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Numerical and analytical assessment of the buckling behaviour of *Blockhaus* log-walls under in-plane compression

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ABSTRACT

Blockhaus structural systems are commonly obtained by assembling multiple timber logs, by stacking them horizontally on the top of one another. Although based on simple mechanisms of ancient origins, the structural behaviour of *Blockhaus* systems under well-defined loading and boundary conditions is complex to predict.

The paper focuses on the assessment of the typical buckling behaviour and resistance of vertically compressed timber log-walls. The effects of various mechanical and geometrical variables such as possible load eccentricities and initial curvatures, openings (e.g. doors or windows), fully flexible or in-plane rigid inter-storey floors are investigated by means of detailed finite-element (FE) numerical models. These FE models were first validated on test results of past buckling experiments performed on scaled log-wall specimens, as well as on recent buckling experiments carried out on full-scale timber log-walls, demonstrating the capability to appropriately describe the effective interaction between timber logs and to correctly predict the expected buckling failure mechanisms and ultimate resistance for the log-walls that were investigated. Comparisons with analytical solutions partly derived from classical theory of plate buckling and column buckling are also presented and critically discussed, in order to assess the applicability of these existing formulations – although specific for fully monolithic and isotropic plates and columns – to *Blockhaus* structural systems. A closed-form solution is finally proposed as a simplified design buckling method for timber log-walls under in-plane compression.

1. Introduction

Blockhaus structural systems represent a construction technology of ancient origins. These structures are commonly obtained by placing a series of timber logs, horizontally on the top of one another, so as to form the walls. The interaction between these basic components is provided by simple mechanisms such as simple corner joints and contact surfaces, in order to reduce the use of metal fastener to a minimum.

Despite the ancient origins, *Blockhaus* systems are currently used in modern residential and commercial buildings. At the same time, currently available standards for the design of timber structures do not provide analytical models for an appropriate verification of these structural systems. As a result, the effective structural behaviour and load carrying capacity under specific loading and boundary conditions is complex to predict.

In the last years, only a few studies have been focused on *Blockhaus* structural systems. In [1–3] numerical and experimental studies were presented to highlight the typical structural behaviour of timber log-walls under in-plane lateral loads, such as seismic loads. These studies emphasized the high flexibility and damping capability of the system. Earlier studies [4,5] presented a preliminary experimental investigation of log-walls under in-plane vertical loads (Table 1). Buckling experiments were performed on scaled log-wall prototypes, in order to assess their effective buckling resistance under in-plane compressive load.

Buckling phenomena and failure mechanisms, as known, involve in structures a complex interaction between strength and deformation capabilities. In this context, a wide series of experimental research studies and simplified analytical methods are proposed for various structural timber typologies – although not specifically related to log-wall systems – in [6–13].

In this investigation, based on these earlier experimental studies [4,5], as well as on further recent full-scale experiments and numerical investigations using ABAQUS/Standard [6], an assessment of the effective buckling resistance of vertically compressed log-walls is presented. Various geometrical configurations of practical interest are analysed, in order to highlight the effect of several geometrical and mechanical parameters (e.g. number and position

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of openings, initial curvatures, load eccentricities, different boundary conditions) on their global behaviour under vertical compressive loads. Numerical predictions are also compared to analytical estimations of simple models derived from literature – both from methods specifically developed for timber log-walls under in plane-compression and from classical theory of plate and column buckling – in order to assess their applicability to the studied systems. The final aim of this research project is the derivation of analytical formulations of practical use for the buckling design and 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 walls, pillars, in-plane rigid diaphragms, etc.).

2. Blockhaus structural systems

In current practice [16], the traditional *Blockhaus* log-wall with height H and length L is obtained by assembling a series of spruce logs with strength class C24 according to [15] (Fig. 1a). These logs typically have cross-sectional dimensions of depth h by breadth b, with the h/b ratio being between 1.6 and 2. 4, and are characterized by small protrusions and tongues that are able to provide interlocking with the upper and lower logs (Fig. 1b). In *Blockhaus* buildings, the structural interaction between the main perpendicular walls is then provided by appropriate corner joints (Fig. 1c and d). Permanent gravity loads are transferred onto each main wall by the inter-storey floors (Fig. 1e), 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 wall top logs.

Since metal connectors are generally avoided or minimized in these structural systems, the typical *Blockhaus* wall can sustain the vertical loads as far as a minimum level of contact among the logs is guaranteed. At the same time, the very low modulus of elasticity (MOE) of timber in the direction perpendicular to grain makes the usually slender (high H/b ratio) *Blockhaus* walls susceptible to buckling phenomena – unlike other squat structural systems such as masonry or concrete walls characterized by higher MOE and lower H/b ratios.

In this context, it should be in fact noticed that the H/b ratio of some log-walls currently manufactured (for example: the walls produced by Rubner Haus AG Spa [16]) has been recently further increased, by replacing the traditional 90 mm × 160 mm 'Tirol' and 130 mm × 160 mm 'Schweiz' cross-sections (dashed line in Fig. 1b) with 80 mm × 190 mm and 120 mm × 190 mm timber log profiles respectively (solid line in Fig. 1b). These variations, in conjunction with possible load eccentricities, particular geometrical configurations (e.g. large size walls with door and window openings close to each other and/or to the lateral ends of the wall) or geometrical imperfections (e.g. initial curvatures) could have significant effects on the load-carrying capacity of the studied log-walls, hence requiring careful consideration in their design and verification.

3. Existing analytical models

3.1. Timber log-walls

Over the last decades, only a few studies have been dedicated to the assessment of the buckling behaviour of timber log-walls under in-plane vertical loads. Heimeshoff and Kneidl [4,5] performed a series of experiments on timber log-walls subjected to concentrated mid-span vertical loads N (Fig. 2). Buckling experiments were carried-out on 28 specimens (16 (1:4)-scaled specimens (series A) and 12 (1:1.4)-scaled specimens (series B), respectively) characterized by various geometrical configurations (e.g. no openings; single door opening; door and window openings).

The typical specimen consisted of a series of overlapping logs made of spruce, laterally restrained at their ends by means of two short orthogonal log-walls working as outriggers (e.g. Fig. 1a) and simply supported at the base. No lateral restraints were introduced at the top log of the main wall (UTL, unrestrained top log), hence suggesting the presence of a fully flexible inter-storey floor enabling possible out-of-plane deformations. Nominal geometrical properties of the tested specimens are schematized in Fig. 2. Buckling experiments on (1:4)-scaled specimens were firstly performed to assess the effects of different timber log cross-sections (e.g. different profiles of grooves along their top and bottom surfaces, Fig. 3a), as well as of small load eccentricities ($e_{load} = 5\text{ mm} \approx b/5$) on the effective buckling resistance of the studied log-walls. Preliminary considerations obtained from this first series of experiments were derived from the experimental measurement of the critical buckling load only. Buckling tests on (1:1.4)-scaled specimens were then performed on selected configurations identified within the first series of experiments. During these additional buckling tests, the transversal displacements of specimens were also continuously monitored at seven control points (Fig. 3b). For specimens with single door opening, the effects of metal profiles introduced along the vertical edges of openings were also assessed (Fig. 3c). As highlighted in [4,5], however, minor resistance improvement was generally found for these specimens, compared to type B02, without metal profiles.

Based on the overall experimental investigation, Heimeshoff and Kneidl also developed simple analytical formulations for the design of log-walls with and without openings, by taking into account the same safety rules of the DIN1052 standard for timber structures [17]. In their theoretical model, the typical log-wall without openings was schematized as a series of horizontal timber logs supported by translational and torsional springs. The buckling

Table 1

Comparison between experimental [4,5], numerical (ABAQUS *eb*) and analytical critical buckling loads $N_{cr,0}^{(E)}$ for specimens without openings, with single door opening or with double door/window openings. (i) Eq. (2); (ii) Eq. (3); (iii) Eq. (4).

Specimen type	No. of openings	Experimental [4,5]		Predicted (UTL)		
		No. of specimens	Average ± St. Dev. (kN)	Numerical *eb* (kN)		Analytical (kN)
				FE-model with outriggers	*FE-model with equivalent boundaries*	
A01	–	4	9.9 ± 1.4	11.1	11.2	5.7$^{(i)}$
A04	–	2	15.1 ± 3.3	15.8	15.9	8.9$^{(i)}$
B01	–	3	202.0 ± 47.3	181.8	182.7	133.6$^{(i)}$
A02	1	4	8.5 ± 1.3	6.0	6.1	3.4$^{(ii)}$
A05	1	2	16.4 ± 1.2	10.8	10.9	5.5$^{(ii)}$
B02	1	3	82.5 ± 9.4	82.1	82.9	48.9$^{(ii)}$
A03	2	4	10.2 ± 2.2	5.8	5.9	2.4$^{(iii)}$
B04	2	3	89.9 ± 6.8	89.2	91.1	37.8$^{(iii)}$