BIOSYSTEMS ENGINEERING 172 (2018) 75–83

Available online at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/issn/15375110

Research Paper

Time-dependent mechanical properties of straw bales for use in construction

Mirko Maraldi [a,*], Luisa Molari [b], Giovanni Molari [a], Nicolò Regazzi [a]

[a] Department of Agricultural and Food Sciences (DISTAL), University of Bologna, Viale G. Fanin 50, 40127 Bologna, Italy

[b] Department of Civil, Chemical, Environmental and Materials Engineering (DICAM), University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

ARTICLE INFO

Article history:
Received 5 March 2018
Received in revised form
17 May 2018
Accepted 30 May 2018

Keywords:
Straw bale
Creep
Relaxation
Cyclic loading
Stretched exponential law

Straw bale construction is a building technique with low environmental impact that has been gaining popularity over the last few decades. The aim of the paper is to contribute to the assessment of the potential of straw bales as a building material by measuring their dynamic mechanical properties and by modelling their response in time to mechanical load. To this end, relaxation tests, creep tests and tests with cyclic loads were performed on small prismatic straw bales at different loading levels. Data were fitted using different models: power models for cyclic load data and stretched exponential models for creep and relaxation data. Results show that bales exhibit a viscous-type response; the models used for data fitting predict that straw bales eventually settle to an asymptotic value of displacement in case of creep and of force in case of relaxation. Under cyclic loading, straw bales can dissipate energy; such capability, as well as the elastic performance of straw bales, decreases as cyclic loading continues, but can be retrieved after some time of resting from loading. A comparison between the creep performance of straw bales and that of conventional building materials showed that, in this respect, straw bales perform on average in a similar manner to masonry brickwork.

1. Introduction

Straw bale construction is a building technique that has been arousing interest all over the world in the last decades (Ashour, 2003). It offers many advantages over conventional building techniques: i) the impact on the environment is dramatically reduced (Singh et al., 2017); ii) since straw bale walls are lightweight and straw bales have an hysteretic behaviour under compression, the seismic performance of buildings constructed using straw bales is excellent; iii) straw bale buildings have superior thermal and acoustic insulation; iv) building costs can, potentially, be much lower; v) since straw is typically sourced from areas near the construction site and buildings can be self-constructed, building with this technique can strengthen social cohesion and the link between the territory and its inhabitants.

Knowing the mechanical properties of the straw bales can sensibly boost the adoption of these techniques (Goodhew, Carfrae & De Wilde, 2010). Straw bales static mechanical properties have been quite extensively studied (Bou-Ali, 1993; Brojan & Clouston, 2014; Garas, Allam, El Kady, & El Alfy, 2009;

* Corresponding author.
E-mail address: maraldi.mirko@gmail.com (M. Maraldi).
https://doi.org/10.1016/j.biosystemseng.2018.05.014
1537-5110/

Nomenclature

E	straw bale mean tangent modulus, kPa
E_∞	asymptotic value of mean tangent modulus, kPa
F	vertical force acting on straw bale, kN
F_0	initial value of force for relaxation tests, kN
F_∞	asymptotic value of force during relaxation, kN
H_0	straw bale initial height, mm
K	energy dissipated per cycle, J
K_∞	asymptotic value of energy dissipation, J
L_0	straw bale initial length, mm
W_0	straw bale initial width, mm
b_C	creep exponent, –
b_E	elastic degradation exponent, –
b_k	hysteretic exponent, –
b_R	relaxation exponent, –
n	number of loading cycles, –
t	time, h
u	straw bale vertical displacement, mm
u_∞	asymptotic value of displacement during creep, mm
ΔE	drop in bale tangent modulus during cyclic loading, kPa
ΔF	force drop during relaxation, kN
ΔK	drop in dissipation performance, J
$\Delta\varepsilon$	strain amplitude during cyclic loading, –
$\Delta\sigma$	force drop during relaxation, kPa
ε	vertical strain, –
ε_0	initial elastic strain for creep tests, –
ε_∞	asymptotic value of strain during creep, –
ε_{mean}	mean vertical strain during cyclic loading, –
σ	vertical stress, kPa
σ_0	initial value of stress for relaxation tests, kPa
σ_∞	asymptotic value of force during relaxation, kPa
τ_C	creep time, s
τ_R	relaxation time, s
$\varphi_{(\infty,0)}$	creep coefficient, –

King, 2003; Lecompte & Le Duigou, 2017; Maraldi, Molari, Regazzi, & Molari, 2016, 2017; Vardy & MacDougall, 2013; Zhang, 2000; Watts, Wilkie, Thompson & Corson, 1995). On the other hand, only few studies have addressed the dynamic mechanical properties of straw bales.

Zhang (2000) performed a 3-cycles compression test on small prismatic straw bales; in the published report of the results, the frequency of the cycles is not provided and it appears that the cycles reach neither the same maximum deformation nor the same load amplitude. From the tests, it was concluded that low-frequency cyclic loading had no significant impact on the load resistance properties of straw bales and that there is a viscous-type recovery of the deformation as the straw bale is unloaded (i.e. rebound).

The most complete studies on the time-dependent behaviour of straw bales subjected to compressive loads are those by Krick (2008) and by Danielewicz et al. (2008). Krick performed cyclic tests as well as creep and relaxation tests on straw bales made of different materials. Three different stages in the stress relaxation/creep curve were identified: a rapid decrease of the stress/strain in the first minutes after the application of the load, followed by a progressive flattening of the curve and, at long time, an almost steady-state in which stress/strain does not change in time. Krick also investigated the influence of different parameters like the dry density, the straw species, the orientation of the bale and the plaster on bales behaviour. The conclusion was that there is a relation between the load level and the relaxation/creep response, while there was no apparent influence of the density and of the straw species. Similar results were obtained by Danielewicz et al. (2008) on prismatic jumbo rye bales. No modelling of the energy dissipation properties or of the time-response of the bales was provided in their studies.

Smith (2003) presented the results of a study on the creep behaviour of straw bale walls subjected to vertical loads over a 12-months period. For all the tested walls (7 unplastered) except one, no noticeable additional creep was found after 10 weeks.

These studies show that the response of straw bales to loading is time-dependent. Investigating the dynamic behaviour of straw bales under dynamic load conditions is of paramount importance in order to predict the response of straw bale structures to potentially dangerous situations such as earthquakes. In these circumstances, plaster coating may fail and the straw bales may be required to carry all the mechanical load and act as a "surviving cell". Understanding the behaviour of straw bales under prolonged compressive loads could also contribute to shed light on a debated point in the straw bale builders community, i.e. how much compression, and at which stage of the construction process, has to be provided to a straw bale wall in order to avoid plaster cracking after a wall has been rendered. The aim of the paper is to contribute to the assessment of the potential of straw bales as a building material by extending the knowledge on their dynamic mechanical properties.

2. Material and methods

2.1. *Bales sourcing and preliminary measurements*

A total of 26 small prismatic two-string bales were tested. Straw came from the farm of the University of Bologna, Italy and was baled using a commercial Gallignani 146 Special baler supplied by a local farmer in Bologna. Bales were stored outdoors in a shed for several months and then in the laboratory for at least a couple of days before testing. Wet basis moisture was checked before each bale was tested and was found to be <18% for all the bales. Tests were conducted at room temperature.

2.2. *Cyclic tests*

2.2.1. *Experimental setup and test procedure*

Cyclic tests were performed on two-strings small prismatic wheat bales (average length 1121 mm, width 504 mm, height 384 mm and density 100 kg m^{-3}) using the custom-made test rig depicted in Fig. 1a. Loading was provided by means of a single ended hydraulic actuator (MTS Systems Corp., MN,