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Usage of Cold Bent Glass Panes as an Approximation for Doublecurved Surfaces

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Abstract

In The Netherlands usage of cold bent tempered architectural glass increases. In the late 1980's cold bent tempered glass was offered on the market as a cheap alternative to annealed and bent tempered glass. The there commonly applied 4m radius of the cold bent glass implied a breakage risk which soon led to abandon its use. As experience grows, recently cold bent tempered glass has again become a commercial product in The Netherlands. It again is marketed by a main Dutch manufacturer as a standard panel filling for rooflights. For a 150m high twisted tower (a 'twister') designed by the author and the Dutch architect Pi de Bruijn, façade builder Van Dool Constructions tendered a cold bent twisted façade of Alcoa Architectural Systems. A 2.4 x 4.8 m mock-up of a twisted segment was built to study material behaviour and assemblage aspects. The building project was won by another developer, due to the long process of preliminary studies by the parties that tendered to the building developer, but the price of the curving façade, based on flat panels and straight profiles was only marginally higher than a standard curtain wall façade. In 2002 a similar usage has been realised in the new town hall of Alphen aan de Rijn (NL). There for doublecurved glass 'ribbons' crossing the roof of this building designed by EEA architects (NL), Octatube Space Structures (NL) developed a system of cold bent glass panes fitted into U-profiles at top and bottom sides. It offered a feasible solution, were embellished solutions proofed too expensive.

The article focuses on geometric details of a 150 m high twisted tower, the built façade prototype and its general application, as well as material behaviour of the glass.

Keywords: glass, cold bent, doublecurved

1. Introduction

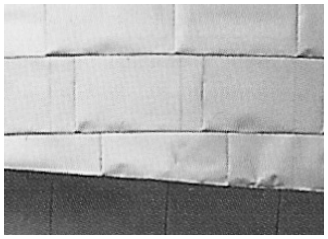
In the late 1980's cold bent tempered glass was offered on the Dutch market as a cheap alternative to annealed and bent tempered glass. Because of the risk of breakage, usage in The Netherlands was soon restricted to spaces extensively used by people, like greenhouses. The greater spans of the panes following the use of tempered instead of annealed glass, enabled roof lights to be constructed with fewer and lighter framing profiles, which implies less sunlight hindrance and therefore more growth of the plants. Also rooflights in arcades sometimes were executed in cold bent glass, as an alternative for tempered bent glass or acrylate. The risk of people getting hurt by glass breakage is small. However, usage was stopped by increasing safety regulations, and liability for consumer goods, i.c. coming from the occurrence of glass fragments in flowerpots or grocery products. Recently cold bent tempered glass made an interesting come-back, being applied commercially as insulated façade and roof panes for apartment and office buildings. The reason is that new façade geometries using cold bent glass became economically feasible as each pane can have a different contour and unique curvature, for the relative low costs of flat produced panes. Within certain limits the panes can be applied to approximate double-curved surfaces that until recently were not available on the market or too expensive for use in building industry.

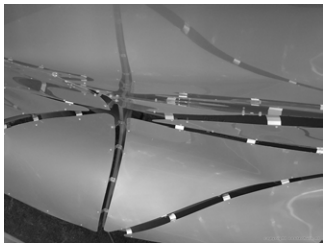
2. Geometrical characteristics of cold bending

Increasingly cold bent panels are used for doublecurved façades. The twisted surfaces of the Guggenheim Museum in Bilbao by architect Frank Gehry were made in glass and in titanium. The glass façades were embellished with flat triangular panes. The titanium cladding was bent manually to connect to the overall twisted geometry. Within their contours the 0.3 mm thick panels bulge and fold irregularly and even lightly flutter in strong winds.

The Web of Noord-Holland pavilion designed by Oosterhuis.nl architects is clad with triangular Hi-lite panels. These sandwich panels of 0.5 mm aluminum sheets separated by a polypropylene core are fitted with flexible clamps to a doublecurved steel superstructure. The geometrical transformations of the relatively stiff panels are similar to those of cold bent glass panes. The panels are

used in many sizes and varying curvatures. Basically the middle areas of the panels flatten or are singlecurved. The unfoldable panels deviate from the desired doublecurved shape. Wide seams hide that panels meet under varying angles instead of making in line connections. The panels also vary in distance to the superstructure. An inner tent makes for the necessary climatised space.





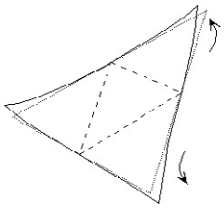


Fig. 1a. cold bent titanium panels (Guggenheim Museum, Bilbao, Spain, 1997)
1b. panels fitted with flexible clamps and open seams (photograph by Oosterhuis.nl)
1c. a triangular panel can be forced into a curving shape

Cold bent panels transform to a complex combination of unfoldable surfaces that consist irregular single curved surfaces; many of these are conical. Glass tends to have evenly distributed bending forces and curvatures in its surface. A flexible cloth will hang with folds of small radii around a tabletop. But glass positioned on a flat surface will due to its stiffness have a more even overall curvature and a more even distribution of bending forces. When a cold bent pane is only supported along its sides, often a central (by approximation) flat surface appears with wings curving to the corners. The surface is a complex combination of various unfoldable surfaces. Transforming varies according to stiffness, panel dimensions and desired curvatures along its contours. A hyperbolical twisted pane with straight profiles around its edges tends to take on a shape with one straight diagonal and one unidirectional curved diagonal. The choise over which diagonal the pane curves mainly depends on pane dimensions, framing curvatures and direction of gravitational forces. A major advantage of cold bending panes of irregular contours and curvature is that they are produced flat, whereas such panes would be hard, if not as yet practically impossible, to position in a tempering furnace.

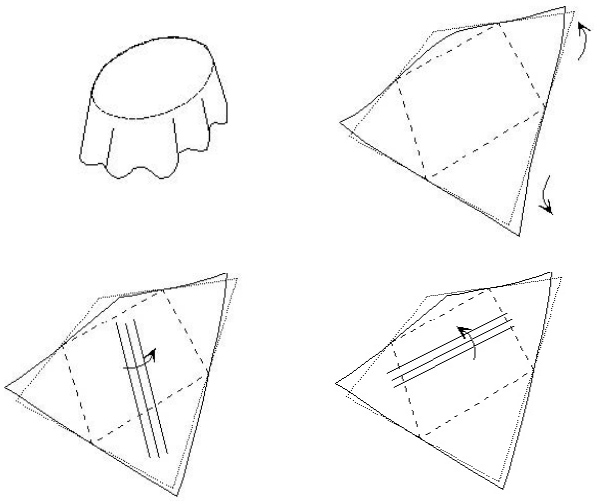


Fig. 2a. cloth draped over a table
2b. four cornered panel with flat central part
2cd. curved panels with alternative directions of curvature

3. Architectural uses of cold bent glass

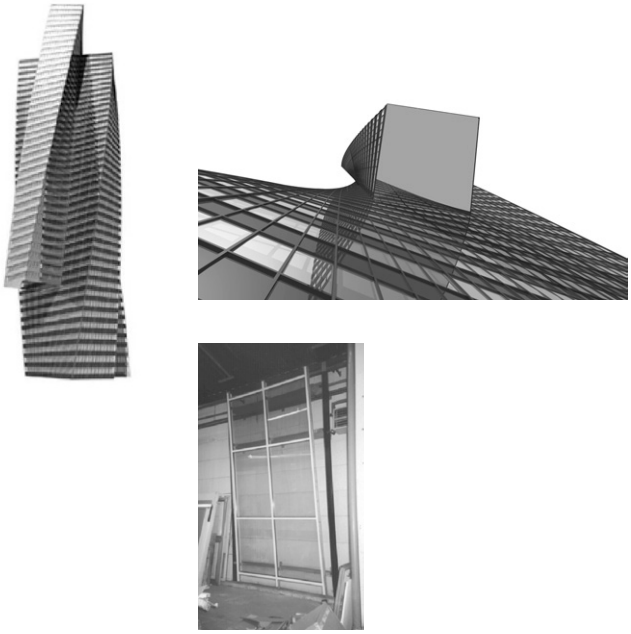
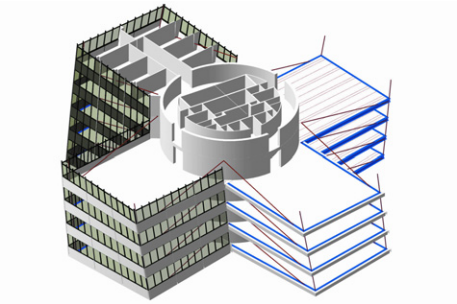


Fig. 3a. Perspective of 150m high twisted tower
3b. Upward view, showing reflections on its twisted façades
3c. Photograph of prototype of cold bent window frame measuring 5.0 x 2.4 m



3d. Isometric drawing of cylindrical core

In the early 1990's Dutch manufacturer Bik Bouwprodukten introduced cold bent glass panes in framed rooflights as an alternative to sheets of acrylate and polycarbonate or bent glass. They in 1995 also marketed insulated glass on site cold bent into the frames. Building regulations now impose laminated glass in façades inclined less than 80'. To meet the growing architectural demand for inclined facades, Tetterode Glasatelier (NL), Eijkelkamp (NL) and the author in 1997 developed laminated cold bent glass, which can be made into insulated panes if required. For a 150m high twisted tower designed in 1998 by the author and the Dutch architect Pi de Bruijn, façade builder Van Dool Constructions tendered a cold bent twisted façade of Alcoa Architectural Systems. [VOL 01] It twisted so little that by cold bending of flat panes and straight profiles the maximum distance to the theoretic twisted shape was smaller than 6 mm, and for the greater part much less than by making tempered twisted glass. The inclination varied less than 10' of the vertical. A 2.4 x 5.0 m mock-up of a twisted segment was built to study assemblage aspects. Optometric studies confirmed manual calculations and that bending forces evenly spread over the surfaces. The price hardly exceeded that of a standard flat facade. Never before had a firm guaranteed such a large amount of cold bent insulated glass. The guarantee implied that use of different panels in state of the art architectural designs with facades of irregular geometry can be tendered.

The structural design with a concrete cylindrical core around which steel floors were hung, rotating 1,3° further on each level, was made by ABT Engineers (NL).

In 1992 a 200m high twister for Rotterdam (NL) was designed by Stefan de Bever (NL). The never built tower was to have an embellished façade with flat glass panes.

The twister Turning Torso in Malmö (Sweden) designed by S. Calatrava will be finished in 2005. The very slightly twisted façade could be build with cold bent façade elements. The 186m high apartment tower has a cylindrical concrete core for stability.

Fig. 5ab. Perspectives of 200m high tower in Rotterdam (NL)

5c. Perspective drawing of Turning Torso tower (completed 2005)

5d. Assemblage of façade

Fig. 4. Ribbon shaped glass zones cross the roof of the new town hall of Alphen aan de Rijn (NL)

The project was commissioned to another building developer, but the prototype inspired a similar usage in the new town hall of Alphen aan de Rijn (NL) in 2002, designed by EEA architects. For doublecurved glass 'ribbons' crossing the façade and roof, Octatube Space Structures in Delft (NL) developed a system of cold bent insulated panes 6-15-6 fitted into profiles at top and bottom ends and connected by clamps to neighbouring panes halfway their sides. It offered a feasible approximation of the desired surface, were an embellished solution with wooden frames and flat panes had proofed too expensive

[OCT]. Inclined panels on the inner side are laminated of 2x5 mm panes, of which 7 N is claimed by torsional forces and the remaining 43 N suffice for wind and snow loads. Cold bent glass panes are a cheap alternative to unidirectional bent glass when small series of different contours and curvatures are required. Within small limits cold bent glass can approximate double curved surfaces.

4. Conclusion

1 Cold bending offers an alternative where bent glass is either too expensive and/or not feasible.

2 If calculated, dimensioned and produced correctly, cold bent glass panes with cold bent aluminum framing enables economically materialising architecture with free geometry.

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Fig. 12. Reduction in Wind Forces (gust factor with respect to 1% damping ratio) as a Function of Damping Ratio

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