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Experimental and Numerical Investigation of the Bending Strength of Glass

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Annealed glass has a high compression resistance but it is fragile and its tensile strength is low due to the random distribution of surface flaws and impurities, which induce cracks without prior warning and each crack is regarded as a failure. This phenomenon is dependent on surface micro-defects in the glass due to inclusions within the glass or to scratches caused by normal use and by the shaping process. Classical four point bending tests are not suitable for glass plates, because of the test's configuration, the maximum stress is reached on the plate edges where, due to the cutting process, the defects are more likely than on the internal part of the plate. A satisfactory way of overcoming this uncertainty is the use of coaxial double ring tests in which the maximum stress is reached approximately in the centre of the glass plate, far from the edges so that the ultimate strength is not influenced by the defectiveness of the cutting edges. This test provides good results when a uniform and equibiaxial state of stress in the core of the specimen is induced because the geometric non-linearities are less significant in this condition. The EN 1288-2 European standard proposes applying an additional overpressure during the load phase, to compensate the second-order effect, especially in the case of big specimens where the non-linearities are more significant. The application of the overpressure makes the test more difficult to perform and furthermore some authors have proved that the induced stress state is not uniform and equibiaxial. In this paper the first results of a bending strength investigation on glass plates are shown. This investigation consists of a numerical non linear analysis in which the geometric non linearity is considered. At the same time an experimental investigation is carried out using coaxial double ring tests in order to compare the results of the numerical analysis with experimental tests using glass plates with different thicknesses. This experimental campaign will provide new and useful information on how to perform an easy testing method to evaluate glass bending strength without the use of overpressure.

Keywords: Glass, Glass bending strength, Double ring test

1. Introduction

Glass is an elastic-brittle behavior material. It is homogeneous and isotropic and its constitutive law is linear elastic up to failure. Its compression strength is very high while its tensile strength is low due to the random distribution of surface flaws and impurities, which induce cracks without prior warning (Speranzini and Agnetti 2014). This phenomenon is dependent on surface micro-defects in the glass due to inclusions within the glass or to scratches caused by normal everyday handling, cleaning or processing. Because of sensitivity to defects, the glass strength is influenced by the size of the specimen and by the ratio between the two principal components of surface stress (Beason and Morgan 1984).

Classical four point bending tests are not suitable for glass plates, because of the test's configuration, the maximum stress is reached on the plate edges where, due to the cutting process, the defects are more likely than on the internal part of the plate (Vanderbroek et al. 2014). Therefore it is necessary to eliminate this uncertainty to obtain strength values that are not affected by edge defects. A satisfactory way of overcoming this problem is the use of coaxial double ring tests in which the maximum stress is reached approximately in the centre of the glass plate, far from the edges, so that the corresponding ultimate strength is not influenced by the defectiveness of the cutting edges. This test provides good results when a uniform and equibiaxial state of stress in the core of the specimen is induced because the geometric non-linearities are less significant in this condition. The influence of edge conditions, in cases where the strength of the edge is dominant, can be taken into account in evaluating the allowable maximum stress through the use of appropriate corrective coefficients that depend on the edge finishing,

The EN 1288-2 European standard (EN 1288-2 2001), in the case of large square specimens of 1000x1000 mm size, where the non-linearities are more significant, proposes applying an additional overpressure during the load phase, to compensate second-order effects. The application of the overpressure makes the test more difficult to perform due to technological reasons such as the controlling system reliability for the simultaneous application of the load and overpressure and furthermore some authors have proved that the induced stress state is not uniform and equibiaxial (Dall'Igna et al. 2010).

The EN 1288-5 European standard (EN 1288-5 2001), in the case of small square specimens of 100x100 mm, proposes the use of coaxial double ring tests without overpressure because in this configuration the second order effects are limited and the stress is almost uniformly equibiaxial. It is to be noted that the small size of the specimen is not representative of the glass defectiveness.

The objective of our work is to perform an easy testing method to evaluate glass bending strength without the use of overpressure for big specimens of annealed glass and overcoming the problems of non-linearity through appropriate calculations. The work started from the analysis of the results obtained by the double ring test in the case of small specimens.

In this paper the first results of a bending strength investigation on glass plates are shown. This investigation consists of a numerical non linear analysis in which the geometric non linearity is considered. At the same time an experimental investigation is carried out using coaxial double ring tests in order to compare the results of the numerical analysis with experimental tests using glass plates with different thicknesses. This experimental campaign will provide new and useful information on how to perform an easy testing method to evaluate glass bending strength without the use of overpressure.

2. Finite element model (FEM)

2.1. Model development

For an accurate representation of glass plates, it is required to account for the geometric nonlinearity described by the theory of large deflections when the deflections are larger than one third of the plate's thickness. This problem must be considered on glass plates because the aspect ratio led to inaccurate results when applying the linear plate's theory of Kirchoff that neglects the strains at the middle of the edges and the membrane stresses.

To this end a complete three-dimensional FE model of the test specimens was thus built in geometrical and physical non-linearity using the commercial software ANSYS. The numerical model was built to accurately reproduce the geometry of the specimens. Minor regularizations were made and the presence of imperfections was disregarded, since the present structure is not sensitive to stability problems.

In order to perform this operation the geometry of the glass plates were firstly reconstructed by means of CAD tools, next the volumes were imported and modelled by means of Solid65 elements (three dimensional eight-node hexahedron isoparametric elements). The average size of the hexahedron elements was chosen so as to have four elements across the specimen thickness: this allows the more critical details to be captured avoiding, at the same time, shear lock effect. The complete finite element model (FEM) is shown in Fig. 1: it consists of 51065 nodes and 15968 elements, corresponding to 94992 degrees of freedom.

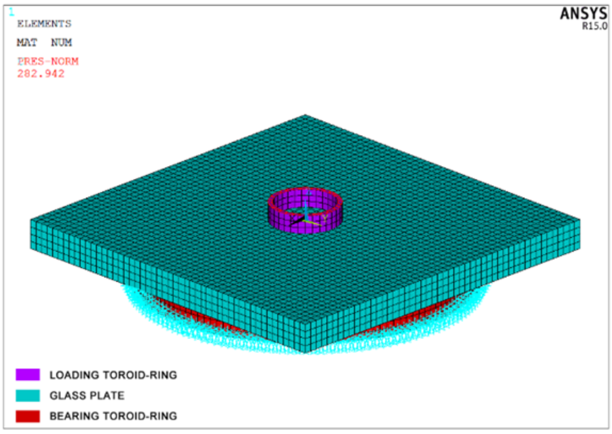


Fig. 1FEM model: mesh discretization.

An assumption was made that the glass has a brittle fracture behavior, with the modulus of elasticity of 70000 MPa and the Poisson's ratio of 0.23. Furthermore, the glass is considered isotropic and homogeneous. To increase the reliability of the proposed FEM, unilateral contact interfaces were then used for the simulation of the contacts between the specimen and the loading and bearing toroid-rings, respectively. The modeling of these contacts necessitates the use of specific flexible/flexible elements. Specifically, for this application, a unilateral contact law was applied in the normal direction of each interface, indicating that no tension forces can be transmitted in this direction and a gap may appear if the stresses become zero. For the behavior in the tangential direction, it was taken into account that sliding may or may not occur, by the usage of the Coulomb friction model with a friction coefficient equal to 0.5.

2.2. Analysis results

In order to determine the actual stress field inside each specimen at breakage, and in particular the breakage stress at the failure origin, a finite element analysis was conducted, in which the glass plate was subjected to both self-weight and a uniform load pressure under different load stages. FEAs proved that the radial and circumferential (or tangential) stresses evocated in the specimen by the external load are not uniform nor equal to each other on the loading area (non-equibiaxial stress filed). More specifically, on the facing-up surface the radial stresses are greater than tangential stresses and reach their maximum value at about 9 mm from the specimen's center, i.e. beneath the loading ring (Fig. 2); conversely, on the facing-down surface the maximum tensile stress is reached by both the radial and tangential stress at the middle of the plate, in correspondence of the surveyed failure origin (Fig. 3).

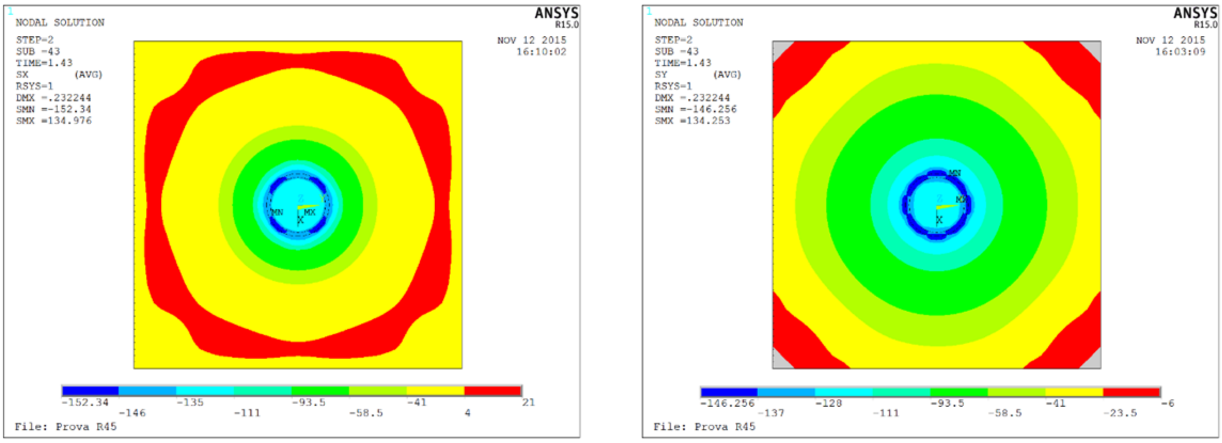


Fig. 2Facing-up surface: a) radial stresses; b) tangential stresses.

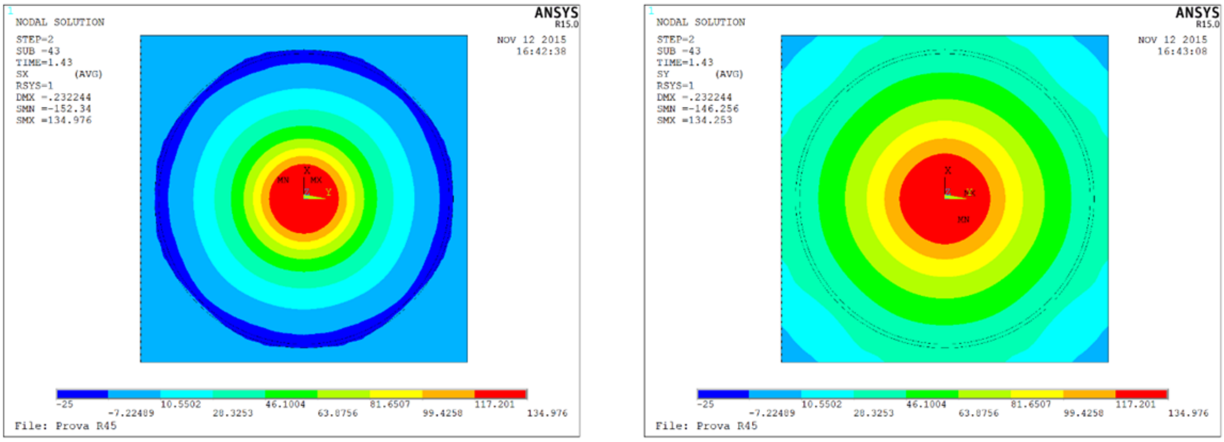


Fig. 3Facing-down surface: a) radial stresses; b) tangential stresses.

3. Coaxial double ring testing

3.1. Test Setup

Tests carried out using equal-sized loading areas subjected to different stress fields (e.g., uniaxial or biaxial tensile stress field) bring about different average strengths, i.e., higher failure stresses are observed under uniaxial stress fields (Wereszczak et al. 2010). This is due to the crack's plane orientation relative to the principal stress directions: the crack-opening stress for a surface flaw not orthogonal to the uniaxial stress field is lower than the maximum principal stress, and the probability of unstable crack propagation is reduced (Beason and Morgan 1984; Vandebroek et al. 2014). Therefore, to separate the influence of crack orientation and defectiveness of the borders (due to the cutting process), in the experimental measurement of the material bending strength a possible solution could be to induce an equibiaxial state of stress in the core of the specimen. To achieve this, tests were carried out using coaxial double rings (CDR), which also have the advantage of being independent of edge conditions, since stresses outside the reaction rings are negligible.

More specifically, the test configuration is without overpressure, according to the layout shown in Fig. 4. The square shape was preferred to the circular one because it is easier to cut and there is not a substantial difference between them in terms of stress. For the commercial thickness of float glass, this geometry represents a compromise between reducing second order effects and achieving a representative tested area, without incurring in stress concentrations at the rings.

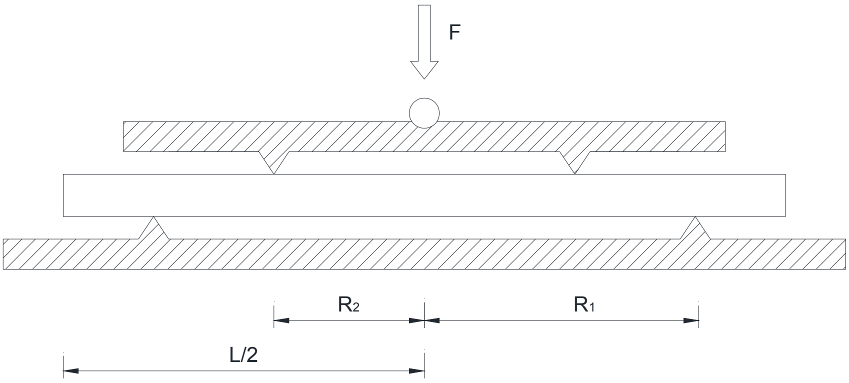


Fig. 4 CDR test configuration with no overpressure (L = 100 mm, R_1 = 45 mm and R_2 = 9 mm).

The samples were provided by a single producer that cut the specimens from large float glass sheets and shipped them directly to the laboratory. All the specimens had the same ichnographical size (100mm x 100mm), but the thickness of the glass plates was different. Each specimen was subjected to the same working (simple cut edges) and handling, so that all the samples probably suffered the same level of surface degradation. An electrostatic 3M polymeric film (approximately 100 μm thick) was applied on the upper surface of the specimens in order to keep together the glass fragments originated at failure, thus making the fracture analysis easier by allowing the experts to trace back the fracture origin (position where the fracture began) without affecting the test results.

All tests were performed under displacement control by means of an INSTRON-4411 dynamometer (maximum load 5 kN, resolution 0.1 N up to 400 N), with a stress rate of 2.0±0.4 MPa/s corresponding to a crossbar's displacement velocity of 1.39 mm/min (Fig. 5). Test geometry consisted in a bearing toroid-ring with radius (R_1) of 45 mm and a loading toroid-ring with radius (R_2) of 9 mm (configuration R45, according to UNI-EN 1288-5 European standard).

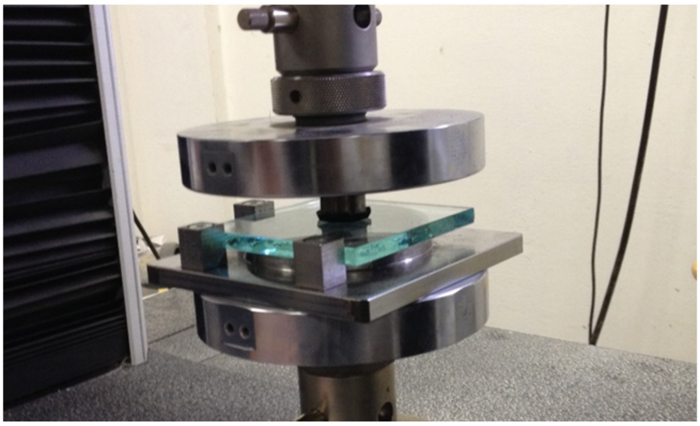


Fig. 5Method of test by coaxial double rings (CDR) - EN 1288-5:2001.

During testing, the load (F) in function of the time and the deflection at the middle of the plate were recorded. After testing, the failure stress values or bending strength values (σ_{bB}) were calculated with the failure loads (F_{max}) for all series with the following equation:

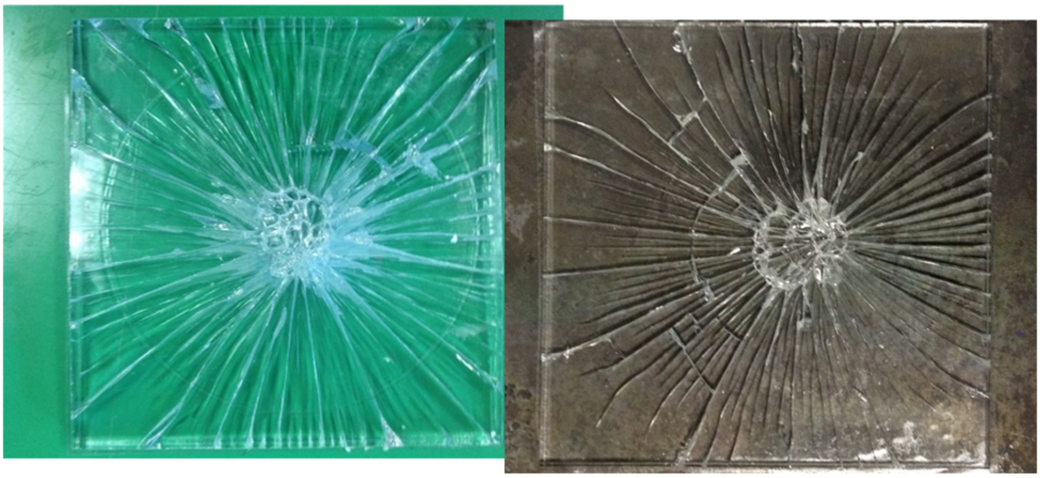
$$\sigma_{bB} = K_1 \frac{F_{\max}}{h^2} \tag{1}$$

where K_1 is a correction coefficient equal to 1.04 according to UNI-EN 1288-5 European standard and h is the height of the specimen.

As reported in Table 1, the number of specimens for each set is variable and not uniform: this is mainly due to time constraint reasons and to a few breakages experienced during the cutting or shipment operations. On average, the number of samples for each set is around 10 units. In spite of the fact that this number is quite small for the derivation of statistical data, the authors believe that this preliminary analysis was very useful in allowing us to identify weak points, fix some process procedures, and develop experience in testing float glass strength for implementing the obtained data in the structural design process.

3.2. Test results

To locate the failure origin, fracture analyses were carried out on the specimens (except those failed at higher loads whose fragmentation prevented us to perform this analysis) and confirmed that the failures started where FEA identified the highest tensile stresses. The majority of failures occurred, in fact, within the loading ring, with a greater concentration of both tangential and radial stresses closer to the ring, reflecting the stress distribution. The image of the specimen in Fig. 6a shows that the cracks are set off from the center of the plate and developed in the radial direction due to the tangential stresses. A number of new glass specimens fractured in locations between the two rings, where stresses are significantly lower, causing circular cracks due to the radial stresses (Fig. 6b). Consequently, such failures gave failure loads in the higher end of the range. Some specimens reached the crisis under very high loads that caused tiny fragments and widespread distributed cracks.



a) b)

Fig. 6 Coaxial double rings test results: a) cracking pattern induced due to a concentration of both tangential and radial stresses close to the loading ring; b) cracking pattern induced due to a concentration of both tangential and radial stresses in locations between the two rings.

The strength testing data, as well as the number of valid test results (all strength data shown is only for test plates that fractured in a valid fashion), are summarized in Table 1 for all four glass thicknesses examined. The data are summarized in mean values of the bending strength calculated using eq.1 and extreme values of the strength range. The last column of the table 1 shows the recorded deflection.

Table 1: Summary of experimental Data.

Specimen thickness [mm]	Number of specimens	Failure load [N]	Bending strength [N/mm^2]			Deflection [mm]
			Max value	Min value	Mean value	
4	10	3322	277	137	216	1.218
5	10	3433	259	107	143	0.974
6	10	4639	191	110	134	0.692
8	15	8634	207	86	140	0.576

Forty-five glass specimens were tested to failure leading to different average strength, i.e. thicker glass specimens showed lower failure stress and a greater dispersion of results. More specifically, while 4 mm thick glass showed a mean value of the ultimate capacity equal to 216 N/mm^2), a higher value of thickness produced lower bending strength (values ranging between 134 to 143 N/mm^2 have been obtained). Far from being exhaustive, this can be explained considering that ribbon shaping technology can effect on the dependence of the glass strength from its thickness, so thicker glass has lower strength than thinner one. Further experiments will allow clarification of the phenomenon in relation to the presence of particular surface defects and comparison of the experimental values with the predicted strength. Also it worth to mention that a significant amount of scatter exists in the strength values highlighted by standard deviations: low values were measured in the case of 4 mm thick glass (21 %), while higher values were obtained for 5 mm (36 %), 6 mm (24%) and 8 mm (27 %) thick specimens.

4. Conclusions

The double ring coaxial bending test appears to be an optimal tool for the determination of the characteristic strength of flat glass plates used for architectural applications. Its simplicity and the biaxial stress field generated on the glass surface (closer to the stress field existing in real applications) are this test method's main merits. Moreover, the absence or reduction of breakage from the edge of the pane allows for improved estimation of the Weibull distribution parameters for the glass surface. Imperfect equibiaxial behavior due to the geometric non-linearity, which increases with the size of tested areacan be overcome through FEM analysis. Nonetheless, equibiaxial behavior is hardly achievable even in pressurized CDR tests (EN 1288-2) due to technological reasons (i.e. airtight pressure loading devices, reliable controlling systems for the simultaneous loads application).

The ultimate loads measured in the experimental tests are in agreement with those of the numerical non linear analysis so as the stresses evaluated by the EN 1288-5 standard code. This experimental campaign will provide new and useful information on how to perform an easy testing method to evaluate glass bending strength without the use of overpressure.

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