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Research Paper

Method for the characterisation of the mechanical behaviour of straw bales

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The use of straw bale construction is strongly on the rise. Despite the need for a deep understanding of the mechanical behaviour of straw bales, there is little research on the testing of single unplastered straw bales and a standard test method does not exist. In this paper, a method able to evaluate the mechanical behaviour of single straw bales is proposed. Force and displacement of the bale in all the three directions was measured in real time without stopping the test; this allowed to best deal with the time-dependent nature of the mechanical behaviour of the bales to be. The test apparatus included a hydraulic press for loading plus digital cameras and a 3D laser scanner for measuring the lateral displacement of the bale. The method was validated by testing six rice bales (three bales laid flat and three on-edge). Results showed that there is no significant difference in the elastic modulus between flat and on-edge orientations. For on-edge bales, string burst was observed, whereas for flat bales no string failure occurred. By using digital image correlation it was observed that straw bales exhibit a typical deformation pattern which is due to the baling process. Measurements also showed that the Poisson's ratio does not remain constant along the longitudinal direction during loading and it is null along the transverse direction. The proposed method can be implemented to evaluate the influence of a variety of parameters and loading conditions on straw bales mechanical response.

1. Introduction

Straw bale construction is a building technique that has been arousing interest all over the world in the last decades. This is due to a number of factors: the technique has a limited impact on the environment; straw has excellent thermal insulation capabilities, great breathability, fire resistance and good mechanical properties; straw bale buildings are light-weight; and building cost can potentially be lower with respect to traditional techniques.

Research addressing the mechanical behaviour of straw bales at different scales has appeared in the literature (Bou Ali, 1993; Carrick & Glassford, 1998; King, 2003; Rakowski, 2010;

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Nomenclature

F	Force exerted by the hydraulic actuator, [N]
H_0	Bale initial height, [mm]
L_0	Bale initial length, [mm]
W_0	Bale initial width. [mm]
u	Vertical displacement, [mm]
u_X	Horizontal displacement on one face of the bale, [mm]
u_Y	Vertical displacement on one face of the bale, [mm]
X_i	Horizontal position of marker i, [mm]
ε_L	Longitudinal strain
ε_V	Vertical strain
ε_{XX}	Horizontal strain on one face of the bale
ε_{YY}	Vertical strain on one face of the bale
ε_{XY}	Shear strain on one face of the bale
ν	Poisson's ratio along the longitudinal direction
σ	Vertical stress, [kPa]

Vardy & MacDougall, 2013; Walker & Ay, 2004). In a straw bale building, the elemental unit can be considered as a composite material consisting of the straw bales and the inner and outer plaster skins. In order to understand and to model the behaviour of the whole composite structure, the properties of all the constituting elements should be known. Moreover, in case of the failure of the plaster skins (due to a variety of causes, including earthquakes) straw bales can act as the "surviving cell". Hence, determining the properties of single unplastered straw bales is the first step towards understanding the post-calamity behaviour of a straw bale building. Nevertheless, to date very few studies have focused on single unplastered straw bales.

The first work reporting the results on tests conducted on single unplastered straw bales was that by Bou Ali (1993), who performed compression tests on wheat bales laid both flat and on-edge. Bales were compressed using a screw-type universal testing machine that was modified with two wooden plates and four steel I-beams on the top of the plates to enable pressure to be evenly applied to the surface of the bales. For all the tested bales, load-deflection and stress–strain curves were obtained. Poisson's ratio was estimated by measuring the bales longitudinal strain. However, details of how longitudinal deformation was measured were not provided.

Zhang (2000) presented the results of compression tests performed on straw bales laid both flat and on-edge. Compressive tests were carried out using a universal testing machine with a rigid top load plate reinforced with timber ribs. A digital deformation meter was used to read the vertical displacement during the tests. Load was applied as a series of steps of 0.5–2 kN of amplitude up to a maximum value, and for each load increment the test was stopped and a deformation reading was taken.

Ashour (2003) presented the results of compression tests performed on wheat and barley straw bales laid both flat and on-edge. Bales were initially compressed with a 200 kg load, then load increments of 100 kg were applied until the maximum load of 1000 kg. At each step the loading device was stopped and bale dimensions were measured. Stress, horizontal (lateral) strain and vertical strain were recorded; modulus of elasticity and Poisson's ratio were also determined.

Krick (2008) presented the results of a series of tests conducted on a variety of straw bales, made from wheat, barley, spelt, switchgrass and rye straw. The results of compression tests, cyclic, creep and relaxation tests were reported. Tests were performed using custom-designed devices for the creep and relaxation tests and a properly modified ultimate testing machine for the other tests.

Vardy (2009) presented the results of compression tests conducted on two wheat bales, one laid flat and one laid on-edge. Load was applied at a constant rate using a ultimate testing machine which had plywood load plates combined with steel beams and wood braces to ensure even load distribution and vertical displacement was recorded using four linear potentiometers. Similar tests were performed by (Garas, Allam, El Kady, & El Alfy, 2009) on straw rice bales using a 100 t hydraulic actuator with a wooden frame manufactured with a rigid round top. Vertical displacement was measured using two linear potentiometers connected to a data acquisition system.

More recently, Brojan and Clouston (2014) reported the results of compression tests performed on rye straw bales laid both flat and on-edge using a 150 kN ultimate testing machine. Bales were loaded at a constant rate, and load and vertical displacement were recorded in real time.

Overall, it emerges that a standard method able to accurately determine the mechanical properties of straw bales has not been developed yet. Only few studies (Ashour, 2003; Bou Ali, 1993; Krick, 2008) have reported measurements of straw bales Poisson's ratio along the longitudinal direction, while no studies have provided details on the Poisson's ratio in the transverse direction. In this paper, a test methodology able to determine the mechanical behaviour of single unplastered straw bales is proposed and the results of validation tests on six two-strings rice straw bales are presented. The method allows the overall stress–strain behaviour and the lateral deformation in both the longitudinal and the transverse direction to be measured in real time and without stopping the test to perform the measurements.

2. Material and methods

2.1. *Determination of the mechanical properties*

A hydraulic press has been used for the tests. The press consisted of an MTS 243.35T single ended hydraulic actuator (MTS Systems Corp., MN, USA) mounted on a custom-made frame (Fig. 1). The actuator stroke length is 508 mm. An ad-hoc steel top plate was designed to compress the bale (TP in Fig. 1; dimensions: 1200 mm × 600 mm). The press has been controlled through a Model 407 PIDF servo controller (MTS Systems Corp., MN, USA) from which the loading rate, the loading path and the final load were set.