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Assessment of the structural stability of *Blockhaus* timber log-walls under in-plane compression via full-scale buckling experiments

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HIGHLIGHTS

- Full-scale buckling experiments are performed on in-plane compressed timber *Blockhaus* log-haus walls.
- Timber log-haus walls are characterized by high slenderness ratio and low modulus of elasticity.
- The effects of various geometrical aspects on their structural response are experimentally assessed.
- Simple analytical formulations are derived from classical theory of plate and column buckling.

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ABSTRACT

Blockhaus structural systems are obtained by assembling multiple timber logs able to interact with each other by means of simple mechanisms (e.g. contacts, tongues and grooves, and carpentry joints, also referred to as 'corner' joints). Although these systems have ancient origins, the structural behaviour of *Blockhaus* systems under well-defined loading and boundary conditions is still complex to predict. The paper focuses on the assessment of the typical buckling behaviour and resistance of in-plane compressed timber log-walls. The effects of various mechanical and geometrical aspects such as in-plane rigid inter-storey floors, load eccentricities, different types of lateral restraints, openings (e.g. doors or windows) or additional metal stiffeners, are investigated by means of full-scale buckling experiments. Results are then critically discussed and preliminarily assessed via analytical formulations taken from classical theory of plate buckling and column buckling. Although further advanced studies are required for the development of a generalized buckling design method, it is shown that several mechanical and geometrical aspects should be properly taken into account to correctly predict the structural capacity of *Blockhaus* systems under in-plane compression.

1. Introduction

Blockhaus (or log-haus, blockbau, etc.) structural systems represent a technology of ancient origins but used in modern practice for the construction of residential and commercial buildings, generally up to two levels (e.g. [1]). These structures are commonly obtained by assembling multiple timber logs stacked horizontally one upon each other, and the interaction between these basic components is provided by simple mechanisms such as tongues and grooves, carpentry connections, often referred to as 'corner' joints, friction phenomena and contact surfaces. Despite these basic mechanisms, from a practical point of view, currently available standards for the design of timber structures (e.g. [2]) do not provide analytical models for an appropriate verification of these structural systems. As a result, their effective behaviour and load carrying capacity under specific loading and boundary conditions is rather complex to properly predict. Due to the continuous research for aesthetically pleasing solutions in modern architecture, moreover, designers are often required to ensure specific architectural solutions which often contrast with pure structural requirements, hence demanding careful consideration and proper assumptions in calculations.

In the last years, few studies focused on *Blockhaus* structural systems. Experimental and numerical studies were dedicated, for example, to the assessment of the structural behaviour of log-walls under seismic loads [3,4]. These studies emphasized the high flexibility and damping capacity of the examined structural systems, as well as the importance of various mechanical and geometrical aspects on their global behaviour. Static friction experiments were discussed in [5], in order to assess the effectiveness of the possible dissipative mechanisms offered by timber logs in contact, when

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subjected to in-plane lateral actions such as seismic loads. Further preliminary studies [6,7] were also dedicated to the experimental investigation of log-walls under in-plane compressive vertical loads. Buckling may be a design issue as log-walls are typically characterised by high slenderness ratios compared to other structural systems, and low modulus of elasticity as timber is stressed in the perpendicular to the grain direction under gravity load. Buckling phenomena involve a complex interaction between strength and deformation capacities of structural members, and wide series of experimental studies and simplified analytical methods were proposed over the past years for the buckling behaviour of various timber structural systems (e.g. [9–11]). Buckling tests were performed also in [6,7], on (1:4) and (1:1.4) scaled log-walls prototypes, in order to preliminarily assess the resistance of *Blockhaus* structural systems under compression. Simple analytical formulations were also proposed, for an approximate calculation of the corresponding Euler's critical buckling load [7], with the recommended partial safety coefficient being calibrated on safety requirements of DIN standards for timber structures [8]. The experiments discussed in [6,7], however, were carried out on log-walls under mid-span concentrated loads, as well as on log-wall specimens laterally unrestrained at their top log (e.g. fully neglecting the restraint provided by inter-storey floors), hence typically resulting in significant underestimation of the actual buckling capacities.

In this work, based on earlier contributions [6,7], full-scale buckling experiments are performed on five different typologies of *Blockhaus* log-walls under in-plane compression. The five specimens differ for the number and position of door and window openings, as well as for the adopted lateral restraints, the presence of additional metal stiffeners, and the imposed load eccentricity. The major difference from buckling experiments discussed in [6,7], however, is given by the assumption of a more realistic distribution of loads (e.g. uniformly distributed compressive loads, rather than mid-span concentrated loads only) as well as of a restraint condition at the top of the examined log-walls typically associated to the presence of an in-plane rigid inter-storey floor. As highlighted in [12,13] by means of Finite-Element (FE) numerical studies validated on former experimental results [6,7], the presence of in-plane rather than fully flexible inter-storey floors typically provides increased flexural stiffness and, consequently, higher buckling resistance for the examined structural systems. As a result, the effects of this additional top support should be properly assessed and taken into account in calculations.

In this paper, the test results of the five full-scale walls tested under in-plane compression are presented and critically discussed. The test results are then assessed against analytical calculations performed by means of classical formulations derived from plate buckling and column buckling theoretical models [14,15]. The final aim of this on-going research project is the derivation of a generalized design buckling method of practical use for the verification of vertically loaded log-walls having different mechanical and geometrical properties (e.g. log cross-section, size and location of openings, load eccentricities), as well as restraint conditions (e.g. orthogonal log-walls, pillars, in-plane rigid diaphragms, etc.).

2. *Blockhaus* log-walls and structural systems

2.1. Geometrical and mechanical properties

In current practice, the typical $H \times L$ *Blockhaus* log-wall is obtained by assembling a series of spruce logs with strength class C24, according to [16] (e.g. Fig. 1a). These logs, obtained by gluing together two 40 mm-thick lamellas of spruce, are stacked horizontally one upon each other and have typical slender $b \times h$ cross-sections (with height h comprised between 160 mm and 190 mm, thickness b varying from 80 mm and 240 mm, and h/b ratios $\approx$ 1.6–2.4) characterized by small tongues and grooves. These tongues and grooves can have specific shapes, depending on the manufacturer, but their general aim consists in providing interlocking between the upper and lower logs in contact. A vapour-diffusible adhesive able to satisfy requirements of standards [17] is also used to ensure an appropriate structural interaction between the glued lamellas.

Each main log-wall is usually attached to a concrete foundation slab by means of steel angle bracket connectors offering an appropriate resistance against in-plane shear loads (e.g. one angle bracket every $\approx$1.5 m width of wall [4]). The typical angle bracket used in practice by [1], for example, is 3 mm thick, and is joined to the bottom timber log of the main wall and to foundation by means of twelve 4 mm diameter, 60 mm long nails and two M10 metal bolts, respectively. The structural interaction between the so assembled main log-walls and the orthogonal log-walls is then ensured by corner joints (e.g. [4]). Several joint solutions derived from tradition – able to respond to both structural and aesthetic requirements – are often realized in modern *Blockhaus* structures. Independently of their geometrical configuration, however, the general aim of these corner joints consists in providing a full interaction between the intercepting logs, so that all the timber components could behave as a fully coupled structural system, despite the absence of metal connectors among the logs. In *Blockhaus* buildings, moreover, permanent gravity loads are transferred onto each main log-wall to the foundation by inter-storey floors which typically realize an in-plane rigid diaphragm (e.g. by using OSB panels and timber joists, or glulam panels arranged on their edges) able to restrain the out-of plane deflections of the top logs (Fig. 1b).

2.2. Susceptibility of Blockhaus log-walls to buckling phenomena

Compared to other structural systems and walls composed of traditional construction materials (e.g. masonry or concrete), the structural response of timber log-haus walls under in-plane compression and their susceptibility to buckling phenomena has been the subject of little research over the past years [6,7]. Furthermore, no information on the design of log-walls is provided in current design standards of timber structures (e.g. [2]). The very low modulus of elasticity (MOE) of timber in the direction perpendicular to grain $E\perp$ [16] ($\approx$1/100 the compressive MOE of masonry or concrete), together with the usually high H/b ratio of *Blockhaus* log-walls, could lead to premature collapse mechanisms. The limited compressive resistance in the direction perpendicular to grain could also result in local crushing and damage. Careful consideration should then be given to the effects of possible load eccentricities. Although the typical intersection between the main log-walls and the floor joists provides a full interaction between them (Fig. 1b), sometimes – due to architectural requirements – the same joists are interrupted within the log-wall thickness (Fig. 1c).

Since metallic connectors are generally avoided or minimized in *Blockhaus* structural systems, it is clear that the typical log-wall can sustain the vertical loads as far as a minimum level of contact and interaction among the overlapping logs is guaranteed. At the same time, it is expected that the flexural behaviour of in-plane compressed log-walls would manifest limited flexibility and resistance, compared to '*fully monolithic*' timber walls. Finally, further issues could be represented by openings of doors and windows, since involving an interruption of timber logs and further discontinuity among the load carrying components of the investigated structural systems.