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Experimental determination of glass units strength under point load from temporary installation tools for blinds and sun protection systems

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Abstract

Due to the possibility of using vacuum mounting suction cups in modern construction practices, it is imperative to determine the safe threshold of point load on glass units that are vulnerable to local forces. The present paper elucidates the findings of an experimental investigation into the strength of a double-layer glass unit with an air gap under the action of a local load typical of vacuum-fixed assembly tools. The research methodology involved varying the angle of force application (0°, 45°, 90°) and the positioning of the suction cup (center/edge), while recording deflections at designated control points using electronic micrometers. It was determined that the suction cup detached when subjected to a load of 86 kg in the "90°, center" glass configuration, whereas other configurations remained undamaged up to loads of 50 kg. To ensure safety and preserve the integrity of the double-glazed unit, tests for loads greater than 50 kg were carried out only in the «90° configurations, centered at the», which was determined to be the most vulnerable based on previous tests. Other configurations showed no signs of damage up to 50 kg, and further testing was considered unnecessary due to the lower stress concentration. The findings can be used to formulate recommendations for the safe application of mounting equipment and to enhance the regulatory framework for the interaction of fasteners with transparent structures.

1. Introduction

In contemporary construction, architectural solutions increasingly prioritize the optimal utilization of transparent enclosing structures. Double-glazed windows have emerged as an indispensable component of façade systems, window assemblies, interior partitions, and skylights. This preference is attributed to a harmonious blend of superior aesthetic qualities, energy efficiency, sound insulation, and adaptability to natural illumination. Consequently, there is a growing reliance on supplementary structural elements, particularly solar control systems – such as blinds, roller shutters, curtains, and internal or external screens. The installation of the said systems is frequently executed after the completion of the primary construction tasks, thereby being positioned directly above the finished glass surfaces [1].

One of the prevalent solutions in installation practice involves the utilization of temporary point fastening elements or supports. Notably, vacuum suction cups equipped with quick-release mechanisms facilitate fixation without necessitating drilling or additional mechanical coupling [2]. However, this technology creates a localized load on the glass surface, namely point pressure, concentrated within a limited area [3]. The damages that can occur in this case not only lead to cost increases and project delays, but also to occupational safety risks during installation,

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demonstrating the serious consequences of the lack of clear guidelines in this regard. This phenomenon can be a critical consideration when installing laminated glass units, particularly under elevated load conditions (e.g., when handling heavy blinds or applying pressure on levers) [4].

Currently, regulatory documents, specifically the Ukrainian DSTU B V.2.6-156:2010, the European EN 12150, and the American ASTM C1048, delineate the general strength parameters of glass [5,6]. They stipulate requirements for tempering, impact testing, thermal exposure, and more. However, there are no specific guidelines concerning the permissible point load during short-term interactions with installation tools. In construction practice, this leaves considerable room for risk, i.e. glass breakage due to force even within the range of several tens of kilograms. Moreover, double-glazed windows constitute a complex multilayered system wherein the outer and inner panes of glass, a spacer frame, and a sealant interact. Even a small local force can cause subtle yet significant consequences, in particular microcracks, chamber deformation, seal failure, or a reduction in structural integrity under further loads [7]. In this regard, the inquiry into the permissible level of point load on a double-glazed window becomes particularly relevant not only for installers but also for designers and manufacturers [8]. Thus, there emerges a compelling need for systematic research: the experimental determination of the maximum permissible loads that can be applied to glass without incurring the risk of breakage or damage [9]. The findings of such an investigation will enable the formulation of well-founded recommendations regarding the selection of installation equipment and its operational modalities. Beyond the immediate advantages to installation practice, such data can serve as a foundational basis for enhancing the regulatory framework and increasing the safety of transparent structures within the construction domain.

The hypothesis of the present study posits that there exists a critical point load value, beyond which microdamage or destruction occurs in the glass unit, and that this value significantly depends on both the angle of force application and the position of the suction cup. The scientific novelty of the study lies in the fact that for the first time a systematic experimental study of the influence of the configuration of a point installation load on the behavior of a glass unit (rather than a separate sheet of glass) was conducted, employing variable angles and positions of the fixing element to accurately simulate authentic installation conditions.

The purpose of the present study is to experimentally test the structural integrity of a double-glazed window when exposed to a point load. This load arises from the various installation tools that can be used when installing sun protection systems or during construction activities. To achieve this aim, the following tasks were delineated:

- Develop an experimental methodology for assessing the tensile strength of a standard double- glazed window under localized point loading, which reproduces the conditions of installation with vacuum suction cups.
- Design and evaluate an experimental mounting device designed for the temporary attachment of elements to a double-glazed window utilizing vacuum suction cups in conjunction with a lever mechanism. Additionally, assess its implications on load parameters and the safety of interaction with the glass surface.
- Conduct a series of experimental tests, the outcomes of which will document the load values that correlate with the onset of microdamage, the emergence of unstable adhesion, and the complete destruction of the glass unit.
- Analyze the test results in light of the design features of the glass unit, the type of applied load and the nature of deformations, ultimately formulating practical recommendations for the safe use of mounting devices.

1.1 Literature Review

In the contemporary scientific literature, a plethora of studies has emerged that delve into interconnected topics, particularly the mechanical behavior of tempered, laminated, and multilayer glass under localized loads. Significant attention is devoted to the influence of holes or mounting near edges, alongside parametric influences such as temperature, duration of loading, and the thickness of interlayer films. In the study, the authors investigate the impact of perforations situated in proximity to the edges of tempered glass on its structural integrity [10]. They conduct empirical tests aimed at elucidating how such perforations may compromise the strength of the glass, a critical consideration when addressing point loads induced by installation tools. The article presents both experimental and numerical investigations into the impact resistance of tempered glass [11]. The authors scrutinize the glass's behavior under diverse loading conditions, which can be useful for evaluating the risks associated with glass damage during the installation of solar protection systems. The article considers the reusability of architectural glass and its structural integrity post-utilization, a critical factor in evaluating the longevity of double-glazed windows [12].

The research presented in focused on the gradual failure of laminated glass under low-velocity impacts [13]. The authors demonstrate how different layers of glass respond to loading, which is useful for understanding the behavior of glass units under point loads. Study examines integrated joints for glass-plastic composite panels under varying temperature conditions, contributing to the understanding of how such compounds influence the strength of glass units [14]. The paper analyzes the load-bearing capacity of lightweight glass-plastic composite panels, which may be relevant when considering alternative materials for sun protection systems [15]. The study includes experimental and numerical analyses of lightweight composite panels consisting of thin glass and PMMA, which may be useful in the development of new glass unit designs [16]. The authors conducted a parametric analysis to determine how temperature, loading duration, and interlayer film thickness influence the behavior of laminated glass under transverse stress [17]. If mounting systems (e.g. blinds) are in contact with the glass unit for a long time or create local pressure, these factors can be critical for long-term strength.

In the study, an innovative multi-camera three-dimensional digital image correlation (3D-DIC) system was developed and applied to measure the strain concentration of suction cups during their removal [18]. This advancement facilitates a deeper understanding of the interaction between suction cups and glass surfaces, as well as the loads they impose. The authors in introduced pioneering vacuum suction cups with the ability to self-close and self-recover, thereby ensuring effective adhesion to diverse surfaces [19]. Such innovations prove advantageous in the development of installation tools for blinds and sun protection systems. In [20], a comprehensive methodology for laboratory testing of a vacuum suction cup utilized in marine automatic mooring systems was developed. Although this testing framework is tailored for marine applications, it is readily adaptable for assessing point-mounting on glass within residential or construction contexts, thereby enhancing the safety of blind installation tools. The article explores soft robotic grippers that leverage vacuum technology to grasp uneven and textured surfaces [21]. This investigation may yield valuable insights into the adaptability of suction cups to various glass surface types.

A thorough analysis of scholarly sources reveals a marked interest among researchers in exploring the characteristics of glass under diverse loading conditions, particularly in scenarios involving impact, bending, and thermal fluctuations, as well as within the framework of multilayer and laminated structures. Many studies have concentrated on issues of durability, reusability, and the effects of interlayer thickness and hole geometry on the mechanical behavior of glass structures.

However, existing studies predominantly overlook the behavior of glass units under short-term point loads. Such loads may occur in real operating conditions, in particular when employing mounting suction cups or other mounts. The specifics of multi-chamber double-glazed windows, characterized by their complex structural and mechanical attributes, remain unaddressed. In this context, it is relevant to undertake an experimental study aimed at evaluating the ultimate load that can be applied to the surface of a double-glazed window without incurring the risk of damaging it.

2. Methods and Models

Glass is an amorphous inorganic material characterized by exceptional hardness, chemical inertness, yet it exhibits a brittle mechanical nature. Its microstructure lacks long-range order (unlike crystalline solids), implying that glass lacks defined slip planes or zones of plastic deformation. Therefore, when the permissible threshold of mechanical stress is exceeded, glass breaks suddenly, without any warning signs (e.g., without plastic deformation), thereby categorizing it as a brittle material [22].

2.1 Glass Strength and Breaking Point.

Tensile strength is the maximum stress that a material can withstand under uniaxial tension before breaking [23]:

$$\sigma_t = \frac{F_{max}}{A} \tag{1}$$

where σ_t is the tensile strength, F_{max} is the maximum force until rupture, and A is the sample's cross-sectional area.

For ordinary glass, σ_t is in the range of 30-90 MPa, depending on surface defects [24]. The theoretical tensile strength (under ideal conditions) can be calculated as follows:

$$\sigma_t = \frac{E}{\varepsilon} \tag{2}$$

where E is Young's modulus.

Equation (1) determines the actual tensile strength based on the experimental breaking force, reflecting the effect of defects and surface quality. Instead, equation (2) gives the theoretical tensile limit obtained from the modulus of elasticity of the material, provided that there are no defects in the structure. Due to microcracks and defects, true glass typically exhibits tensile strength values that are significantly lower than the theoretical maximum. Flexural strength is the value of the maximum stress that occurs on the surface of the sample during bending. For a 3-point bend, it is calculated as follows:

$$\sigma_f = \frac{3FL}{2bd^2} \tag{3}$$

where F is the maximum applied force, L is the length of the span between the supports, b is the specimen's width, d is the specimen's thickness. Given that a stress gradient manifests across the thickness of the specimen during bending, the flexural strength facilitates a better modeling of local critical stresses compared to simple axial tension. However, it is worth acknowledging that the values derived from the formula are contingent upon the sample's thickness: as thickness increases, the computed stress value diminishes, even though the actual fracture resistance enhances due to greater structural rigidity.

The failure point is the state of a material at which a material, subjected to external load, undergoes a sudden and irreversible transition from elastic or elastic-plastic deformation to complete failure. In the case of glass, as a typical brittle material, this process occurs without noticeable plastic deformation. Within a stressed-deformed state, the body accumulates energy. The failure point occurs when the local stress exceeds the material's capacity to resist rupture, particularly in the presence of defects such as microcracks. For brittle bodies, the failure point almost coincides with the ultimate strength, since there is no noticeable yield or plasticity stage.

Alan Griffith formulated a fracture theory that takes into account the presence of microcracks within brittle materials [25]. The fundamental premise is to balance the potential energy associated with elastic deformation against the surface energy of creating a new crack. Griffith's critical stress formula is as follows:

$$\sigma_c = \sqrt{\frac{2E\gamma}{\pi a}} \tag{4}$$

σc is the critical stress, E is the Young's modulus of the material, γ is the surface fracture energy, a is the half-length of the initial surface crack.

Microcracks and defects serve as stress concentrators. Upon reaching a critical stress threshold near the crack tip, energy is released in the form of a new crack, resulting in unstable crack growth leading to sudden failure of the material. In the case of glass, the value of a even within micrometers (10^{-6} m) can diminish its strength by tens of times from the theoretically possible limit of ~7 GPa to ~50–100 MPa).

2.2 Frictional Forces of Interaction Between Suction Cup and Glass

The frictional interaction of a rubber suction cup with glass epitomizes a complex amalgamation of adhesion, friction, and hydrostatic vacuum effects, which confer the suction cups to a glass element. The primary mechanisms governing this interaction encompass dry friction at the rubber-glass interface, adhesive pressure arising from Van der Waals molecular forces, a pressure differential (vacuum) within the suction cup, and the deformability of the elastomer that facilitates the formation of a tight fit contour. The frictional force that opposes the displacement of the suction cup across the glass surface is determined by the classical Coulomb friction formula:

$$F_f = \mu N \tag{5}$$

where Ff is the frictional force, μ is the coefficient of friction between rubber and glass (depends on conditions: surface humidity, rubber material, etc.), N is the normal pressing force - the total force caused by vacuum pressure and elastic deformation of the rubber ring. In addition to friction, the main source of force N is the pressure difference between the external atmospheric $P0$ and the internal Pin pressure in the suction chamber:

$$N = (P_0 - P \quad)A \tag{6}$$

where A is the effective contact area of the suction cup. Then the frictional force is:

$$F_f = \mu(P_0 - P \quad)A \tag{7}$$

In real-world scenarios, a suction cup not only creates a vacuum but also leverages adhesive forces resulting from Van der Waals interactions and the capillary effect. This phenomenon significantly enhances the overall grip strength. The better the elasticity of the rubber material (low Young's modulus), the better it adapts to the micro-irregularities of the glass, reducing the likelihood of air penetration. Factors that reduce frictional force include contamination of the glass or suction cup (such as oil or dust), damage of the rubber edge, elevated humidity levels, deformation from repeated use, and depressurization.

2.3 Forces Acting on Glass

In general, glass structural elements are influenced by both external and internal mechanical forces and loads, which may be static, dynamic, localized, or distributed. The characteristics of deformation, stress distribution, and the overall behavior of glass depend upon its configuration: single-glazed (comprising a single pane of glass) or double-glazed (consisting of two or three panes of glass separated by a gas or air layer) [26]. List of forces acting on glass:

- Self-weight (gravitational force: $Fg = mg$. Always acts vertically downwards.
- Wind load is the difference in air pressure. It mainly has a horizontal load.
- Atmospheric pressure is the difference between external and internal pressure. Can create internal deformation.
- Temperature load – uneven heating, thermal expansion. Creates internal tensions.
- Physical point load – pressure, fastening, etc. Creates local stresses.
- Shock loads are sudden contacts.

Figure 1 shows a diagram of the influence of external forces on the glass structure. Figure 2 shows the difference between double-glazed windows and single-glazed windows.

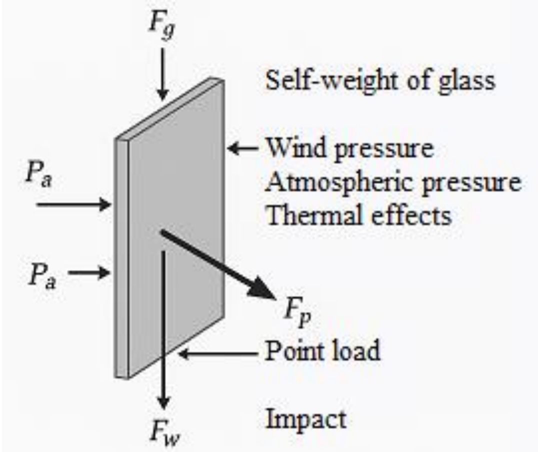


Fig. 1. Schematic representation of external forces acting on the glass panel

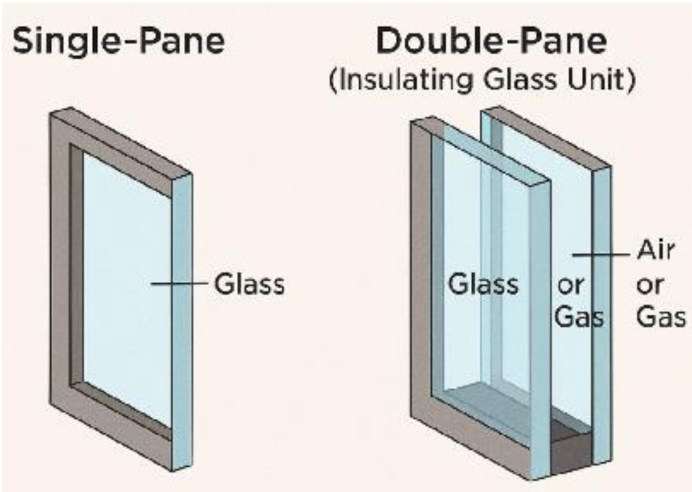


Fig. 2. Scheme of mono-glass and double-glazed structures

Monoglass refers to a single sheet of glass. The behavioral characteristics of such glass are predominantly linear, with the application of forces occurs without an internal compensation mechanism. In other words, when a force is applied, the outer surface undergoes deformation independently. For a flat monoglazed window measuring $a{\times}b$, subjected to a uniformly distributed pressure q (for instance, wind load), the resultant bending deformation is determined by the plate bending equation as follows:

$$D\nabla^4 w(x,y) = q(x,y), \tag{8}$$

$$where \quad D = \frac{Eh^3}{12(1-\nu^2)},$$

where D is the bending stiffness, h is the glass thickness, E is Young's modulus, υ is Poisson's ratio, $w(x,y)$ is the deflection. External forces cause local or global deformation that is not counterbalanced for on the other side (unlike double-glazed windows).

$$D_i = \frac{E_i h_i^3}{12(1-\upsilon_i^2)} i = 1{,}2 \tag{9}$$

A double-glazed window is two or three layers of glass glued together around the perimeter with an air or gas layer between them. Its behavior under load is characterized by nonlinearity and interdependence. Let's consider the double-glazed window consisting of an outer glass with a thickness of $h1$ and an inner glass with a thickness of $h2$, a hermetic layer d. The surface area of the glass is represented as $A=a{\cdot}b$, the Young's moduli are $E1$ and $E2$, and the Poisson's ratios are $\upsilon 1$ and $\upsilon 2$. Consequently, the bending stiffness of each glass is expressed as:

Let the maximum deflection of the first and second glass be $w1$, $w2$, respectively. If the glass bends elastically towards the air chamber, the volume changes:

Then the reaction of the air layer according to the Boyle-Mariotte law for a sealed gas is:

$$V \approx A(w_1 + w_2) \quad (10)$$

Then the reaction of the air layer according to the Boyle-Mariotte law for a sealed gas is:

$$(p_0 + \Delta p)(V_0 - \Delta V) = p_0 V_0 \quad (11)$$

$$\Delta p \approx \frac{p_0}{V_0}\Delta V = \frac{p_0}{Ad}(w_1 + w_2)$$

where p_0 is the initial pressure in the layer, Δp is the excess pressure in the layer. So, the load on the outer glass is:

$$q_1 = p_{ext} - \Delta p \quad (12)$$

on the inside:

$$q_2 = \Delta p \quad (13)$$

The bending equation for each glass is:

$$D_1 \nabla^4 w_1 = q_1 = p_{ext} - \Delta p; \quad (14)$$

$$D_2 \nabla^4 w_2 = q_2 = \Delta p.$$

After introducing the relationship between w_1, w_2 and Δp:

$$w_1 = \alpha \frac{(p_{exr} - \Delta p)a^4}{D_1} \quad (15)$$

$$w_2 = \alpha \frac{\Delta p \cdot a^4}{D_1}$$

$$w_1 = \alpha \frac{(p_{exp} - \Delta p)a^4}{D_1},$$

$$w_2 = \alpha \frac{\Delta p \cdot a^4}{D_2}.$$

The combined equation for calculating Δp and deformations is presented as follows:

$$\Delta p = \alpha \frac{p_o}{AD}(w_1 + w_2) \quad (16)$$

2.4 The Influence of Micro-Scratches, Defects and Surface Contamination on The Strength of Glass

Glass, as a fragile material, is extremely sensitive to surface imperfections. Micro-scratches, chips, inclusions, and residual contaminants on the surface can reduce the actual strength by dozens of times when compared to the theoretical strength. This phenomenon arises from the concentration of stresses around these defects, which catalyze fracture through the mechanism of crack growth. Consequently, the actual strength of glass is typically significantly inferior than the theoretical strength (2). To idealize the defect, an empirical crack is considered (according to Griffith's theory):

$$\sigma_{max} = \sigma_{\infty}\left(1 + 2\sqrt{\frac{a}{\rho}}\right), \quad (17)$$

where σ_∞ is the applied stress, a is the half-length of the crack, and ρ is the radius of curvature at the end of the crack. As ρ approaches zero, the stress concentration escalates dramatically, resulting in brittle failure. In accordance with the Griffith model (4), a crack will grow when the energy released during its growth exceeds the energy required for the creation of a new surface.

Micro-scratches caused by transportation, assembly, or manufacturing serve as precursors to crack formation. Contaminants such as sand, dust, grease, and chemical residues can alter local chemical interactions, thereby facilitating the growth of corrosive cracks. In a humid environment, cracks develop gradually under static loads, a phenomenon known as stress corrosion cracking. The cleanliness of the glass surface directly influences its resilience. Techniques such as optical polishing or chemical hardening enhance surface integrity. Employing protective films, anti-friction suction cups, or gaskets during installation mitigates the risk of micro-damage.

Therefore, given that microdefects may serve as a potential cause for local glass failure, it is worth to briefly evaluate the potential impact of the structural elements supporting the glass. Frame structures, anchoring fasteners, and mounting systems employed in the installation of double-glazed windows typically possess a safety margin that far exceeds the load limit of up to 50 kg. For instance, conventional steel anchors are capable of withstanding loads exceeding 1 ton, while aluminum or steel frames are engineered to endure wind forces, thermal fluctuations, and dynamic loads associated with installation. Consequently, within the purview of this study, the influence of frames and fasteners on glass failure is non-critical, with the primary emphasis placed on the interaction between the glass and the suction cup. Operation of the loading system levers;

$$M=F \cdot d, \tag{18}$$

where M is the moment of force, F is the applied force, d is the arm of force (distance from the fulcrum to the point of application of the force).

Levers in the context of lifting devices or fixing systems with glass or double-glazed windows perform the function of redistributing forces, reducing the applied moment of force, or precisely controlling the load. The lever's principle of operation is based on the law of moments:

In mechanisms with suction cups or glass grippers, levers can:

- compensate for variable weight distribution when maneuvering;
- reduce the load on the handle or control element;
- ensure symmetrical distribution of force across all points of contact with the glass;
- serve as a damper, reducing the risk of exceeding the maximum contact force (and consequently damage to the glass).

In systems with multi-link levers, kinematic amplification can be achieved, wherein a minor movement or force applied to the handle produces a substantial effect at the other end of the structure. The coefficient of this amplification is defined as the ratio of the length of the output arm acting on the glass to the length of the input arm controlled by the user.

2.5 Experimental Methodology

2.5.1 General Methodology

The experiment was conducted by attaching a vacuum suction cup equipped with a lever and lifting mechanism to the surface of the glass unit. Once the suction cup was firmly secured, the load was gradually increased until either the suction cup was detached from the glass or the glass unit was destroyed. The load was applied approximately perpendicular to the surface of the glass with controlled changes in direction (0°, 45°, 90°) relative to the plane of the glass to simulate various real mounting scenarios.

2.5.2 Tool Description

Assembly tool (Fig. 3) consisted of four main parts. The first was a vacuum suction cup with two 11.43 cm diameter rubber cups connected by an aluminum handle. The vacuum in the suction cups was created manually using a mechanical lever. The suction cup was always positioned vertically on the glass. A steel pipe with a diameter of 28 mm was attached to the suction cup handle using a hinge, which served as a horizontal partition. The other end of this partition was connected to the lifting mechanism. The lifting mechanism consisted of two telescopic tubes, a steel rod, a control handle, and an upper platform. It was oriented vertically upwards, parallel to the glass surface and the suction cup handle.

The load on the glass was carried out by extending the central rod using a lever-handle mechanism similar to a sealant gun. The upper platform of the lifting mechanism rested on the piston of an electronic dynamometer, which made it possible to control the applied force. The amount of pressure on the glass was determined as the sum of the dynamometer readings and the mass of the instrument itself, which was 2020 grams. To measure loads exceeding 50 kg (the limit value of the dynamometer), calibrated weights were used, which were placed on the upper part of the partition at the maximum distance from the glass defects. The hinged connection of the suction cup and the partition provided the possibility of conducting experiments with different positions of the partition relative to the glass.

Fig. 3. Mounting device for point loading of double-glazed windows

2.5.3 Experiment Progress

The experiment consisted of six series of tests that systematically varied two parameters (Table 1): the inclination angle of the horizontal partition (0°, 45°, 90°) and the location of the suction cup (center or edge of the glass unit). Three angles of inclination of the horizontal partition (0°, 45°, 90°) were used to reproduce different directions of load in real conditions during installation. The 0° configuration simulated the near-axial tensile force acting to disconnect the suction cup. The 45° configuration introduced a combined shear and tension load, reproducing the oblique force application. The 90° configuration generated a perpendicular bending load representing the most critical state with the maximum stress concentration on the glass surface. This approach enabled us to simulate various scenarios for employing assembly tools under authentic conditions.

Table 1. Experimental parameters

No.	Partition angle	Suction cup position	Impact mechanics	Expected glass reaction
1	0°	Glass edge	Direct tension	Uniform load through coupling
2	0°	Glass center	Direct tension	Balanced deformation with minimal shear
3	45°	Glass edge	Combined shear/compression	Asymmetric loading, bending stresses
4	45°	Glass center	Combined shear/compression	Centric deformation with loading of both suction cups
5	90°	Glass edge	Mostly bend	Highest point load, probability of failure
6	90°	Glass center	Mostly bend	Internal voltage at the center, maximum sensitivity

In configurations where the angle was set to 0°, the force was predominantly directed towards detachment, enabling us to investigate the adhesion characteristics of the rubber suction cup to the glass surface. The 45° angle created a combined load, incorporating both shear and bending components. Conversely, the 90° position corresponded to the maximum pressure model, which generates significant deformation stresses within the surface layers of the glass.

At the same time, varying the positioning of the suction cup, designated as "Glass Edge" and "Glass Center", permitted an assessment of edge effects, because in real conditions, installation often takes place near frames and lintels. For all configurations, we documented the coordinates of the suction cups and sensors, alongside the alterations in glass deflection during the loading process. This comprehensive data collection facilitated the tracking of deformations at various stages, from the initial application of force to the ultimate moment of destruction or detachment.

2.5.4 Additional Measurements

Throughout the experiment, regular checks were conducted to ascertain the functionality of the window and its fittings. The load data and micrometer readings were documented for each of the six-test series. By varying the angle of force application (0°, 45°, 90°) and the positioning of the suction cup (either at the center or the edge of the glass), a thorough examination of the influence of these parameters on the integrity of the glass unit was achieved. The measurement of deformations provided insights into the glass's response to point loading and facilitated the identification of the moment at which fracture initiation occurred.

In each test, the load was applied gradually using a manual lever mechanism that extended a central steel rod pressing perpendicularly to the surface of the glass by means of a suction cup. The applied force was transmitted through a mechanical partition that acted as a lever connected to a vacuum suction cup, providing a stable directional application (0°, 45°, or 90° to the surface).

The amount of load was continuously recorded using a digital silometer (dynamometer) (NITERUS DF-500 model) located between the top of the load mechanism and the test bench. The meter displayed both real-time and peak values in kilograms, newtons, and pounds with an accuracy of ±0.5 g. Simultaneously, the deflection of the glass at the two control points (A and B) was measured using electron micrometers with an accuracy of 0.01 mm. These micrometers were mounted on a rigid frame and aligned orthogonally to the glass surface to fix vertical displacement. Additionally, during and after each load cycle, a visual inspection was performed to detect any signs of damage (microcracks, delamination, seal deformation) or suction cup detachment. In configuration 6 (90°, centered), the time to peel off under maximum load (20 seconds) was also recorded.

All measurements were documented at each load increase (step 10 kg), which allowed a comprehensive correlation between applied force, deformation, and structural response of the glazing unit.

2.6 Window Construction

The investigation was conducted on a wooden sash window manufactured by Andersen, produced in 2003. The size of the window frame was 64.77 × 134.62 cm. The window was securely fastened to the concrete floor using metal brackets to the cinder block wall. The window design included two vertically sliding parts. The Andersen window was chosen because it is a commonly used type of sash window in residential construction. Its wooden frame and typical sash geometry with two vertically sliding parts reproduce common boundary conditions for double-glazed windows, including typical support stiffness and edge restraints. This geometry was expected to reflect real-world mounting scenarios, while providing a potentially less rigid boundary than metal frames, thus offering conservative results in terms of deformation under point loads.

2.6.1 Double-Glazed Window

A double-glazed window measuring 54.61 × 58.42 cm was installed in the window. The thickness of each of the two layers of no tempered glass was 2.3 mm, and the total thickness of the double-glazed window was 12 mm. The double-glazed window was glued into the window sash.

2.6.2 Environmental Conditions

The ambient air temperature during the experiment was 20°C. The humidity was normal and was around 50%.

2.6.3 Measuring Equipment

The following measuring equipment was utilized:

- Electronic dynamometer (NITERUS DF-500) with a measurement limit of up to 50 kg (500 N), the accuracy of 0.5 g, digital display and real-time, peak and first peak value modes. Measurements were made in N, kg;
- two electronic micrometers with a range of 0–30 mm and an accuracy of 0.01 mm, equipped with displays and stainless-steel probes.

The use of an electronic dynamometer ensured accurate determination of the applied force. For loads exceeding the 50 kg (500 N) limit of the electronic dynamometer (NITERUS DF-500), additional calibrated loads were applied, and their values were summed with the dynamometer reading and tool weight to obtain the total applied force. This approach made it possible to accurately estimate forces up to 86 kg while maintaining the reference value of the dynamometer for all test series. Micrometers enabled us to meticulously record even the most minute deflections, thereby facilitating a comprehensive analysis of the deformation processes occurring at various points within the glass unit.

3. Results and Discussion

Six series of experiments were conducted to evaluate the impact of the installation tool configuration on the behavior of the glass unit. They involved different angles of force application (0°, 45°, 90°) and variation in the position of the suction cup (center/edge of the glass). In each case, the applied load, deflections at control points A and B, and visual signs of damage or their absence were recorded. Each experimental series was repeated n times (minimum n=3 recommended) and the results in tables 2–7 represent the mean values of the recorded deflections. This ensures the reproducibility and reliability of the obtained results.

Table 2. Results of experiment 1 (0°, Edge)

No.	Load	Visible damage	Deflection A	Deflection B
	kg		mm	mm
1	10	-	0.04	0.07
2	20	-	0.06	0.14
3	30	-	0.06	0.2
4	40	-	0.08	0.2
5	50	-	0.08	0.23

Table 2 presents the results for the configuration with the partition position at 0° and the suction cup location near the glass edge. The upper suction cup position in millimeters (m) is X = 470, Y = 317.5. The position of the lower suction cup is X = 470, Y = 108. The position of the upper micrometer is X = 381, Y = 320.7. The position of the lower micrometer is X = 387.35, Y = 50.8. There is a clear relationship between the magnitude of the applied load and the deformation of the glass unit. There is a gradual increase in deflection at points A and B with increasing load. The appearance of microcracks was not detected. Different values of Deflection at points A, B under the same load indicate uneven deformation of the glass, which may be due to the point nature of the applied load, the conditions of fixing the glass unit in the frame, and its own elastic properties.

Table 3 presents the results for the configuration with the partition position at 0° and the suction cup location in the glass center. The position of the upper suction cup is X = 470, Y = 406.4. The position of the lower suction cup is X = 470, Y = 108. Upper micrometer position is X = 267, Y = 413. The lower micrometer position is X = 298.5, Y = 184.15. The deflections at point A grow much faster than at point B, which indicates increased flexibility in the central part of the glass unit. No visible damage was detected. An uneven distribution of deformation was observed, characteristic of local vertical tension in the central zone.

Table 3. Results of experiment 2 (0°, Center)

No.	Load	Visible damage	Deflection A	Deflection B
	kg		mm	mm
1	10	-	0.24	0.03
2	20	-	0.47	0.15
3	30	-	0.66	0.2
4	40	-	0.8	0.2
5	50	-	0.87	0.24

Table 4 presents the results for the configuration with a 45° partition position and the suction cup location near the glass edge. The position of the upper suction cup is X = 470, Y = 317.5. The position of the lower suction cup is X = 470, Y = 108. The upper micrometer position is X = 381, Y = 321. The position of the lower micrometer is X = 387.35, Y = 50.8. The increase in load is accompanied by significant deflection at point B, while point A exhibits markedly less deformation. This observation indicates a pronounced asymmetry in the load under the combined action of shear and compression. No structural damage was detected.

Table 4. Results of experiment 3 (45°, Edge)

No.	Load	Visible damage	Deflection A	Deflection B
	kg		mm	mm
1	10	-	0.04	0.17
2	20	-	0.02	0.26
3	30	-	0.06	0.7
4	40	-	0.08	1.09
5	50	-	0.1	1.24

Table 5 presents the results for the configuration with a 45° partition position and the suction cup location in the glass center. The position of the upper suction cup is X = 470, Y = 406.4. Position of the lower suction cup is X = 470, Y = 108. The upper micrometer position is X = 267, Y = 412.75. The lower micrometer position is X = 298.5, Y = 184.15. Both points show a gradual and predictable increase in deflection. The values of Deflections A and B are larger compared to the edge configuration, which is consistent with the larger bending in the central part. No damage was recorded. The deflections at both points increase consistently, with larger values than in Table 2. The center of the glass unit exhibits increased flexibility under combined loads, but no damage is recorded even at 50 kg, which this indicates good adaptation of the structure to non-standard loads.

Table 5. Results of experiment 4 (45°, Center)

No.	Load	Visible damage	Deflection A	Deflection B
	kg		mm	mm
1	10	-	0.1	0.3
2	20	-	0.12	0.38
3	30	-	0.2	0.74
4	40	-	0.33	1.04
5	50	-	0.36	1.3

Table 6 presents the results for the configuration with a 90° partition position and the suction cup location near the glass edge. The position of the upper suction cup is X = 470, Y = 317.5. The position of the lower suction cup is X = 470, Y = 108. The position of the upper micrometer is X = 381, Y = 320.7. The position of the lower micrometer is X = 387.35, Y = 50.8. The deflection at point B increases much faster than at point A, especially after 30 kg. This indicates a pronounced local bending load in the lower suction cup area. Despite the high deformations, no damage was observed. None of Experiments No.1-No.5 was able to achieve separation or breakage of the glass unit under a load of 50 kg. For measurements beyond the 50 kg load, weights were used only for the "center of the glass, partition 90" position (Table 6), as the most vulnerable position.

Table 6. Results of experiment 5 (90°, Edge)

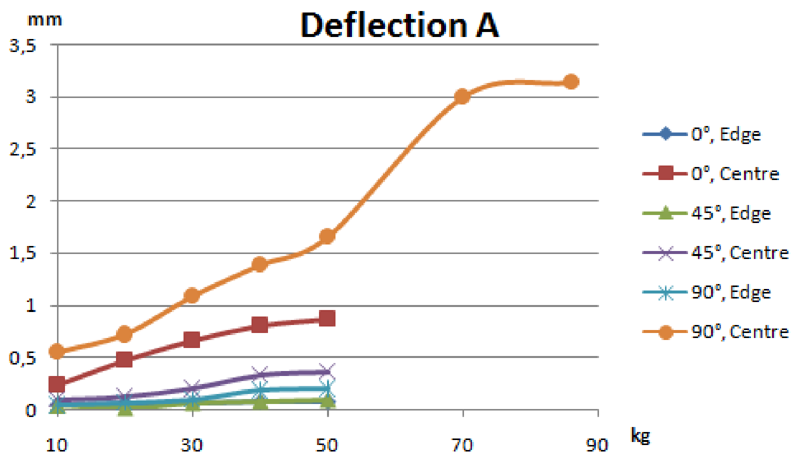
No.	Load	Visible damage	Deflection A	Deflection B
	kg		mm	mm
1	10	-	0.04	0.3
2	20	-	0.06	0.5
3	30	-	0.1	0.7
4	40	-	0.18	1.78
5	50	-	0.2	2.18

Table 7 presents the results for the configuration with a 90° partition position and the suction cup location in the glass center. The position of the upper suction cup is X = 470, Y = 406.4. The position of the lower suction cup X = 470 Y = 108. The upper micrometer position X = 267 Y = 412.75. The lower micrometer position X = 298.45, Y = 184.15.

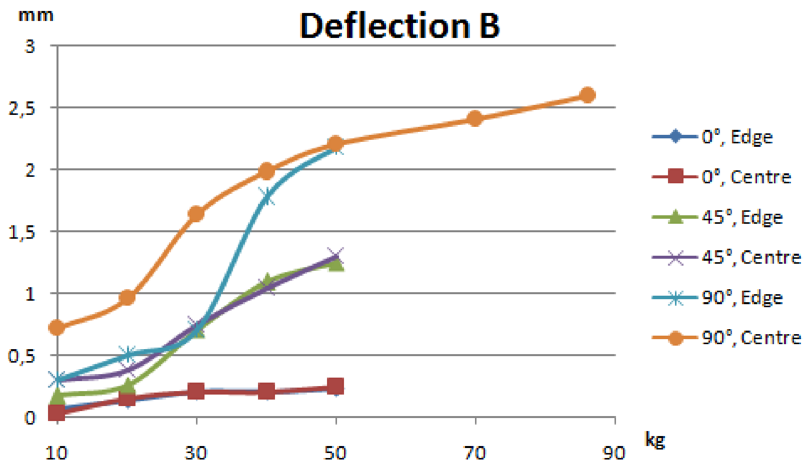
Table 7. Results of Experiment 6 (90°, Center)

No.	Load	Visible damage	Deflection A	Deflection B
	kg		mm	mm
1	10		0.55	0.72
2	20		0.72	0.96
3	30		1.09	1.64
4	40		1.39	1.98
5	50		1.66	2.2
6	70		3	2.41
7	86	There was no damage to the glass. The suction cup disconnected after 20 seconds of loading	3.14	2.6

The deflections at points A and B are much higher than in all previous series. At a load of 86 kg, no damage to the glass was recorded; instead, the suction cup involuntarily broke off after 20 seconds. This exemplifies the ultimate capabilities of rubber vacuum cups. Fig. 4 presents graphs illustrating the values of Deflection A and Deflection B.



(a)



(b)

Fig. 4. Graphs of the values dependence of deflections (a) A and (b) B on the load

The load-deflection curves of Fig. 4 illustrate the mechanical response of the glazing unit under different point load configurations. They show that deformation increases with load, and the amount of deflection is highly dependent on the load angle and the suction cup location. The central configuration of 90° generates the largest deflection, indicating the most critical state for potential glass damage, while the edge load of 0° creates the smallest deflection. The difference between points A and B confirms that the deflection distribution is heterogeneous due to the localized load..

The Deflection A graph shows the change in glass deformation at point A for six experimental configurations. The smallest deflections are recorded at the 0° position, Edge, which indicates the stability of the glass edge under axial tension. The configuration "90°, Centre", exhibits a rapid increase in deflection exceeding 3 mm, indicating significant stress accumulation in the central zone during vertical bending. The remaining configurations demonstrated a moderate increase in deflection within the range of up to 1 mm, devoid of any pronounced anomalies.

The Deflection B graph confirms the same tendency: the configuration "90°, Centre" is the least stable – the deflection exceeds 2 mm even at a load of 50 kg. At the configuration "90°, Edge" deflection B also increases sharply, indicating a localized bending effect near the edge. In contrast, the configurations "0°, Centre" and "0°, Edge" exhibit the least sensitivity to load, making them potentially safer for temporary installation.

The results obtained demonstrate the increased resistance of a double-glazing unit with two layers of glass 2.3 mm thick to local point loading from mounting suction cups. The double-glazing unit withstood a load of up to 86 kg in the central configuration without visible damage, which significantly exceeds the working loads from conventional sun protection systems (up to 20 kg). Below is a comparison with the results of other studies.

Efferz et al. investigated local stresses in tempered glass with holes near the edge and showed that the presence of such holes significantly reduces strength, leading to destruction under loads close to 30–50 kg [10]. Our results for integral double glass without holes show a higher endurance load limit, confirming the negative effect of perforations on the local strength of the glass. Zemanová et al. studied the behavior of laminated glass under low-speed shock loads, where gradual delamination of layers was observed [13]. In our experiment, static point loads, which are more characteristic of the installation of sun protection systems, were investigated. Compared to impact loads, static loading only resulted in elastic deformations without fracture, even at 86 kg. Kozłowski et al. conducted numerical and experimental modeling of the behavior of tempered glass under various types of force effects, obtaining significant deflections and the risk of destruction already under loads of about 70 kg in cases with local defects [11]. Our data for air-bundled double glazing show a more complex deformation character and a higher safety load limit, suggesting the ability of the multilayer system to distribute local stresses.

A series of works by Hänig et al. showed that the use of fiberglass composite panels increases the load-bearing capacity of structures, especially at elevated temperatures [14-16]. Our results for conventional double glazing under standard conditions (20 °C) show a slightly lower rigidity compared to composites, but confirm a similar multilayer effect in reducing local stresses. Cupać et al. studied the reduction of the strength of reused glass with defects [12]. In our case, the double-glazed window of a 20-year-old window was used, probably with microdamage, making the results conservative. Despite this, the destruction did not occur even with the maximum load, which indicates a significant margin of safety in such structures. Galić et al. showed that the thickness and material of the intermediate layers in laminated glass affect stress distribution and load-bearing capacity. In our case, the role of the damping layer was performed by the air layer between the two glasses, which is especially noticeable in the 0° configuration, where deflections were minimal [17].

Studies by Guo et al and Kim et al. have shown that vacuum suction cups create zones of increased stress when the glass is removed and held, and that their overload can lead to localized failure [18]. Our experiment confirmed that the limiting factor in most cases is the separation of the suction cup itself, not the destruction of the glass, indicating a relatively safe load range of up to 70 kg when the tools are used correctly. Wang et al. proposed innovative self-sealing suction cups that reduce the risk of local overload [19]. Our data confirm the need for such improvements, since traditional suction cups are able to create dangerous local stresses with large load levers.

The results obtained are consistent with the proposed hypothesis of the study: the double-glazed window exhibits a distinctly pronounced dependence of the ultimate load on the configuration of force application. The lowest resistance to point loading was recorded in the configuration with a 90° angle and a central suction cup location. This unequivocally substantiates the assertion regarding the critical influence of geometric factors on the localized strength of a glass structure. Given the above, the proposed testing methodology enhances contemporary approaches to evaluating the mechanical stability of transparent structures. It may serve as a foundational framework for reassessing regulatory requirements pertaining to the temporary attachment of elements to glass. Moreover, it holds significant use for professionals engaged in the development of no-drill fasteners, including installers of blinds and sun protection, facade engineers as well as installation equipment manufacturers.

3.1 Limitation

Despite the careful experimental design, the study is not without certain limitations. Only one type of double-glazed window with an air gap was examined, without any variation in glass thickness or structural composition. Furthermore, fatigue effects or repetitive loading, which is relevant for regular assembly and disassembly of elements, were also not analyzed. For the experiment, a window that had been previously utilized, with double-glazed panes that likely have micro-scratches after 20 years of service, was specifically chosen as the potentially least durable option. The glass thickness of 2.3 mm represents the minimum standard employed in the window industry. In most instances, contemporary window glass measures 3.2 mm or 4 mm in thickness. However, no comparative analysis was conducted with 4 mm thick glass with significant, visible scratches. Also, real installation conditions may entail additional disturbances (such as vibrations and distortions), which were systematically eliminated under laboratory conditions.

4. Conclusions

The purpose of this study was to experimentally evaluate the resilience of double-glazed windows when subjected to point loads from various installation tool alternatives. These tools are employed during the installation of sun protection systems or in the course of construction activities. The need for such research arises from practical requirements within the construction and interior design sectors. Incidents of window damage during installation are a prevalent issue, resulting in increased costs and project delays. Understanding the strength limits of glass under specific loading conditions, particularly those encountered with temporary fastening instruments, is crucial for preserving the strength of window installations. This understanding aids in mitigating accidental damage throughout the installation process.

In the course of the experiment, evaluations were conducted utilizing vacuum suction cups featuring a lever mechanism, along with the capacity to accommodate additional loads. Three configurations regarding the orientation of the installation tool relative to the surface of the glass unit were investigated, alongside two placements for the load application on the glass. This setup generated diverse vectors and moments of applied force. Such an approach enabled a comprehensive assessment not only of the load magnitude but also of the influence exerted by the force application method on the glass unit's strength.

The results of a series of experiments conducted with a partition positioned at 90 degrees, referred to as "Glass Center", demonstrated that the tested double-glazed window endured a concentrated point load of up to 86 kg without exhibiting any visible damage. When subjected to loads of 70 kg and above, it became apparent that the upper vacuum cup deformed under the weight. The suction cup was capable of sustaining the ultimate maximum load of 86 kg for approximately 20 seconds before detaching from the glass; however, the glass itself remained undamaged. Deflection measurements at points A and B indicated a progressive increase in deformation correlating with the increasing load, thereby signifying the uneven nature of the glass deformation. The maximum deformation exceeded 3 mm.

The data obtained underscore the considerable resilience of the examined double-glazed window, constructed from no tempered glass with a thickness of 2 mm, against concentrated point loads. The largest and heaviest blinds weigh approximately 20 kg, and their weight can be effectively distributed across two supports. No destruction occurred under a load that was eight times the rated working load of the blinds. The findings can be used to formulate recommendations for the safe utilization of assembly tools, design more reliable devices, and establish industry standards. Future research endeavors could focus on investigating the impact of glass type and thickness, window frame design, and the characteristics of various temporary installation tools on the load-bearing capacity of double-glazed windows.

4.1 Recommendations

The findings of the study give the grounds to formulate a series of practical recommendations for the safe application of mounting suction cups on double-glazed windows. When temporarily affixing blinds or sun protection systems, it is advised not to exceed a point load of 25 kg without the intermediary protective elements. The most precarious configuration involves positioning the suction cup at the center of the glass at a 90° angle. Further, it is recommended to conduct supplementary testing of the installation equipment on identical glass units before using it in real conditions. In particular, it is advisable to conduct the following tests:

- On different types of glazing, including higher thickness structures (3.2–4 mm) and different layer combinations to define universal safe limits of point loads.
- with different levels of wear and the presence of microdefects to assess the impact of real Operating conditions on strength.
- Include cyclic and long-term loads that simulate regular fastening and removal of mounting tools.
- Take into account the influence of vibrations, distortions, and other mechanical disturbances that may occur in real installation conditions.

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