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Exploratory numerical analysis of two-way straight cable-net façades subjected to air blast loads

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ABSTRACT

Based on numerical and analytical results of previous literature contributions, the paper investigates the dynamic behaviour of a structural two-way straight cable-net façade subjected to medium-level blast loads. Numerical studies are dedicated, specifically, to a cable-net prototype already experimentally investigated under seismic loads. Several numerical finite-element (FE) models are developed in ABAQUS/Standard. A geometrically simplified, lumped-mass FE-model (M01), a detailed cable-glass model (M02) and a further simplified but computationally efficient cable-glass model (M03) are presented. The models are assessed and calibrated to test data of literature, as well as to simplified SDOF analytical formulations, in order to investigate the dynamic response of the façade under high-rate impulsive loads. Since axial forces in the cables and maximum stresses in the glass panels abruptly increase when the explosion occurs, specific viscoelastic and frictional devices are applied at the connection between glass and cables, as well as at the end of the cables. The main advantage of the presented technological solution is given by the partial dissipation of the incoming energy. In the first case, viscoelastic connectors add flexibility to the point-supported glass elements, hence reducing the amount of incoming blast energy. In the latter case, frictional devices dissipate through friction mechanisms the strain energy stored by the bearing cable-net. A proper combination of these multiple devices, in conclusion, can manifest a marked increase of structural efficiency for the examined structural typology.

1. Introduction

The rising desire of transparency in modern buildings markedly increased the use of glass as a construction material able to carry-on loads in the form of innovative structural members, roofs, curtain walls. As a result, during the last decades traditional design concepts rapidly evolved, in conjunction with ongoing manufacturing developments, in order to provide appropriate technological solutions to continuous advanced architectural demands [1–8].

Glass façades, specifically, highlighted several technique improvements and optimizations, aiming to cover wide surface often characterized by irregular shapes.

While the "traditional" unitized curtain wall or "stick" systems, for example, typically consists of modular units in which the glass panels are sustained by a metallic frame composed of aluminium transoms and mullions rigidly connected to the structural backup (e.g. concrete slab), cable-supported façades are especially used when large volumes and surfaces must be enclosed. Although firstly built about 20 years ago, due to their transparency, easy constructability and energy savings, the latter solution rapidly propagated in worldwide as a new kind of glazing system. Compared to other steel-glass typologies (e.g. unitized curtain walls), cable-net systems represented for several years a marked evolution of the usual design concepts, since typically associated to high transparency and extreme minimization of the steel supporting systems. The main advantage of cable-net façades is in fact given by the intrinsic stiffness and stability offered by appropriately pre-tensioned stainless steel cables.

In practice, single-way or two-way plane cable nets are typically designed to sustain gravity loads and orthogonal distributed ordinary loads (e.g. wind). In the latter case, the appropriate limitation of out-of-plane deflections due to in-service pressures represents the most critical design goal for these flexible structural systems, since although subjected to often moderate pressures, large deflections could derive from their typical overall dimensions and complex geometries (e.g. New Beijing Poly Plaza Cable-Net Wall (Fig. 1a, [9]), Kempinski Hotel at Munich Airport (Fig. 1b, [10]), etc.).

In this context, numerous authors investigated through numerical, experimental or analytical models the static and dynamic response of cable-net façades in different loading conditions.

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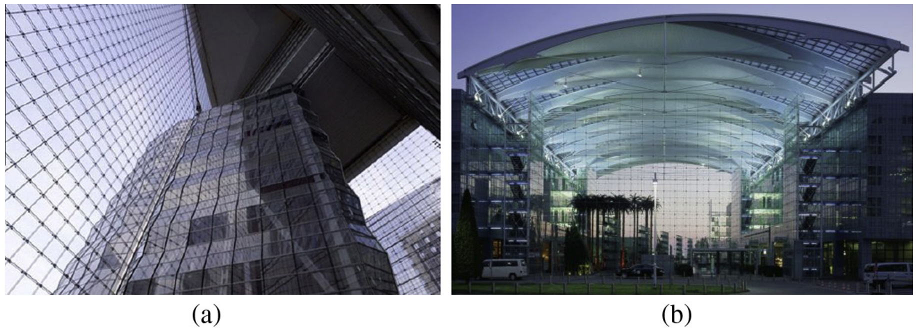

Fig. 1. Examples of two-way straight cable-net façades. (a) New Beijing Poly Plaza Cable-Net Wall [9] and (b) Kempinski Hotel at Munich Airport [10].

Careful attention was paid especially for the study of the interaction between the glass panels and metal connectors [11,12]. Feng et al. [13,14] deeply investigated the behavioural trends of cable-net façades subjected to seismic events. In [15], they also highlighted the effects of glass panels stiffness on the global dynamic response of steel-glass façades, providing critical discussion and comparison of experimental and numerical predictions. Studies presented in [16,17] have been dedicated to the nonlinear behaviour of cable-supported façades under wind loads. Main features and comparative discussion of cable-truss glass façades are proposed in [18].

While extended rigorous investigations are available for steel-glass façades under ordinary loads, further knowledge is currently required to understand and optimize their structural behaviour under exceptional loading conditions. The dynamic behaviour of glazing systems under high-strain rate and impulsive loads such as explosion, for example, still represents a research topic of great interests and a challenge for designers. Wide series of shock tube experiments, analytical investigations and FE numerical studies, in this context, have been dedicated to single laminated glass panels subjected to air blast loads [19–25]. Weggel et al. [26] investigated the dynamic behaviour of unitized curtain walls under low-level explosions. Numerical parametric simulations have been discussed in [27], in order to provide pressure-impulse (PI) design curves for the blast verification of laminated glass curtain walls. Analytical and numerical studies have been recently proposed for the dynamic buckling verification of monolithic and laminated glass beam-like and columns under blast loads [28].

For the specific topic of cable-supported façades, Teich et al. [29] focused on the analysis of the dynamic response of these systems under explosive events, emphasizing the influence of the negative phase of a blast wave pressure on their global structural behaviour. Wellershoff et al. [30] highlighted, through application to the case study of the World Trade Center building, the typical behaviour of a single-way straight cable supported façade under blast loads, suggesting possible mitigation techniques for the limitation of damages and improvement of the expected dynamic performances.

As also highlighted in [31], the design of a blast resisting cable-supported façade strongly differs from the conventional design of a glazing system subjected to ordinary loads. When an explosion occurs, the structural components of a cable-supported façade are in fact affected by exceptional stresses – both compressive and tensile, due to mainly flexural deformations involved by the acting impulsive pressures – and extreme deflections. While glass presents typical high nominal compressive strength, however, maximum tensile stresses should be properly checked and limited, to preserve the façade integrity and avoid brittle failure mechanisms in it.

In that earlier contribution [31], appropriately designed elasto-plastic devices were proposed to be installed at the ends of the vertical bearing cables, in order to prevent their possible brittle collapse under high-strain impulsive loads. The same cable-supported façade – markedly flexible due to the presence of a single layer of pre-stressed straight cables – has been successively further improved [32] by implementation of combined multiple devices, namely consisting in elastoplastic devices at the cables ends and opportune viscoelastic connectors introduced at the connection between the glass panels and the cables [33]. Certainly, under exceptional loading scenarios, the structural dynamic performance of these structural systems should be optimized in order to avoid, or at least minimize, possible injuries and structural damages, hence preserving the activities within the building.

In this paper, based on extended numerical and analytical results of previous literature contributions [31–33], the behavioural trends of a two-way straight cable-net façade subjected to medium-level blast loads are numerically and analytically investigated. In particular, studies are dedicated to the dynamic behaviour of a cable-net façade prototype already analyzed in [15] under seismic events.

Based on [31–33], multiple typologies of dissipative devices are introduced both at the connection between the glass panels and the pretensioned cable-net, as well as at the cable ends.

Modal analyses and nonlinear dynamic incremental simulations are performed on a lumped-mass model (M01), a geometrically detailed cable-glass model (M02) and a further simplified but computationally efficient cable-glass model (M03), able to take into account the bending stiffness contribution of glass panes in the form of equivalent beam elements. Parametric dynamic simulations are then performed, in order to highlight the efficiency and the criticalities of each possible solution.

As shown, by means of appropriate energy dissipating components, the increase of maximum axial forces in the bearing cables and the maximum tensile stresses in the glass panels can be markedly reduced, hence the structural stability of the façade system can be prevented.

2. Structural behaviour of cable-net façades under blast loads

2.1. Cable-net façade layout

In this paper, the cable-net façade recently analyzed under seismic events [15] is numerically investigated to demonstrate the feasibility and potentiality of passive control systems discussed in [31–33] for the mitigation of blast effects on single-way cable-supported façades to high-strain impulsive loads, by application of the same mitigation technique to a two-way planar cable-supported façade. The mentioned glazing system consists, specifically, in a net of pretensioned steel cables, a series of square monolithic glass panels and special clamping joints able to provide appropriate structural interaction between glass and steel