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Behaviour of cold bent glass plates during the shaping process

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Abstract

Cold bending is an effective and relatively inexpensive way of creating double curved glass surfaces that are required in modern architectural applications. This paper focuses on the shaping of the plate with the application of a vertical out-of-plane load at one of its corners. It has been reported that a phenomenon of buckling instability may occur during cold bending. To analyse this instability, finite element analysis validated by experimental testing was undertaken taking into consideration different support conditions and geometrical characteristics of the glass plate. It is shown that by preventing in-plane translation at two opposite corners of the plate, a change in the deformation mode is observed as the plate deforms. One diagonal becomes stiffer preventing significant change in its shape and consequently the vertical deflection is confined to the other diagonal. The change in the deformation mode appears in the form of a ripple. This ripple that can be referred to as "cold bending distortion", can exceed the allowable limits of roller wave distortion, resulting in the degradation of the optical quality of the cold bent panel. The results presented in this paper can be useful for setting the geometrical limits for the shaping process in order to prevent unwanted optical distortions of the cold bent panel.

Keywords: cold bending, monolithic glass, boundary conditions

1 Introduction

The use of curved glass in building applications facilitates the creation of unique, free form facades characterised by a combination of aesthetic appeal, transparency and use of natural day light in buildings. Cold bending is an energy efficient method of creating curved glass panels based on the elastic deformation of glass at ambient conditions with the application of out of plane loads to create the desired shape.

However, an instability has been reported during the cold bending process by Eekhout and

Staaks [1]. According to their findings, the cold bending process is described by two deformation modes when forcing one corner of the plate out of plane in order to create a hyper surface. In the first mode the diagonals are characterised by a curved shape and the edges preserve their initial straight shape. However, when the out of plane displacement is larger than 16 times the plate thickness, a change in the deformation mode is observed. At this point the plate buckles causing an instability where one diagonal straightens and the edges suddenly become curved.

The same behaviour has also been reported by Galuppi et al. [2] who described this phenomenon as snap through buckling. The same authors [3] proposed an analytical model based on Mansfield's inextensional theory to account for the bending across the diagonal whose curvature increases and also taking into consideration the membrane strains that are created in the direction of the second diagonal as the cross sectional inertia is based on the curved shape.

In this paper, the influence of the boundary conditions at the corners of plate on the buckling behaviour of the plate during the cold bending process will be developed by means of experimental investigations and numerical models. Besides differences in boundary conditions, the influence of the geometrical characteristics of the glass plate will also be investigated.

2 Investigation of instabilities during the cold bending process

2.1 Experimental approach

The stability of cold bent glass plates was studied in monolithic plates. The tests were initially conducted on an aluminium plate and subsequently on a fully toughened glass plate by applying an out of plane load at the free corner of the plate while the other three were restrained (Figure 1). The speed of loading was not considered, as it is not expected to affect the results in monolithic glass, but will most likely be a significant factor in laminated glass. The dimensions of both plates were 1 by 1 m with a thickness of 5 mm. The influence of the boundary conditions at the corners of the plate on its buckling behaviour was investigated. The experiment stopped short of failure of the specimen.

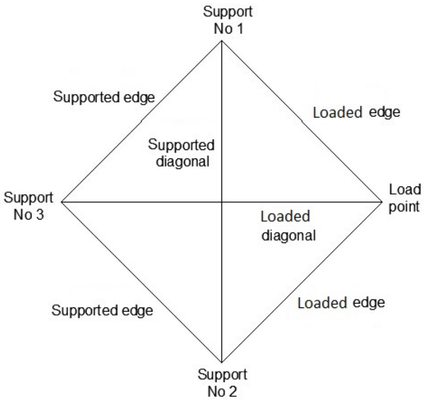


Figure 1: Schematic representation (top view) of test

The boundary conditions in this study involved different combinations of rotational and translational restraints. The variations in boundary conditions were limited to support No. 1 and 2 along the supported diagonal while support No. 3 prevented translation and rotation. No rotational or translational restraints were applied on the load point.

2.1.1 Case A: Clamped supports, rotationally and translationally restrained

The specimen (Figure 2a) was clamped between two steel plates; the lower steel plate was welded on a larger steel plate which was bolted to a pedestal; the upper steel plate was prevented from sliding using a beam across its surface. Torque of 80 Nm was applied on the two bars passing through the beam in order to compensate for the horizontal force created during the test by means of friction.

2.1.2 Case B: Clamped supports, translationally restrained

Figure 2b shows the layout used for supports No 1 and 2 in order to prevent sliding but simultaneously allow rotation at the restrained corners of the plate. The specimen was clamped between two steel plates with the application of 20 Nm of torque on two M8 bolts. In order to allow free rotation an articulated joint was used.

2.1.3 Case C: Semi rigid (partial rotation) joints, translationally restrained

In this case sliding was prevented while rotations were partially restrained (Figure 2c). The specimen was resting on a spherical support in order to allow rotation which was partially restrained by a thread. Sliding was restrained by means of friction through the thread, achieved with the application of 80 Nm of torque on the thread.

(a) (b)

(c) (d)

Figure 2: (a) Clamped supports translationally and rotationally restrained, (b) Clamped supports translationally restrained, (c) Semi rigid joints translationally restrained and (d) Rotationally free roller supports

2.1.4 Case D: Rotationally free roller supports

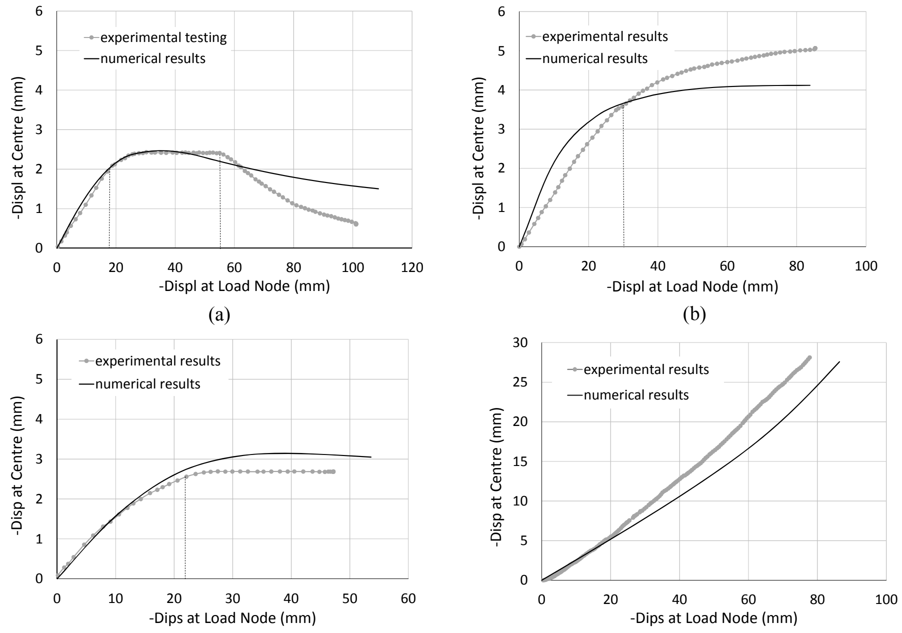
In this case sliding and rotation was allowed in two and three directions respectively. The specimen was resting on a spherical support attached to a sliding bearing (Figure 2d).

2.2 Numerical Modelling

Finite element analysis, validated by the experimental results was performed with Abaqus/CAE 6.12-2 software. In particular the Riks analysis method [4] was used to account for geometrical nonlinearities evaluating the progress of the solution through the arc length across the static equilibrium path in load – displacement space. Initially, two identical models were constructed, one with solid (C3D20R) elements and the other with shell elements (S4R). The simulations showed that the differences between the two models were negligible, therefore in order to reduce the computational time shell models were used thereafter. Convergence tests were also employed to define the appropriate density of the mesh.

2.3 Results

Figure 3 shows that as the load is applied on the free corner, a change in the deformation mode is observed except for the case with the free roller supports (Figure 3d).



(a) (b)

(c) (d)

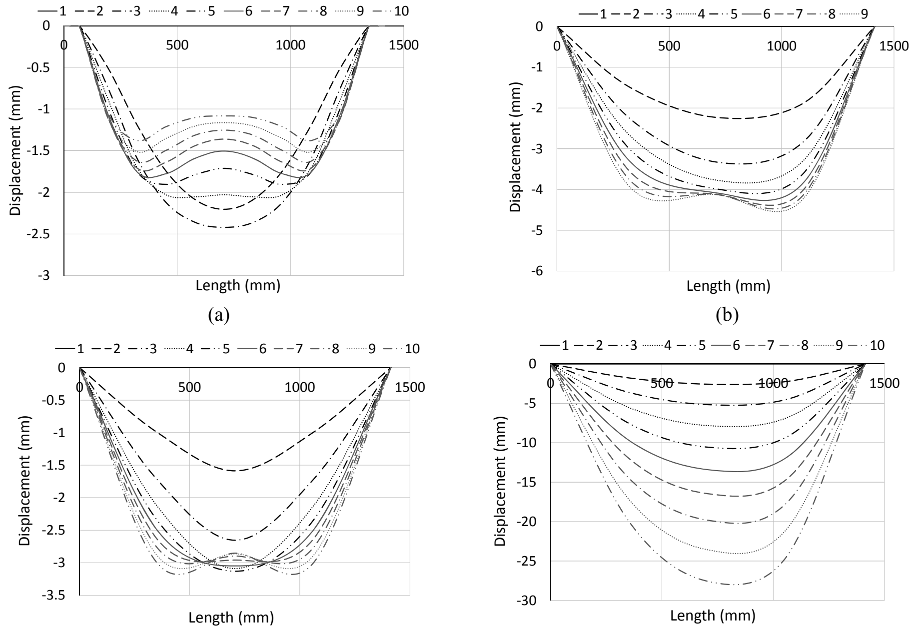
Figure 3: Displacement of the centre of the plate in relation with the applied displacement on the corner
(a) Clamped supports translationally and rotationally restrained, (b) Clamped supports translationally restrained, (c) Semi rigid joints translationally restrained and (d) Rotationally free roller supports.

In the case of the clamped supports that are translationally and rotationally restrained (Figure 3a) the change occurs when the applied vertical displacement on the free corner exceeds 19 mm. After this value of displacement the centre of the plate stays relatively stationary until the displacement of the load node reaches 55 mm. At this stage the centre displacement starts moving in the opposite direction.

Likewise, the change in the deformation mode for the clamped translationally restrained supports and the semi rigid supports occurs at a load node displacement of 30 and 21 mm respectively (Figure 3b and 3c). In the former case, this change occurs as a deceleration of the rate with which the centre of the plate moves towards negative values of displacement while in the latter, the centre of the plate stays stationary after this point.

The rotationally free roller supports provide the largest vertical centre displacement (Figure 3d). The magnitude of this displacement increases constantly with increasing applied displacement (no change of the deformation mode). Contrary, the clamped supports, translationally and rotationally restrained provide the smallest vertical centre displacement.

The above mentioned change in the deformation mode for the three first cases of the boundary conditions can also be seen in Figure 4. This shows the deformed shape of the supported diagonal at consecutive displacement steps during the bending process.



(a) (b) (c) (d)

Figure 4: Curvature of the supported diagonal in consecutive steps obtained from the numerical model. (a) Clamped supports translationally and rotationally restrained, (b) Clamped supports translationally restrained, (c) Semi rigid joints translationally restrained and (d) Rotationally free roller supports.

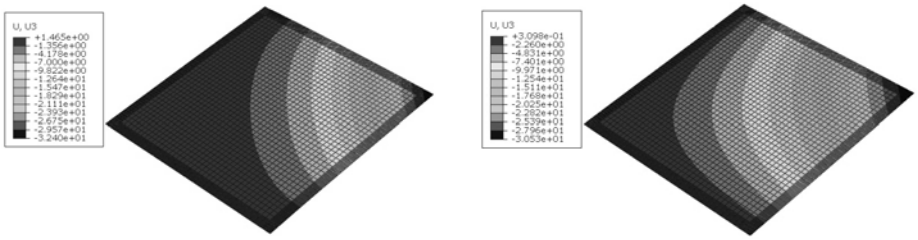
Figure 4a shows that for the case of the clamped supports translationally and rotationally restrained the supported diagonal becomes stiffer after the fourth step ($\delta_{applied} \approx 32$mm), creating a change from a positive to a negative curvature (ripples) along its length. In particular, sagging is observed near the edges of the diagonal and hogging at the centre.

The same behaviour is also apparent in the case of the clamped supports that are only translationally restrained (Figure 4b). The difference in this case is that the centre of the plate does not show a reversal of displacement (i.e. does not lift) but the rate of displacement becomes noticeably smaller thereby, while creating a ripple effect similar to case A.

The semi rigid supports (Figure 4c) show an in between behaviour as the centre of the plate shows a reversal of displacement but the quarter parts of the supported diagonal continue their downward movement.

Figure 4d shows that for the case of the free roller supports no change of deformation mode occurs and that the sign of curvature for the supported diagonal remains unaltered during the cold bending process.

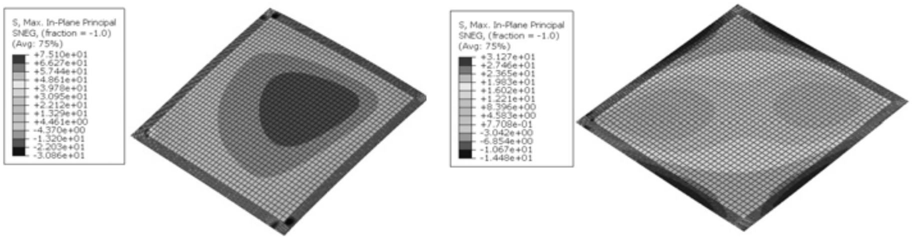
In the cases where the ripple effect is apparent, increasing the applied displacement on the free corner of the plate results in gradual stiffening of the left part of the plate (Figure 5a). However, this is not observed in the case of the free roller supports (Figure 5b). When the increase in stiffness coincides with the point when the change in the deformation mode occurs (Figure 3), significant vertical displacement is only confined at the right part of the plate.



(a) (b)

Figure 5: Vertical displacement of the plate at the instant of the deformation mode change ($\delta_{applied} \approx 32$mm, step 4) for: (a) Clamped supports translationally and rotationally restrained, (b) Rotationally free roller supports.

After this point, as the applied displacement is increased, in-plane compressive stresses (membrane stresses) appear in the central part of the supported diagonal (Figure 6a) resulting in the occurrence of the ripple that can be attributed to buckling. This does not apply for the case of the roller free supports (Figure 6b).



(a) (b)

Figure 6: Maximum in plane principal stresses of the deformed plate when the ripple has occurred ($\delta_{applied} \approx 90$mm, step 9) for: (a) Clamped supports translationally and rotationally restrained, (b) Rotationally free roller supports.

The amplitude of the ripple can affect the optical quality of the panel as it can cause unwanted visual distortions similar to roller wave distortions in heat treated (heat strengthened and fully toughened) glass. In a similar way, this ripple can be referred to as "cold bending distortion". The maximum ripple amplitude appears in the case of the plate with the clamped supports (case A). For these boundary conditions the value of the ripple amplitude was calculated for plates of various thickness between 2 and 7 mm (Table 1).

According to EN12150-1:2000 [5] the allowable limit for roller wave distortion on thermally toughened glass is 0.5 mm over a length of 300 mm. Table 1 shows that as the thickness of the plate increases the maximum depth of the ripple also increases with values reaching close to the allowable limit. For the 1 by 1 m plate with clamped corners (case A) this distortion limit will be exceeded when the thickness of the glass is 8 mm or larger. This raises concerns on the optical quality of this cold bent glass. However, the amplitude of the ripple does not always increase with increasing applied displacement. After a certain value of applied displacement that varies for plates of different thickness (Table 1) the amplitude of the "cold bending distortion" decreases with increasing applied displacement.

Thickness [mm]	Max ripple amplitude [mm]	Applied displacement [mm]
2	0.11	59
3	0.18	92
4	0.26	125
5	0.33	146
6	0.39	178
7	0.46	200

Table 1: Maximum ripple amplitude for plates of different thickness with clamped supports translationally and rotationally restrained.

3 Conclusions

When cold bending a square glass plate by the application of an out of plane load on one corner while the other three are restrained an anticlastic shape (one diagonal of the plate is convex and the other concave) is created.

The boundary conditions at the restrained corners of the plate during the cold bending process have a significant effect on its buckling behaviour. When in-plane plate displacement is allowed at two opposite corners (translationally free), no instability is observed. However, when in-plane displacement at two opposite corners is prevented (translationally restrained) a change in the deformation mode occurs in the central regions of the plate. In this case the supported diagonal becomes stiffer than the diagonal perpendicular to it, resulting in significantly smaller vertical displacements compared to the other diagonal.

Changes in the deformation mode are also noticed when different rotational restraints are applied. When rotation of the corners is fully restrained a change in the deformation mode is observed at lower displacement values during the process (19 mm of applied displacement) compared to the case when rotation is allowed (30 mm of applied displacement).

The change in the deformation mode appears in the form of a ripple (cold bending distortion) along the supported diagonal. It has been shown that the thickness of the plate has a significant effect on the amplitude of the ripple. Thicker plates exhibit a larger amplitude that can exceed the maximum acceptable limit of the roller wave distortion. This could compromise the optical quality of the curved panel.

4 Acknowledgements

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