Available online at www.sciencedirect.com

ScienceDirect

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

Research Paper

Analysis of the parameters affecting the mechanical behaviour of straw bales under compression

Mirko Maraldi [a,*], Luisa Molari [b], Nicolò Regazzi [a], Giovanni Molari [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, 40127 Bologna, Italy

ARTICLE INFO

Article history:
Received 27 January 2017
Received in revised form
28 May 2017
Accepted 12 June 2017
Published online 29 June 2017

Keywords:
Straw bales
Mechanical properties
Bales density
Poisson's ratio
Strings strain

Straw bale construction is a building technique that has excellent thermal performance and limited impact on the environment. Improving knowledge of the mechanical properties of straw bales is important to understand the behaviour of straw bale buildings, especially in case of natural calamities, where straw bales may carry mechanical load and act as a "surviving cell". The results of extensive tests conducted on bales of different materials are presented. The influence of the material, bale density, bale orientation, baling process and loading rate on the mechanical properties of straw bales was investigated. Force-displacement curves obtained from monotonic compression tests were analysed and relationships between the mechanical properties of straw bales and their geometry and density were determined. Continuous measurements of bales lateral displacement allowed Poisson's ratio to be calculated and, using a simple model, the strain to which bale strings are subjected during loading was estimated. Young's modulus was shown to mainly depend on the square of the density, while no influence of the loading rate and of strings pre-tension was observed. The Poisson's ratio did not remain constant during loading and it exhibited a different trend depending on the orientation of the bales. Moreover, it was observed that for flat bales a rearrangement of the straw fibres during loading occured and the maximum strings strain remained limited. Strings strain reached higher values for on-edge bales instead, and strings bursts occured more frequently.

1. Introduction

Straw bale construction is one of the most popular sustainable building techniques since it ensures excellent thermal insulation and great breathability on a lightweight structure that has good mechanical properties (Conti, Barbari, & Monti, 2016; Costes et al., 2017). A clear understanding of the behaviour of a straw bale construction cannot be separated from a deep understanding of the behaviour of straw bales

* Corresponding author.
E-mail address: maraldi.mirko@gmail.com (M. Maraldi).

http://dx.doi.org/10.1016/j.biosystemseng.2017.06.007

Nomenclature

P	Vertical force acting on the bale [N]
u	Vertical displacement [m]
C	Bale's elastic compliance [m N^{-1}]
u_l	Asymptotic displacement [cm]
P_t	Linear–nonlinear transition force [N]
ρ	Bale density [kg m^{-3}]
H_0	Bale initial height [mm]
L_0	Bale initial length [mm]
W_0	Bale initial width [mm]
σ	Vertical stress [kPa]
ε_V	Vertical strain
E	Young's modulus [Pa]
ν	Poisson's ratio along the longitudinal direction
ν_{max}	Maximum value of the Poisson's ratio
ν_{rate}	Rate of change in the Poisson's ratio
ε_{string}	Strings strain
V_{press}	Loading rate [mm min^{-1}]
V_L	Lower value of the loading rate [mm min^{-1}]
V_M	Medium value of the loading rate [mm min^{-1}]
V_H	Higher value of the loading rate [mm min^{-1}]

themselves. In practical applications, the wall of a straw bale building can be considered as a composite material consisting of straw bales plus the inner and outer plaster skins. Although plaster skins are the stiffer elements in the construction, and carry almost all the load, in case of failure of the plaster (due to different causes, earthquakes included), the straw bales are required to sustain the load that under normal conditions would be carried by the plaster. Understanding and predicting this post-calamity behaviour of a straw bale building is therefore of paramount importance. Moreover, straw bales are pre-compressed before being plastered and it is not clear if this practice is beneficial for the structure and what is the optimal level of pre-compression that has to be provided. For these reasons, the behaviour of single unplastered straw bales is worth investigating. The determination of the mechanical properties of unplastered straw bales is also a necessary step to set up theoretical models able to effectively predict the behaviour of straw bales constructions and assist designers and builders in their practice.

Over the last few decades, some works on the mechanical response of straw bales have been reported, albeit the behaviour of single unplastered straw bales has not been investigated exhaustively. The first work that appeared in the literature was that by Bou-Ali (1993). Bou-Ali performed compression tests on wheat bales laid both flat and on-edge and estimated the Poisson's ratio along the longitudinal direction. Results show that bales laid flat exhibit a stiffening behaviour and that bales with a higher density were stiffer. Bou-Ali also observed that bales recovered almost all their deformation upon load removal - a phenomenon called “rebound”. Later, Vardy and MacDougall (2013) performed tests on one wheat bale laid flat and one on-edge; results confirm the stiffening behaviour for flat bales, while the on-edge bale behaved linearly.

Thompson et al. (1995) performed compression tests on wheat, oat and barley straw bales laid flat. They found that the mechanical behaviour is more influenced by the bale density than by the kind of straw used; they also found that the stiffness of the bale depends on its moisture content. Similarly, Ashour (2003) presented the results of compression tests performed on wheat and barley straw bales laid both flat and on-edge and found that wheat bales are stiffer than barley bales; Ashour also found that bales with a higher density are stiffer. Notably, the stress–strain diagram does not show any stiffening in the case of wheat bales; only barley bales laid flat appear to exhibit a stiffening behaviour. This may be due to the fact that the maximum stress in these tests was low.

Compression tests were performed by Zhang (2000) and Brojan and Clouston (2014) on flat and on-edge straw bales and they found a non-linear stress–strain behaviour. Four stages for straw bales compression were identified and an explanation for the mechanical behaviour of bales laid flat was proposed by Zhang (2000). Zhang also performed a cyclic test in which a straw bale was subjected to three complete loading and unloading cycles, although neither the maximum stress on the bale nor the maximum bale deformation were kept constant from cycle to cycle.

Krick (2008) performed compression tests, cyclic tests as well as creep and relaxation tests using wheat, barley, spelt, switchgrass and rye straw bales. Results show that the stiffness of a bale under compression is proportional to its density. In the same year, a report of a study promoted by the German straw bale building association (FASBA) appeared in which the results of a series of tests similar to those described by Krick (2008) were presented (Danielewicz et al., 2008); tests were conducted using big rye straw bales. The relaxation and creep tests showed that the straw bales response is time-dependent, but compression tests performed at different loading rate showed no difference in the stress–strain response.

Results of compression tests performed on flat rice straw bales were reported by Garas, Allam, Kady, and El Alfy (2009); the bales used in the study were produced using two different balers and a closed die press. Unlike all the other studies that have appeared in the literature to date, they found that their bales exhibited a softening behaviour. More recently, Lecompte and Le Duigou (2017) performed compression tests on two different batches of wheat straw bales obtained using two different balers. Results were presented in terms of true stress and true strain, starting from force and displacement measurements under the hypothesis that the perimeter wrapped by the strings remains constant both for flat and on-edge bales. They found that the mechanical behaviour of their straw bales was non-linear and that, for densities in the range 90–110 kg m^{-3}, the Young's modulus of the bales at low stress was independent of the bale orientation and depended on the ratio between straw bulk density and bale density. For low values of the bale density, they found that the Young's modulus at low stress depends also on bale orientation.

Overall, all the studies to date have agreed that bale stiffness depends on its density; however, it is not completely clear whether the straw material can have an influence on the stiffness and whether the mechanical response of straw bales has to be considered as linear or non-linear. Furthermore, in many of the studies performed, the number of specimens tested has been limited (Table 1); consequently, the range of the conclusions that could safely be drawn is