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Experimental characterization of non-linear behavior of monolithic glass

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ABSTRACT

This paper presents the results of a combined experimental and analytical study on one-dimensional slender elements of monolithic glass subjected to simultaneous compression and bending, which progressively increased up to the collapse. The experiments were performed on 32 quintuplets; each quintuplet was composed of five identical specimens, while the quintuplets differed from each other in the geometry and glass of the specimens. The load and restraints applied to a specimen of a quintuplet were different from those applied to the other specimens of the same quintuplet; hence, five different types of tests were performed on the 160 specimens. In each test, the load and the displacements were measured continuously.

The collapse, which occurred when the maximum tensile stress reached glass tensile strength (first cracking), exhibited large deflections. Cracking always initiated away from the edges, since the tests had been designed to avoid edge effects. The results proved that geometric non-linear behavior of glass members cannot be described using the same model as steel structures. An analytical model was then constructed to describe the behavior of glass members subjected to combined compression and bending, which predicts the load-carrying capacity and allows safety to be assessed.

1. Introduction

The slenderness of glass elements that are intended to be transparent and the deflection limits that are usually considered in design imply that geometric non-linearity strongly influences the behavior of compression glass members.

1.1. Deflection limits for horizontal and vertical glass members

Glass members are usually thin and the elasticity modulus of glass is not high; thus, the stiffness of glass members is moderate. If the maximum allowable deflection of structural glass members was the same as steel or reinforced concrete members, consequently, potential applications of structural glass in civil engineering and architecture would be drastically limited.

For that reason, typical deflection limits referenced in design codes and standards for structural glass are high. In particular, these limits allow the ratio between the maximum deflection and the span of glass members to reach values much higher than the ratios that members made of other structural materials are allowed to reach. Indeed, in contrast to the ultimate limit states of glass where the definition of failure is reasonably clear (i.e., first cracking), there is no clear distinction between what is serviceable and what is not, for structural glass. Moreover, typical deflection limits of reinforced concrete and steel codes are an embodiment of professional experience with traditional structures and materials that, for the most part, have performed satisfactorily in service. These limits are not, however, appropriate for structural glass; thus, glass codes define the serviceability limit states using different criteria, which lead to more generous limits. Unfortunately, professional experience with structural glass is not yet sufficient to provide reliable deflection limits.

Users – occupants, visitors, owners and tenants – are not likely to take movement of structural glass members as an indication that the building is unsafe, since these members are not expected to be as rigid as members made of traditional structural materials, especially in the case of vertical structural glass (façades and partitions). Considering this, the serviceability limit state of structural glass members is not defined by the vibration that is perceived by occupants and the deflection that is visible or affects the appearance of the building. Instead, the serviceability limit state is defined by the threshold beyond which vibrations may lead to occupant discomfort.

In properly designed and detailed structural glass members, the above-defined serviceability limit state is far lower than the

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movements that may cause damage. Therefore, serviceability limit state is sufficient for avoiding (or for minimizing) damage to the glass and building.

In more detail, the deflection limits in common usage for horizontal glass members are 1/100–1/250 of the clear span [1–4]. These limits define the maximum allowable deflection for glass floors and staircases subjected to the full nominal live load, and for glass roofs, ceilings, and overhead glazing subjected to the full nominal load. The deflection limit in common usage for vertical glass members is of the order of 1/60 of the span [1–4]. This limit defines the maximum allowable deflection for glass façades subjected to the nominal wind load, and for glass partitions, parapets, railings, and barriers subjected to the full nominal live load (however, sometimes the limit 1/50 of the span is used for parapets).

Ultimately, in order to comply with the moderate stiffness of glass members, on one hand, the serviceability limit state does not guarantee that the members will remain stationary. Under ordinary conditions and normal use, thus, occupants may perceive the vibrations and may feel the deflections. On the other hand, however, it guarantees that the members will not reach the threshold of annoyance for transient vibrations, let alone the threshold of damage. Under ordinary conditions and normal use, hence, the vibrations are lower than the level of motion that building occupants are willing to tolerate. In fact, also considering that a transient vibration lasts several seconds (since the amount of structural damping present in glass structures is low, so the vibration damps out after several cycles), service load vibrations are however not annoying, objectionable, uncomfortable or alarming. Under ordinary conditions and normal use, furthermore, the function of the structure is not disrupted because of local minor damage or deterioration of glass members and other components.

Under the design load for the ultimate limit state, clearly, the deflection-to-span ratio reaches even higher values. In glass members, thus, the undeformed and deformed configurations can be very different from one another, especially beyond the serviceability limit state. Thus, structural glass poses the serious problem of high deflections, which must be addressed.

1.2. Geometric non-linearity of glass systems

Forces are only truly in equilibrium in the deformed configuration. Hereafter, the collocation “deformed configuration” denotes the transformation of the one-dimensional member from the reference straight configuration to the deflected shape due to transverse loads, as well as the deviations from the straight line due to imperfections (although the latter, contrary to the former, do not imply any strain). When the deflections are small, however, static equilibrium can be applied to the undeformed structure.

On one hand, this is not the case for glass members, since they are allowed to reach high deflections; on the other hand, however, if the forces are only applied perpendicularly to the longitudinal axis (transverse loads) this is a reasonable assumption for glass members too. In fact, force equilibrium in the structure is not critically dependent on the mere deflection, but on the normal force multiplied by the distance between its line of action and the deformed axis.

In this paper, the collocations “geometrically linear” and “geometrically non-linear” denote structural analyses and results (deflections and stresses) that have applied static equilibrium to the undeformed and deformed configuration, respectively.

When the normal force is negligible, hence, no considerable geometric non-linearity arises, and force equilibrium is commonly applied to the glass member in its undeformed configuration, independently of whether the deflection is low or high (geometrically linear analysis). In so doing, the relationship between the applied load and the structural response does not depend on the deflection, i.e. the stiffness does not depend on the applied load. Moreover, since glass is utterly elastic, physical non-linearity cannot arise. In this case, hence, the behavior of the glass system is linear.

When the normal force is non-negligible, conversely, a clear distinction has to be made between the undeformed and deformed configurations of the glass member. In structural glass, in fact, the former and the latter can be significantly different from one another, and the latter can provide the normal force with significant lever arms (geometrically non-linear analysis).

Ultimately, when the normal force is non-negligible, significant geometric non-linearity arises, and structural analysis must apply force equilibrium to the glass member in its deformed configuration. As a result, the relationship between the applied load and the structural response depends on the deflection, i.e. the stiffness depends on the applied load. In this case, hence, the behavior of the glass system is geometrically non-linear.

1.3. Glass members subjected to normal force

We are currently witnessing rapid growth in the use of glass in modern structural engineering [5,6]. Glass is being increasingly used for non-load-bearing members over large spans and, for some time now, as a structural material. Much of this growth is being driven by demands for transparency, light appearance and lighting functions, which allow for extraordinary and amazing creations in the world of civil engineering and architecture. This can be seen from the wide variety and the huge amount of recent structural applications, ranging from simple barriers to continuous façades over large spans, as well as glass members with primary structural functions.

Due to its transparent and ethereal nature, glass has become more and more important not only for the envelope of a building but also for inner parts, so as to obtain comprehensive glass solutions. Examples include pavilions with vertical structures made of wall-like or pane-like glass members; sometimes also the horizontal structures are made of glass (all-glass buildings). Often these buildings include glass fins and sometimes glass columns, although a fin cannot be thin and thus will be translucent but not transparent, and a column is thick and thus will not be translucent, let alone transparent, however this does not detract from their beauty.

Glass also offers the possibility of obtaining a wide range of long lasting colors. For this reason, it may be preferred over conventional materials for members that are thick, and thus neither transparent nor translucent, as columns are. Nevertheless, also walls sometimes use colored glass, although they are thin and thus could be transparent.

Glass walls bear the horizontal actions due to wind and impacts (in some cases earthquakes too), and the vertical forces transferred by the floors and/or the roof (as well as the own weight). The glass panes that compose a wall are typically restrained at the two opposite horizontal edges (while each vertical edge is contiguous but free, with respect to the vertical edge of the next pane). Hence, a glass wall has one-dimensional behavior, which consists of the combination of an axial compressive force and an out-of-plane bending moment. Considering the deflection limits of vertical structural glass (Section 1.1), the force equilibrium must be applied to the deformed configuration also if the normal force is moderate (Section 1.2). From the structural perspective, hence, a glass wall is a thin column, i.e. a member with one-dimensional non-linear behavior.

Glass fins and columns included into architectural glazing, although not thin, require that the force equilibrium is applied to the deformed configuration too. In fact, these members are subjected to the combination of axial compressive force and out-of-plane bending moment, and their deflection limits are those of Section 1.1.