Mechanical Characterization of Straw Bales for Use in Construction

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Abstract. From the point of view of environmental awareness, construction sustainability is a theme that is gaining considerable attention. This has brought to a re-discovery of the use of straw as a construction material, a technology that has been widely used in the past centuries. Straw is a natural material having excellent insulating capabilities, considerable mechanical properties when packed in bales and is relatively low cost (it is indeed a by-product of farming activity). Two are the techniques adopted in straw bale construction: post-and-beam, where the load is sustained by a wooden frame and straw bales are used merely as infill material; and load-bearing, where the entire load is sustained by the plastered straw bale walls. Especially regarding the latter technique, there is a need for a deeper understanding of the mechanical properties of straw bales. The characterization of the material is made difficult by the variability brought about by the variety of plants from which straw can be obtained, unpredictability of the baling process, moisture content in the bale and other parameters. Moreover, there is not a standard regulating the productive chain of straw bales to be used for construction. In this paper, a literature review on the tests performed on single unplastered straw bales is conducted and, based on this, some ideas are proposed for the development of a model describing the mechanical behavior of straw bales.

Introduction

In the past, straw has been extensively used as a construction material, mainly mixed with earth: traces of straw have been found in adobe bricks in Jericho dated 8300 BC \cite{1}. In the modern era, the oldest known constructions are those built in the Sand Hill region in Nebraska at the end of the 19\textsuperscript{th} century; here, straw bales have been used which were produced with horse-powered balers. After that, construction techniques employing straw sank into oblivion until the 80’s, when their potential was re-appreciated. Straw bale buildings offer many advantages over those built using conventional techniques, namely:

- superior thermal insulation, which makes the idea of “passive houses” feasible
- reduced building costs: the reduction amounts to 50\% - 75\% on walls costs and to 10\% - 15\% on the total costs, since walling contributes approximately to the 20\% of the overall building cost
- increased resistance to earthquakes due to: a) the reduced density of straw bales with respect to conventional materials which translates into lightweight walls; b) the energy dissipation properties of straw bales. This aspect makes straw bale buildings suitable for areas at high risk of earthquakes; as an example, straw bales have been used for the construction, in 2004, of “Casa Mary Jane”, located in Managua, Nicaragua \cite{2}
- establishment of a link with the surrounding territory: straw is typically sourced from areas near the construction site; this fact helps strengthen the relation between the construction and its surroundings and contributes to increase the awareness of the territory and its roots
- little impact on the environment: not only using straw bales avoids the production of
emissions related to the manufacturing of conventional construction materials, but it also avoids, or at least postpones for the life-cycle of the building, the emissions due to straw burning.

Straw is a by-product of agricultural activity; it is usually baled and stored to be used as a bedding material for livestock housing. However, this use does not absorb the entire availability of straw and the remaining amounts are buried or, where local regulations still allow it, burnt. The practice of burning straw has obviously a negative impact on the environment, since a considerable amount of CO₂ and other pollutants is produced and released in a short time. For this reason, finding new uses for straw can be extremely beneficial to the environment. The percentage of straw burnt in Italy in 2008 is listed in Table 1.

<table>
<thead>
<tr>
<th>Plant</th>
<th>Overall Qty [x 10⁶ kg d.m.]</th>
<th>Burnt</th>
<th>Conventional uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wheat</td>
<td>2100</td>
<td>30% - 40%</td>
<td>Bedding, animal feeding, paper industry</td>
</tr>
<tr>
<td>Barley</td>
<td>380</td>
<td>50% - 60%</td>
<td>Bedding</td>
</tr>
<tr>
<td>Oat</td>
<td>120</td>
<td>40% - 60%</td>
<td>Bedding</td>
</tr>
<tr>
<td>Rice</td>
<td>550</td>
<td>70% - 80%</td>
<td>Bedding</td>
</tr>
</tbody>
</table>

Table 1. Straw availability and amount burnt for different types of plants. Estimations for 2008 [3].

Although the data presented refer only to Italy, the scenario they depict is significant and worth mentioning. Wheat is the plant whose straw is most used (for bedding and paper industry); however the quantity produced is so high that the total amount of burnt straw is relevant. Table 1 shows also that roughly half of the straw obtained from barley and oat is burnt and that, as it regards to rice, most of the straw produced is burnt.

The Development of Standards and Deeper Understanding of the Material Behavior. Provided all the aforementioned advantages of straw bale construction over conventional methods, another factor that could be beneficial to spread this construction technique could be the development of suitable design codes. Some countries (like the United States) have already adopted standards for straw bale construction, while other countries still do not have standards especially with regard to the use of the “Nebraska style” technique (a technique employing load bearing walls, without a structural frame). Furthermore, the achievement of a deep understanding of the behavior of straw bales when used as walling material could provide a solid, reliable basis for the spread and the development of straw bale construction. To this end, the following section reports a critical analysis of the state of the art in terms of experimental and theoretical research on the mechanical behavior of straw bales; in the third section, a review of some fundamental work on the production of wafers/briquettes by pressing fibrous agricultural materials is presented which can give insights into the modeling of straw bales behavior; the fourth section contains some physically-based ideas for the development of a mathematical model that can capture the main features exhibited by a straw bale under compression. At the end of the paper, some conclusions are drawn.

Understanding the Mechanical Behavior of Straw Bales: the State of the Art
Since the re-discovery of straw bales as a construction material, some papers addressing their mechanical behavior under compression have appeared in the literature. Some of them deal with entire plastered walls, some others with single plastered bales and some are concerned just with the behavior of single unplastered straw bales.

With regard to this latter group, the 1993 seminal paper by Bou Ali [4] presents the results of a compression test on 3-strings wheat bales; one bale was tested flat (i.e. with the straw fibers oriented horizontally), while another bale was tested on-edge (i.e. with the straw fibers oriented vertically). The relevance of this publication lies with the fact that it is the first known work that
discusses the results of a straw bale compression test. Despite this, it can be observed that only one bale was compressed for each test, hence the reproducibility of the obtained results was not verified; moreover, it does not appear clear how the values of stress reported were calculated, since they are not consistent with the values of force and bale cross section measured during the experiment. Other similar experiments are reported in the literature, the results of which, however, can be accessed only in few cases. This is a limitation for the research in this field, since only in few cases the results obtained by the authors of these works can be compared and used for other purposes like the development of theoretical models. More recently, Garas and co-workers [5] performed compression tests on rice straw bales pressed to different values of density by using three different kind of balers. They determined which type of baler gives the best results in terms of reproducibility of the geometrical features of the bales and of the force-displacement response, and provide force-displacement curves for each case. The straw bale behavior appears to be that of a softening material. Zhang [6] conducted compression tests on 2-string straw bales (straw material not specified) both flat and on-edge. The tests revealed a multi-stage behavior of straw bales under compression: an initial hardening stage is followed by a softening one and another hardening stage; this result is reported by other authors [6, 7], while is in contrast with the monotonic behavior obtained by others \([5, 8]\). In addition, Zhang performed a test in which the bales were subjected to a 3-cycles loading; despite the fact that the frequency of the cycles is not provided and that apparently the cycles reach neither the same maximum deformation nor the same load amplitude, this test represents an acknowledgement of the fact that understanding the behavior of straw bales under dynamic loading is also important. Vardy [8] conducted a thorough experimental campaign on the subject, testing both plastered and unplastered straw bales and straw bale walls under concentric and eccentric loads. As it regards single, unplastered straw bales, he performed tests on 2-strings wheat bales laid flat and on-edge; the bales were stored at constant temperature and humidity and a rig for obtaining bales with the same dimensions was designed and used. Notwithstanding the fact that only one bale per experiment was used, Vardy obtains a monotonic hardening behavior for the flat bale, while an almost linear behavior for the bales on-edge. This is in contrast with the aforementioned results obtained both by Zhang and by Garas and co-workers and demonstrates that a deeper understanding of the origins of such variable results is needed. Nevertheless, the work by Vardy goes in the direction of providing guidance for making compression tests on straw bales replicable and represents, from this point of view, a significant improvement over the papers previously appeared in the literature. Along this line, Danielewicz and co-workers [9] produced a technical report, in which they presented the results of a wide variety of tests on straw bales, including creep and relaxation tests. To our knowledge, this is the only publication presenting the results of time-dependent tests performed on straw bales. Its importance lies with the fact that the viscoelastic behavior of straw bales is acknowledged. Overall, it can be observed that in many of the works appeared so far in the literature, the number of specimens used in the tests was little; the result is that the reliability of such results cannot be verified in depth and the variability in the behavior of the material cannot be clearly quantified. Moreover, only few authors have conducted tests on straw bales subjected to dynamic loading; nevertheless, investigating the material behavior under these conditions is of paramount importance in order to predict the response of straw bale structures to potentially dangerous situations like earthquakes. More work on this aspects is needed, thus.

**Critical analysis of state of the art of straw bale modeling**

So far, few authors have attempted to explicitly model the mechanical behavior of single straw bales. Most of them, in explaining the behavior of straw bales under compression, make implicit use of a linear elastic model, in that they attempt to give a range of variability of the Young’s modulus
along the stress-strain curve depicting the response of the material. However, straw bales behavior is highly nonlinear and non-elastic and a modelization in terms of the Young’s modulus only is not satisfactory, since it does not capture all the relevant rheological aspects of the problem. Indeed, the high nonlinearity of the material response can be appreciated in Fig. 1, where the stress-strain curves obtained by the experiments performed by Zhang [6] and Vardy [8] on bales loaded both flat and on-edge are depicted. Besides, the variability in the data available in the literature is evident from Fig. 1; the source of such variability has not been completely clarified yet, and certainly this aspect deserves deeper investigations.

Vardy [8] provided a modelization of the composite sandwich structure constituted by the straw bale and the plaster coatings on the two lateral faces of the bale. In his work, a comparison between the stiffness of the straw bale and that of the coatings is provided and, based on the fact that the straw bale is far more compliant than the plaster, it is concluded that the straw bale contribution to the mechanical behavior of a load-bearing straw bale wall is almost negligible. However, Vardy’s analysis did not consider the following two aspects:

i. straw bales are pre-compressed before being plastered
ii. the roof is in many cases placed before the plaster is applied to the wall

An accurate analysis of the mechanical behavior of a straw bale wall structure has to account for the fact that one of its constitutive elements is pre-compressed and, more important, that the load of the roof is entirely sustained by the straw bales; the structure formed by the straw bales and the plaster behaves as a composite sandwich only with respect to the “accidental loads”, i.e. the loads other than the roof. Based on this consideration, the contribution of straw bales to the behavior of the walls cannot be neglected.

The response of straw bales to compressive loads is essentially non-linear, inelastic and time-dependent. So far, no modeling of the mechanics of straw bales have accounted for this and, from the experimental point of view, only few papers have investigated the time-dependent response of straw bales [6, 9]. These studies can be a starting point for the development of a rheological model of straw bales behavior, albeit the topic deserves a deeper investigation from both the theoretical and the experimental point of view.
Mechanical Behavior of Fibrous Materials during Wafering/Briquetting Processes

The idea of modeling the rheology of straw bales accounting for non-linearities, time-dependent and inelastic phenomena is not new: a similar approach has been followed in the past for the modeling of processes like wafering, pelleting and briquetting, i.e. processes in which fibrous materials are compacted by being pressed into a closed die. Eventually, rheological models have also been applied for the determination of the pressure distribution inside the compression chamber of square balers [10].

Many are the similarities between these compaction processes and the compression of a straw bale; in both cases straw is the material employed, to which a compacting load is applied. From the microscopic point of view, in both cases stalks will deform elastically, will move relatively to each other inhibited by internal frictional forces and, eventually, can collapse (crushing). Moreover, when the material is compacted, air must flow out of the voids.

Nevertheless, there certainly are differences between straw bales compression and compaction processes: in the latter, the material under compression is confined in a rigid-wall chamber, while during compression of a straw bale only the strings constrain to some extent the lateral expansion of the material; in wafering, pelleting and briquetting the material is initially loose and then is packed into a coherent form, whereas straw bales always appear in a coherent form; in straw bales, the stalks are generally long and have a preferential orientation which cannot always be found in the material undergoing a compaction process; straw can be chopped or ground for compacting purposes, hence the microscopic texture of wafers, pellets and briquettes can be much finer that that of a straw bale. Moreover, the maximum value of the axial load on the briquette samples can be some order of magnitude higher with respect to the typical compression load on a straw bale; as a result, some chemo-mechanical processes can be activated during fibrous material compaction but not during straw bales compression.

Some authors proposed compression-ratio models to determine a relation between the compression pressure and the density of the sample (see the work by O’Dogherty [11] and that by Fabolore and O’Callaghan [12] for a review of these models); these kind of models appear useful for capturing the initial phase of the compacting process, where the material is loose and the compression of the air in the chamber is the dominating phenomenon.

Other authors have attempted to model the behavior of the material under compaction using a variety of rheological models: Kelvin models [13], Generalized Maxwell models [14] and Burgess models [15] among others.

Notably, Peleg [16] proposed a non-linear viscoplastic model comprising a nonlinear elastic element in series with another element constituted by a viscous damper, a second elastic element and a Coulomb damper. The Coulomb damper accounts for the internal friction of the stalks moving across each others, while the viscous damper is responsible for the time-dependent behavior and the elastic elements introduce nonlinearities in the model. Despite the fact that the adoption of nonlinear elastic elements is not clearly linked to any microscopic phenomena occurring in the compression of fibrous materials and that a constraining relation between the two elastic elements is assumed without any rigorous justifications, the model is relatively simple yet it captures many of the features of the processes it intends to describe.

The Peleg model appears useful also for the description of the mechanical behavior of straw bales under compression, albeit the origin of the nonlinearities in straw bales response needs to be further investigated and represented in a more consistent way in the model.

Rheological Modeling of Straw Bales

In modeling the mechanical behavior of straw bales under compression, the peculiarities of the straw bale response have to be taken into account. As mentioned above, any hardening and/or softening effects have to be given a solid physical basis to be consistently incorporated in a rheological model; conversely, the development of a rheological model can shed light on what the physical basis for such a behavior is.
The deformation of the bale is the combination of contributions of different nature, namely:
- elastic contribution, due to the elastic deformation of single stalks
- viscous, time dependent deformation, primarily arising from the fact that when straw is compacted, voids are closed and the air filling them has to flow out of the bale; also when stalks undergo elastic return upon unloading this process is active, since air has to flow back in and fill the voids created
- permanent deformation: nesting of stalks occurs when the straw bale is compressed; since the nesting stalks move past each other, internal friction dissipates energy
- permanent deformation due to crushing of stalks: upon loading, when the load on a stalk exceeds a critical value, the stalk collapses; this mechanism is thought not to contribute a lot on the overall permanent deformation of a straw bale, since many stalks are already crushed when a straw bale is produced.

It has also to be considered that straw fibers do have a preferential orientation: if the bale is loaded flat, stalks are mainly aligned perpendicular to the direction of the load, whereas if the bale is loaded on-edge, stalks are mainly aligned parallel to the load direction. Moreover, it has to be considered that many authors report that the deformation of straw bales is almost completely recovered some time after the load is removed; this means that permanent deformations do not have a great relevance on the overall straw bale deformation, although the collection of more experimental evidences regarding this aspect is recommended. Last, the presence of strings constraining the lateral expansion of the straw bale should be accounted for. If the straw bale is loaded on edge, strings are clearly always under tension, independently on the amount of lateral expansion due to the axial compression; if the bale is loaded flat, as depicted schematically in Fig. 2, the string is under tension if the following relation holds:

\[ \Delta L_s = 2 \Delta L + 2 \Delta W > 0, \]  

(1)

Figure 2. Schematic representation of a bale laid flat; representative string in red.

where \( \Delta L_s \) is the string elongation, \( \Delta L \) is the elongation of the strawbale in the lateral direction and \( \Delta W \) is its elongation in the axial direction. Introducing the absolute value of the axial deformation \( \epsilon \) and the coefficient of lateral expansion \( \nu_L \), Eq. 1 translates into:

\[ \Delta L_s = 2 \epsilon |\nu_L L_0 - H_0| > 0, \]  

(2)

hence into the requirement:

\[ \nu_L > H_0 / L_0. \]  

(3)

Eq. 3 means that if the coefficient of lateral expansion of the straw bale exceeds a certain threshold depending on the straw bale undeformed geometry, the string is under tension and is constraining the straw, thus.
Summary
Straw bale construction is a building technique offering many advantage over the use of conventional materials, especially in terms of reduction of emissions, residues of the agricultural activities and resistance to earthquakes; it represents a suitable solution for a wide variety of markets and economic settings, thus.
In this paper, ideas for the development of a rheological model for the description of the mechanical behavior of straw bales have been cast based on the behavior of straw bales as reported in the literature. More work on both the modeling and the experimental determination of straw bales response to compressive and dynamic loading has to be conducted, in order to shed more light on some critical aspects and to favor the diffusion of this highly sustainable construction technique.

References