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Exploratory Finite-Element investigation and assessment of standardized design buckling criteria for two-side linear adhesively supported glass panels under in-plane shear loads

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ABSTRACT

In this paper, the buckling response of glass panels linearly supported along the top and bottom edges, under the action of in-plane shear loads, is investigated by means of analytical and Finite-Element (FE) methods.

The typical buckling behaviour is first assessed in the hypothesis of fully neglecting the possible deformability contribution of adhesive linear supports, while successively the effects of linear, flexible sealant joints on the overall structural response of the same panels are also properly taken into account and highlighted. Based on extended parametric FE linear buckling and nonlinear incremental simulations, the influence of initial geometrical imperfections with various shapes and amplitudes, adhesive stiffnesses and glass types is investigated, both for monolithic and laminated glass panels. In the latter case, the accuracy of an equivalent thickness approach derived from early contributions is also demonstrated. Analytical approximating curves are proposed for the fitting of numerically derived buckling coefficients, so that they could represent a practical tool in the calculation of the expected Euler's critical load. A normalized buckling curve for ideally simply supported glass panels under in-plane shear loads is finally recalled from past research projects and proposed as a rational design method for the examined loading and boundary condition.

1. Introduction

Glass panels are widely used in modern buildings as structural elements. Frequent applications in façade envelopes, for example, involve the use of glass panels spanning from floor to floor (e.g. restrained at the level of foundation and roof) able to ensure lightness, transparency and energy efficiency to wide surfaces and interiors (Fig. 1). Often, the same glass panels are used for architectural and comfort requirements, but especially in the form of 'glass shear walls' able to ensure stabilization and stiffening contributions to entire buildings and structural systems. As a result, their design and calculation strictly depends on a complex structural interaction between the glass panels themselves and their connections to the substructures, namely consisting in bonded connections, adhesive joints, special metal fasteners, steel or aluminium frames, as well as timber framing systems.

Some studies of literature have been dedicated over the past years, for example, to the structural performance of shear glass walls and assemblies under in-plane dynamic loads, such as seismic events. In [4–6], the dynamic behaviour of full-scale curtain wall mock-ups was experimentally investigated to assess the seismic vulnerability and flexibility of glass façade panels under in-plane earthquake loads. Parametric studies were also carried out (e.g. by changing the glass type, thickness, etc.) on glass assembiles in which the interaction between the glass panels and the supporting aluminium frames was realized by means of special rubber gaskets. Antolinc et al. [7,8] investigated, by means of full-scale shake-table experiments, the seismic capacity of glass walls interacting with timber frames.

Concerning the structural performance of shear glass walls and metal-glass assemblies under quasi-static in-plane shear loads, as for example in presence of wind pressures, the major number of research projects has been dedicated to the development and validation of novel design concepts for the connection systems, as well as to the implementation and calibration of standardized design methods of practical use in presence of ordinary loads. Huveners et al. [9,10] experimentally investigated the structural behaviour of glass panels subjected to in-plane shear loads and circumferentially glued to metal frameworks. The structural

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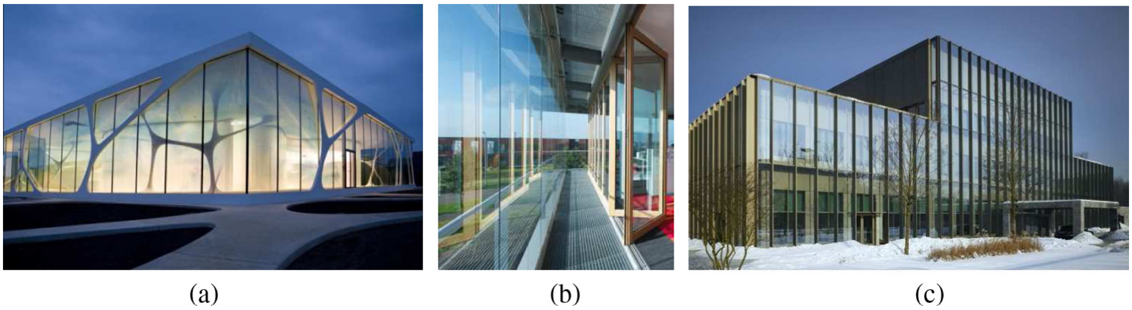

Fig. 1. Examples of glass façades and envelopes. (a) Leonardo Glass Cube by 3Delux (Bad Driburg (DE)) [1]; (b) double skin façade: Solarlux® CO_2mfort façade for administrative building (Nijverdal (NL)) [2]; (c) double skin façade: British Embassy Warsaw (PL) by Tony Fretton Architects [3].

interaction between glass panels and adhesively bonded steel frames has been also studied in [11]. Mocibob [12] focused on the experimental and Finite-Element numerical investigation of the structural behaviour of laminated glass panels under in-plane shear loads. In that work, careful consideration was paid for glass walls point supported to the substructure by means of bolted metal fasteners, as well as for glass panels linearly supported at the top and bottom edges only via flexible, linear adhesive joints. The validity of both the design concepts was assessed, with specific attention for the overall shear buckling response of the so restrained glass walls, when mainly subjected to in-plane shear loads but also to combined in-plane loads/out-of-plane pressures. Wellershoff [13,14] assessed via experiments and FE numerical simulations the buckling response of glass panels under in-plane shear and linearly supported along the four edges. Analytical and Finite-Element (FE) numerical studies were proposed in [15] for the assessment of the buckling response and resistance of glass panels ideally simply supported along the four edges, under the action of in-plane shear loads. Based on a further validation of a simplified equivalent thickness approach, the study was extended in [16] to laminated glass panels composed of two (or three) glass sheets and one (or two) shear flexible interlayer. In that case, the calibration of a Eurocode-based design curve to experimental test results of literature, FE simulations and analytical calculations was also proposed as a rational buckling design procedure for the examined loading and boundary conditions. In [17], a normalized resisting domain was finally presented for the buckling verification of the same simply supported panels under the combined action of in-plane shear and in-plane compressive loads. The mentioned standardized design methods are currently implemented in technical documents for structural glass elements (e.g. [18,19]), due to their general validity and simplicity of application, when properly calibrated. Their actual limitation, however, is represented by the assumption of ideal restraint conditions only (e.g. fully rigid, continuous simply supports along the four edges).

In this work, the buckling response of glass panels subjected to in-plane shear loads but linearly supported along the top and bottom edges only, is investigated by means of extended FE parametric simulations [20] and analytical methods derived from past works [12,16] and classical theories [21]. In them, the top and bottom edges are linearly restrained to the foundation and the substructure (e.g. usually at the level of inter-storey floors) by means of structural adhesives, while the vertical edges are unrestrained against in-plane or out-of-plane deformations. Throughout extended parametric studies, careful consideration is paid to the amplitude and shape of possible initial geometrical imperfection. As shown, differing from glass panels continuously supported along the four edges [16], the investigated boundary condition is characterized by significant out-of-plane deformations. Their overall behaviour, moreover, strictly depends on the almost moderate stiffness of the adopted linear adhesive joints, as also highlighted in [12], since they allow further in-plane deformations between the glass panels and the substructure components. As a result, although preliminary and conservative buckling calculations could be developed by fully neglecting the possible stiffness contribution of these adhesive linear supports, careful attention should be dedicated to the correct estimation of their effects in terms of expected fundamental buckling shape, shear buckling resistance and buckling failure mechanism.

For this purpose, buckling coefficients numerically derived from linear bifurcation FE simulations are numerically derived and proposed in this paper, so that the Euler's critical load of the studied panels could be calculated by means of classical formulations derived from shear buckling theories [16]. Based on extended nonlinear incremental FE analyses, the validity of the buckling design method presented in [16] for continuously supported glass panels under in-plane shear, is properly assessed. The same normalized approach is finally proposed as practical buckling design method for the specific boundary and loading condition. Certainly, extended full-scale experimental investigations could provide a further substantial validation of the presented analytical methods. In this sense, it is expected that the current research outcomes could provide a strong theoretical background for the examined structural typology.

2. Theoretical background and buckling design proposal for glass panels under in-plane shear

2.1. Glass panels simply supported along the four edges

The buckling behaviour of isotropic panels, simply supported along the four edges and subjected to in-plane shear loads has been widely investigated over the last decades [22–26].

In the case of panels composed of glass, for example, a normalized design buckling curve developed in accordance with current standards for steel structures (e.g. the Eurocode 3 [27]) was presented in [16] as simplified verification approach for panels composed both of monolithic or laminated cross-sections. The mentioned design approach, validated also towards experimental studies available in past research works (e.g. [13,14]), was proposed so that the buckling shear strength of a glass panel with general geometrical properties and possible initial geometrical imperfections could be calculated.

For this purpose, Fig. 2 shows the undeformed and deformed configurations for a $H \times b$, t-thick monolithic panel composed of glass (with $E = 70$ GPa the Young's modulus and $\nu = 0.23$ the Poisson's ratio [28]). The panel is continuously supported along the four edges and subjected to in-plane shear loads V. Its shear buckling collapse should be properly prevented by limiting the applied