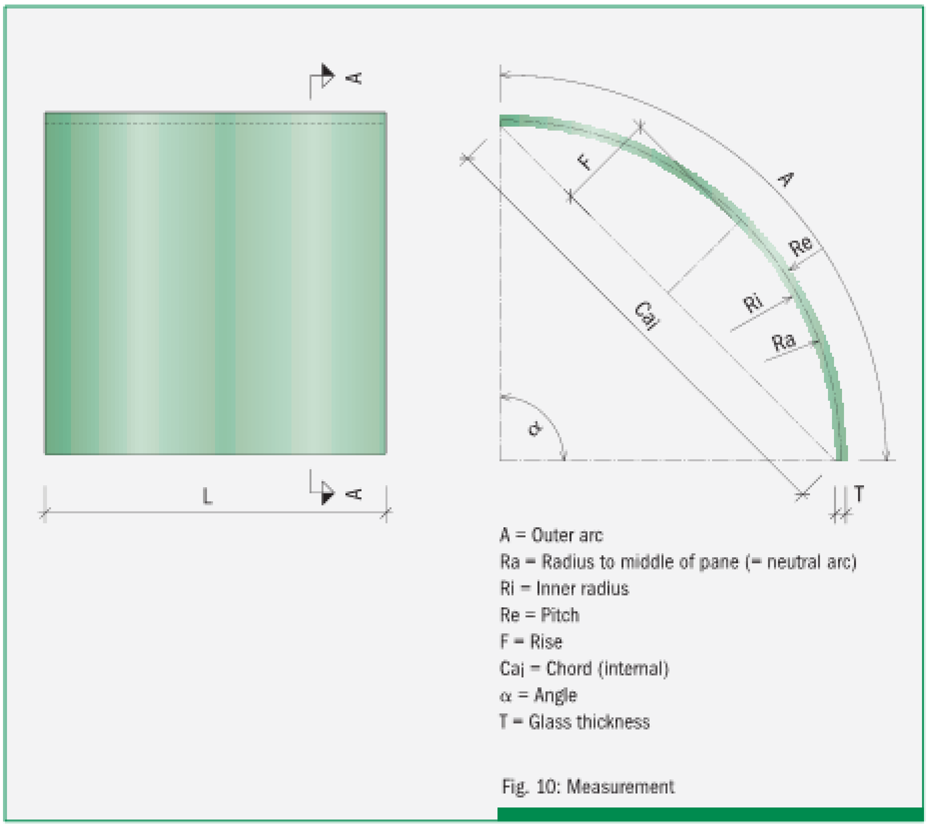


Figure B.34: Excerpt from BF 009 2011 Fig 10: measurement

Generally the guidance adds to the information in BS ISO 11485 and ASTMC 1464-06 as it covers further criteria for storage, transportation, blocking for the units which are not considered in the other standards.

Curved glass Part 1:2011 Generalities – Definitions, Terminology, Properties and Basis of Measurement and Test. GGF.

This guidance again notes the definitions used for curved glass. It has dimensioning characteristics which relate to edge straightness, side straightness, cross bend deviation (SAG) and also twist.

In section 6.1 for optical quality, it states that the curved glass will be of a lower quality than the base glass and that the reflection will highlight surface distortion. It also states that laminating the glass will exacerbate this. This is the first guidance to note that these are a visual quality issue.

It does then state that the glass should be viewed at 3 meters and the angle of observation be 90 degrees to the glass being assessed. This may not be practical depending on the curvature.

It again lists potential faults: body faults, such as bubbles and seeds; surface faults such as scratches and interlayer defects.

Although it gives the definitions for curved tempered glass, the bibliography only refers to BS 572 series Parts 1-3. BS ISO 11485 and ASTM C 1464-06 as it covers further criteria for storage, transportation, blocking for the units which are not considered in the other standards.

Curved glass Part 2:2011 Curved annealed glass. GGF.

This refers back to the Part 1 standard of this series for visual and optical quality.

Curved glass Part 3:2011 Curved thermally treated glasses. GGF.

In section 8.1 for optical quality, it states that the bending process will provide a product of a lower quality than the base glass and that the reflection will highlight surface distortion. It also states that body tinting coating or enamelling can exacerbate this. This is the first guidance to note that these are a visual quality issue.

It does then state that the glass should be viewed at 3 meters and the angle of observation be 90 degrees to the glass being assessed. This may not be practical depending on the curvature. It also suggests that the assessment of body faults use the criteria in BS 572-2 for flat glass. It does not give a base reference for surface faults.

8.4 Manufacturers Guidance

http://www.doeringglas.de/englishVersion/architekturglas_e/architekturglas_english.html

Note that the Saint Gobain curved glass refers to:

*' * Notice: Limits of size, dimensions, possible glass thickness and bending angles are determined according to individual arrangement and thorough technical examination. Restrictions in the form of shape must be expected. Tolerances according guidelines for*

thermally-curved glass in the building industry from Bundesverband Flachglas. (BF-Bulletin 009/2011)'

FROM Doering Glas Glassolutions Saint-Gobain – Technical information for cylindrical curved glass. refers to:

For Cylindrical curved float glass, Cylindrical curved insulating glass, Cylindrical curved laminated glass and Cylindrical curved toughened glass/heat-strengthened glass

*'*Notice: The values listed under Technical Data are only for guidance The geometrical parameters of a curved glass pane, the min./max values of the parameters as well as the requested glass assembly are closely linked and influence the corresponding limiting values of each other. Limits of size, dimensions, possible glass thickness and bending angles are determined according to individual arrangement and thorough technical examination. Restrictions in the form of shape must be expected.'*

'For all curved glass products manufactured in our company, the general tolerance and conditions in accordance to "Guideline for thermal bend architectural glass products ", BF-datasheet 009/2011 from Bundesverband Flachglas e.V. and the "Guideline to Assess the Visible Quality of Glass in Buildings." are valid (unless otherwise agreed in writing).'

8.5 Visual Assessment Guidance

HADAMAR 2009 Guideline to Assess the Visible Quality of Glass in Buildings.

This standard is more widely used within specification in UK and Europe now. Makes no reference to curved glass. For the assessment, it advises viewing at 1 metre from the glass from the inside and that there should be diffuse daylight conditions without direct sunlight or an artificial sky.

It provides a table of allowable discrepancies and illustration for the zoning the glass for assessment. This is as 1 section in the guidance as shown below:

3. Allowable Discrepancies for the Visible Quality of Architectural Glass Products

Table prepared for coated or uncoated float glass, toughened safety glass, heat-strengthened glass, laminated sheet and laminated safety glass, plus their combinations as two-layer insulating glass

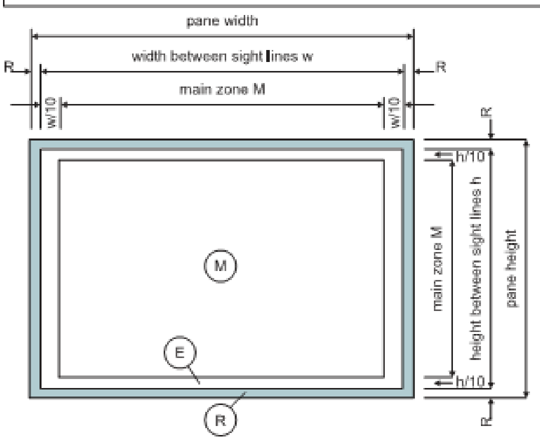
Zone	The following are allowable per unit:	
R	External shallow damage to the edge or conchoidal fractures which do not affect the glass strength and which do not project beyond the width of the edge seal.	
	Internal conchoidal fractures without loose shards, which are filled by the sealant.	
	Unlimited spots or patches of residue or scratches.	
E	**Inclusions, bubbles, spots, stains, etc.:** Pane area ≤ 1 m²: Pane area > 1 m²:	 max. 4 cases, each < 3 mm ∅ max. 1 cases, each < 3 mm ∅ per meter of perimeter
	Residues (spots) in the gas-filled cavity: Pane area ≤ 1 m²: Pane area > 1 m²:	 max. 4 cases, each < 3 mm ∅ max. 1 cases, each < 3 mm ∅ per meter of perimeter
	Residues (patches) in the gas-filled cavity:	max. 1 case ≤ 3 cm²
	Scratches: total of individual lengths:	max. 90 mm - Individual length: max. 30 mm
	Hair-line scratches: not allowed in higher concentration	
M	**Inclusions, bubbles, spots, stains, etc.:** Pane area ≤ 1 m²: 1 m² < Pane area ≤ 2 m²: Pane area > 2 m²:	 max. 2 cases, each < 2 mm ∅ max. 3 cases, each < 2 mm ∅ max. 5 cases, each < 2 mm ∅
	Scratches: Total of individual lengths:	max. 45 mm - Individual length: max. 15 mm
	Hair-line scratches: not allowed in higher concentration	
E+M	Maximum number of allowable discrepancies as in zone E. Inclusions, bubbles, spots, stains etc. of dimensions 0.5 - 1.0 mm are allowable without any area-related limitation, except when they appear in higher concentration. "Higher concentration" means that at least 4 inclusions, bubbles, spots, stains etc. are located within a circle with a diameter of ≤ 20 cm.	

Comments:
Discrepancies of dimensions ≤ 0.5 mm will not be taken into account. The optically distorted fields they cause may not be more than 3 mm in diameter.

Allowable discrepancies for three-layer thermal insulating glass, laminated sheet and laminated safety glass:
The allowable frequency of discrepancies in the zones E and M is increased by 25% per additional glass unit and per laminated glass pane over the above values. The result is always rounded up.

Toughened safety glass, heat-strengthened glass, laminated sheet and laminated safety glass of toughened safety glass and/or heat-strengthened glass:

1. The local roller waves on the glass surface (except for toughened safety glass and heat-strengthened glass of ornamental glass) may not exceed 0.3 mm relative to a length of 300 mm.
2. The warp relative to the total glass edge length (except for toughened safety glass and heat-strengthened glass of ornamental glass) may not be greater than 3 mm per 1000 mm glass edge length. Greater warps may occur for square or near square formats (up to 1 : 1.5) and for single panes with a nominal thickness < 6 mm.



R = rebate zone
the visually concealed area in the installed state (no limits on discrepancies, with the exception of mechanical damage to the edges)

E = edge zone
Area around edge with width w/10 or h/10 respectively – see diagram (less stringent assessment)

M = main zone
(most stringent assessment)

Figure B.35: Excerpt from Guideline to Assess the Visible Quality of Glass in Buildings 2009-06

Section 4 does note that there are differences in glass colour due to the raw materials and that the glass thicknesses will make this more evident. Also coatings will alter the colour.

Section 4.2 also mentions interference effects which “occur at random and cannot be influenced.” Also that certain effects can be caused due to an IGU such as pillowing of the panel and multiple reflections. Anisotropy is described. Also condensation and the effects of wetting the glass surface which will vary due to effects on the glass surface such as rollers, residues etc..

CWCT Technical Note No 35 Assessing the appearance of glass.

The guidance in this document does state on page 2 that “most of the procedures for visual inspection include subjective assessment criteria.” And “Where assessment is based on subjective assessments agreement between the relevant parties should be obtained at an early stage.”

This document is useful as it summarises the other standards that may be referred. It includes summary of GGF guidelines and Hadamar 10/96.

It advises that viewing distance to be 3m if there is any doubt for the distance.

9 APPENDIX C – NOTES OF MEETINGS AND FACTORY VISITS

The following notes are a summary of the meetings and factory visits carried out during research for this study.

MEETING

Held with Gerd Hoenicke, Director Pre-Construction Services of Schüco International. The meeting was held at Meinhardt offices, 10 Aldersgate Street, London, EC1A 4HJ on 22nd May 2015.

Cold bent methods

- Cold bent forced method is best visually.
- Can be cold bent forced on site or at the workshop.
  - Unitised systems can be bent at the workshop or on site.
  - Stick systems are bent on site.
- Over bending will cause distortion
- 1 point bending is best suited to cold bent forced.
- 2 point bending is best suited to laminated bending in an autoclave. However, visual quality issue due to lamination process.

Design and specification

- Parametric design is used to minimise hot bent panels.
- Roller wave can be managed to be less than 0.15mm. A reasonable value is 0.1mm.
- Consider maximum stress in the butyl tape for cold bent IGU. If overstressed, then warranty is an issue.
- The aspect ratio is paramount for optimum bending. Ratio of 1:2 is a reasonable, and 1:3 is better.
- New production methods such as the airbed method by Lisec could improve visual quality, however is far slower for production compared to hot bent radial methods.

MEETING

Held with Nelli Diller – Managing Director of Seele Gmbh (specialist façade contractor) and formerly Managing Director of Sedak (glass processing division of Seele). The meeting was held at Meinhardt offices, 10 Aldersgate Street, London, EC1A 4hJ on 1st July 2015.

Discussion on whether there is adequate guidance?

Industry is ahead of guidance. In-house quality procedures are followed. These are kept in-house and not shared written guidance.

Curved glass and architectural trends

Architects have more freedom with computer programmes

Last 5 years there is an increase in the amount of curved glass orders. More architects are considering freeform.

The quality of glass bending is improving as analysis of the bending is better.

Review of cold bent methods

10mm thick glass can be laminated bent to a radius of 15 metres.

Support method will assist. Caps will give extra hold on site. Example is Strasbourg Station, which is single glazed laminated cold bent with pvb interlayer and caps for support.

EVA is more suitable for hot climates.

Review of hot bent methods

- Hot bent radial
    - For a true radius and tempering required, then the method using the roller machine can be used.
    - The glass is heated and then rolled when it is cooling.
    - This method has the worst visual distortions. Worst visual quality, roller wave, edge dip, roller pick up, tolerance from the bending furnace,
    - monolithic and 2 layer laminated is ok, 3 layer lamination is difficult.
    - Glass can be heat soak tested.
    - Glass up to 10mm thick can be heat strengthened.

- Slump formed
    - If a panel has a part that is curved and a part flat, then this is bent using slump formed in a mould and is therefore annealed.
    - Disadvantage is that it is annealed, so needs to be chemically toughened or laminated – still accommodates less load that tempered glass though. Covent Garden curved stair is chemically toughened and laminated so it is a safety glass.
    - General quality is good.
    - 500mm radius can be achieved with 10mm glass.
    - Edges will have small marks.

- Not much breakage with this method.
- If laminating, then need to heat together with a deviation layer. Heat up for 8 hours and then cool for 8 hours. The glass layers can then be laminated together. The heating for the lamination is not hot enough to relax the glass.
- This has a lengthy programme especially if there are many unique moulds.

Review of coatings

Most low e coatings are not bendable.
Some coatings can deal with slump formed hot bending.

Review of tolerances

Tolerances should be considered for edge dip, twisting and radius.
0.08 can be achieved for roller wave
Tolerances must be measured with the glass in the final position. Hadamar does not state final position for inspection.
Tong marks are out of date. There is limited vertical toughening used.

Review of costs – 1 most costly 3 least costly

1. Most costly – Slump formed hot bent (cost of the mould and time taken for bending)
2. Next most costly – Cold bent laminated bent due to time taken and the moulding
3. Hot bent radial is not much more than tempered flat glass as the bending takes place as it is quenched, so is only a few seconds.

Cost of force bent cold will depend on the support etc.

MEETING AND FACTORY VISIT

Summary of notes of meeting and factory visit with Ferran Figuerola and Joan Tarrus of Cricursa (specialist glass processor dedicated to curved hot bent glass production) at Polígon Industrial Coll de la Manya, Calle Camí de Can Ferran, s/n, 08403 Granollers, Barcelona, Barcelona, Spain on 27th July 2015.

Items clarified:

Review of hot bent radial glass

- Maximum thickness for radial bending of glass on tempering machine is 8-10mm. If thinner suffers excessive roller wave and if much thicker, the glass does not cool uniformly.
- Above 12mm, the cost goes up
- Main distortion in radial is roller wave. There is no approved or practical way to measure roller wave in radial bent glass.

- Small cracks can appear at the end of the glass as it is heated prior to tempering if the glass is very big – over 6m length due to the inconsistency in heat along the length of the glass. These faults occur prior to tempering and can normally be covered by the cap.
- Hot bent slumped glass is laminated after bending. During bending a layer is put between the glass panes to simulate the interlayer.
- Radial hot bent glass has a 100mm flat zone at its edge

Review of hot bent slump formed glass

- Slumped glass up to 10m
- Main distortion in slumped glass is the mould marks.
- Slump formed stretches the glass and may cause the edges to 'pull in'.
- Timescales for forming slump formed glass are dependent on glass thickness.
- It is not feasible to produce annealed glass on the radial tempering machine as the glass would have to remain in position too long to anneal.

Coatings

- Coatings cannot be applied after curving.
- Coatings are a big issue for quality of consistency

Visual issues

- Key item affecting distortion is the reflectivity of the glass and this is governed by tolerances.
- Visual defects such as spots, scratches etc. are negligible.
- Quench marks are an issue for tempered radial glass
- The roller waves are vertical with the curvature for smaller glass pieces and the quenching marks are in the same direction. Above a certain size these become horizontal due to the machinery. The specifier should be aware and this is then perpendicular to the quenching marks.
- Tolerances between panels are very important
- Fritting can be applied before or after bending.
- Advise to keep the frit off the mould side
- Lower reflection may give the appearance of less distortion
- Distinct difference in appearance of reflectivity with frit on face 1 or face 2. Face 1 has less reflectivity.

MEETING AND FACTORY VISIT

Summary of notes of meeting and factory visit with Francesc Arbos, President of Bellapart Group (specialist façade contractor with experience of hot and cold bent glass projects) at Edifici Free Minds, Ctra. de la Parcel·lària, 32, 17178 Les Preses, Province of Girona, Spain on 28th July 2015.

Project notes

- The Bombay Sapphire project with Heatherwick architects was hot bent radial glass that was then cold bent.

Achieving good quality bent projects

- Mock ups are essential and testing
- Edge treatment is critical to recover the original strength of the glass.
- Geometry can give high quality if it can be proved mathematically
- Mathematics is the language to meet the appropriate translation
- Mathematical equation can lead to better quality
- Everyone has software now to analyse curvature, so quality should improve.
- Consistent reflection is the key
- “Mathematics leads design”

Bending practicalities

- Cost is dependent on number of elements and repetition.
- SGP as an interlayer can be heated to 130 degrees. In an autoclave it becomes liquid.
- PVB better for cold bending, but may require SGP for other reasons.
- If using SGP, then warm the panels to 60degrees C before cold bending.
- Better to cold bend in the summer
- Control the temperature of the glass before bending