



Mechanics of straw bales for building applications



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ABSTRACT

Straw bales are seen as increasingly viable for building insulation and even for the construction of small load-bearing straw houses in the last decades, especially in view of the need to seek low environmental footprints. Straw bales can be used as load-bearing structures but they are currently mainly used as a filler insulation material associated with a timber structure. Up to present, very few studies are available concerning the mechanical behaviour of straw bales in buildings. This study aims at investigating the behaviour of straw bales and leads to recommendations for required bales densities. This allows to derive compression models which describe their behaviour in a wall. Therefore, the results show that, in the density range 90–110 kg/m³, the elastic and strength characteristics are similar whatever the position of the bales (laid flat or on their edge).

The behaviour of the straw bales is found to be in correlation to the straw wisp density and to the initial wisp packing into the bales. The bale should therefore be considered as a system consisting out of the straw and the polymer links: when laid flat, it exhibits a particular type of deformation under single compression leading to a constant perimeter. In this position, the mechanical properties are controlled by two factors: (1) the packing density induced by the machine during the baling process, and by the elasticity and creep of the links; (2) the solid volume fraction of straw wisps, conditioned by the agronomic parameters and the pressure level in the baler.

1. Introduction

In Europe, about 40% of natural resources are currently used in the construction and building industry [1]. Agricultural by-products can be used as a resource to reduce the environmental footprint of building materials and also provide supplementary income for harvesters.

Apart from representing an agricultural by-product basically used for animal feed or litter, straw can be re-grown annually, and can be considered as a local building material with very few processing transformation steps and low fertilizer input. Over the past twenty years, the scientific interest in straw as a building material increased (Fig. 1) to develop this material from both the architectural and scientific points of view [2].

Construction rules regarding insulating materials have even been recently validated in several countries, such as in France [3] and the U.S.A. [4]. In the United Kingdom, some low-cost bale house concepts have been developed [5] and are now on the market [6]. These concepts use prefabricated straw and timber hybrid systems.

Straw bales are generally made directly on the cereal field, just after the grain harvest. Three principal formats exist: round bales, small oblong bales of low to medium density (50–150 kg/m³) and large oblong bales with high densities (> 150 kg/m³). For building, the straw

bales are generally laid flat, by hand. Thus, the small bale is the most commonly used format, with a weight of barely more than 15 kg and maximal dimensions of approximately 40×50×100 cm.

During harvesting of the cereal crop, the combine harvester collects the grains, and pours straw windrows onto the field. After an optional tedding step, baling consists of picking up the windrows and pressing the straw wisps together. In small balers, the wisps are picked up from the field and oriented by the feeding screw (Fig. 2). During the baling process, the main pressure is applied according to the long axis of the bale and is maintained at the desired compaction state by strings (generally two or three strings, made of thermoplastic polymer).

Straw bales are currently considered as an insulation filling material for construction applications. In the so called hybrid systems, specific prefabricated panels are added to bear the load. However, some self-builders and municipalities are attracted by using the bale itself as load bearing structure in small building. Such load bearing structures are made up of vertical walls of straw bales laid flat and associated with horizontal timber frames. The timber frames and straw walls are held together with tensioning wires that also pre-stress the straw bales. This structure is sometimes supplemented with wooden bracing. The coating of such constructions can be made up of render (plaster, lime or earth) or timber cladding. The building generally has a maximum of

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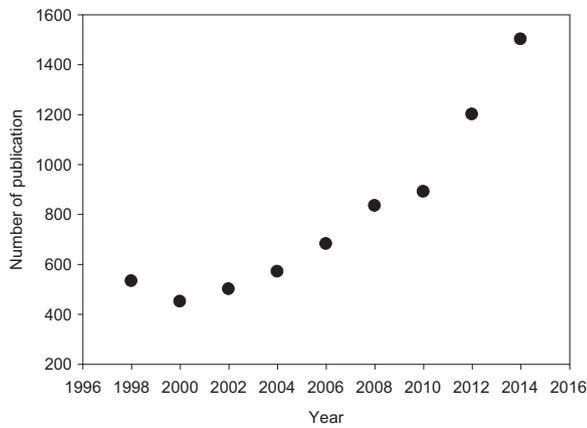


Fig. 1. Evolution of number of publications in Elsevier® with keywords (straw + building).

two floors (ground+1), with a light roof. This technique raises some new questions about the stiffness, creep and stability of straw-bale walls and, more generally, the influence of straw-bale mechanics.

Until now, studies of straw building materials have been almost exclusively concerned with their hygro-thermal characteristics. The durability of straw insulation materials against moisture has been demonstrated [9,10] and their hygro-thermal properties are now well known [11–14]. However, there are only very few studies on the mechanical behaviour of straw subjected to a compressive load. Some studies have considered the compressibility of straw as a raw material in silos or during a compression process [14,15] or the mechanical behaviour of individual stems [16]. Nona et al. [17] have investigated the compression characteristics of bulk straw, fitting its compression and stress relaxation behaviour with models such as the Maxwell model.

Studies of the mechanical behaviour of straw bales used as a building material are always associated with a given construction technique. For example, Arnaud et al. [18] studied a specimen containing a combination of load-bearing timbers and straw bales reinforced by nails and straps, while Rakowski and MacDougall [20] and Vardy and MacDougall [21] considered straw-bale plastered walls. To our knowledge, there is a lack of available data in the literature about the compression behaviour and properties of individual straw bales. The only articles on this subject [13,18] deal with a low number of samples combined with a narrow range of densities, which is hardly representative of the natural variability of such a building material. In addition, the main identified weakness in straw-bale construction is the highly variable geometry and density of the bales arising from the baling process.

The aim of the present study is to establish a baseline on compressive strength and elasticity characteristics (behaviour and

properties) of small straw bales, using two different batches with densities varying from 65 to 115 kg/m³ processed by two different straw balers, supplemented with literature data [13,19]. The target application is the use of wall filling as a load-bearing material, even associated with other materials. The further goal is understanding the levers for assessing straw building technology.

The anisotropic behaviour is also studied by loading some bales laid flat and others laid on their edge. The analytical models of compression tested here are based on the mechanics of granular media, allowing us to explore the relationship between permanent loading and deformation for the current load-bearing technique.

2. Materials and methods

2.1. Material

The straw making up the bales comes from wheat stems harvested in South Brittany, France. The two batches described in Table 1 display a large range of densities, allowing us to investigate the influence of both density and process on the mechanics of straw bales.

Batch 1 was harvested in the summer of 2013 and batch 2 in 2014, in different fields, and by two different farmers. The wheat sowing density was the same: 280 seeds/m². The density distribution of each batch is given in Fig. 3. These distribution curves show the importance of the choice of the agricultural machines in the aim of a use for building.

Building regulations for straw [3] used essentially for insulation applications in timber structures recommend bale densities of between 80 kg/m³ and 120 kg/m³, which therefore includes our samples. Batch 1 will never be used in construction as its average density is too low. But it permits to enlarge the investigation range and raise the trends and correlations on a mechanical point of view.

Indeed, as illustrated in Fig. 3, most of the variability arises from the differences between processing machines and agricultural practices, while a marked variability is also observed within each batch (coefficient of variation of 6% in each batch), i.e. within bales specimens produced with the same baler and tractor and on the same field. This variability within the same batch can come from different baler tunings during harvesting and from the variability of the straw itself in a field, due to differences of the soil nature or wind and sun exposures.

The density and moisture of the wisps also varies between batches: even if both batches come from wheat that was sowed at 280 seeds/m², the first batch was derived from organic farming, with no chemical treatment, whereas the second was provided by a conventional farmer who also used some stem-shortening agent. This can lead to differences in the stem cross-section, particularly affecting the amount of woody core in the inner part [16]. Furthermore, the first batch was drier (about 9% moisture content by mass of dry material, measured by heating in a drying oven until weight stabilization) and the second was

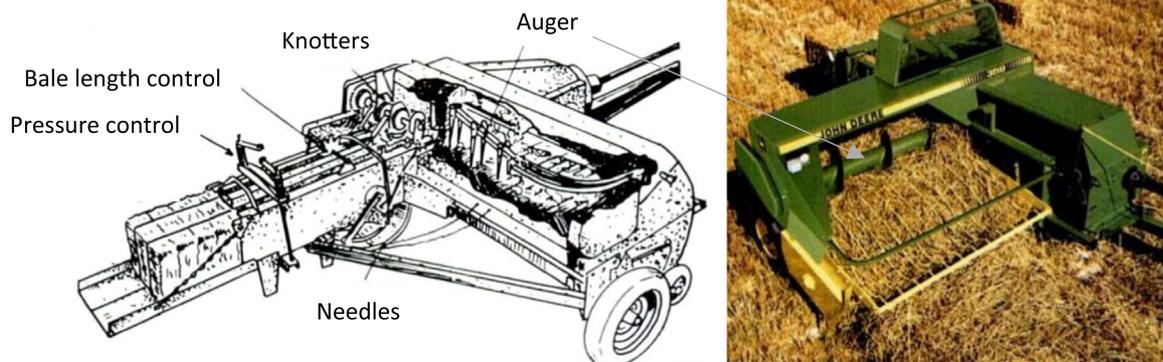


Fig. 2. operating principle of small square straw baler [7,8].

Table 1
Description of straw bale batches.

	Nb of bales	Straw pressing machine	Bale density[kg/m ³]		Straw bulk density [kg/m ³]	Straw bale moisture content (%) db)	Bale dimensions [cm]		
			Average	Standard deviation			Thickness	Width	Length range
Batch 1	60	Case IH 422	66	± 4	39	~9%	37	49	80–100
Batch 2	123	Massey Ferguson 124	93	± 5.6	53	~20%	37	48	75–95

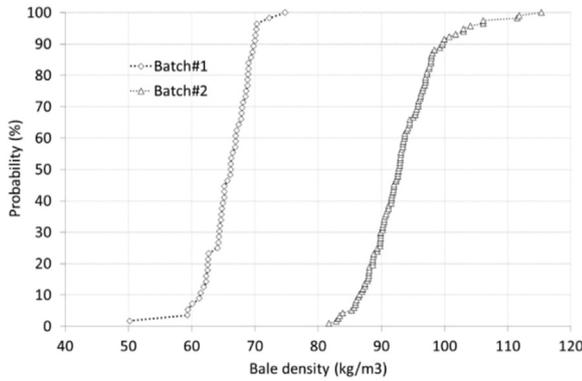


Fig. 3. Density distribution of the two batches of straw bales.

wetter (about 20% of humidity), due to the variable weather conditions during harvesting and storage. This has led to a difference in the wisp densities and therefore the bulk density of straws (Table 1). This straw bulk density was measured by untying several bales of the same batch, and weighting a given volume of bulk straw. It is then dependent of the density of the wisps packed into the bale.

Another explanation can be put forward to explain the differences between the two batches: the second batch was more tightly compacted into the baler, and then tied with polypropylene strings, whereas the bales of batch 1 were tied together with sisal strings. Therefore, the two batches were subjected to different loading paths (baling process and creep at rest). As a result, the wisps of the second batch may have undergone more creep, by flattening, buckling or ovalization of their cross-section [16]. In this way, the solid volume fraction of the wisps in batch 2 could be increased.

Variability in geometry and density is one of the main issues that slows down the widespread application of straw buildings. In fact, only some modern straw-baler brands are known to process small straw bales with well controlled high densities.

2.2. Experimental device and data processing

The bales were directly loaded by single compression under a hydraulic press, at a controlled displacement rate of 1 mm/s. Each batch was split into two equal parts: one for compression in flat

position and the other for compression in edge position, to study the anisotropic behaviour (Fig. 4).

Considering the high levels of deformation, the strain is computed as the true strain ϵ (Eq. 1) and the stress as the true stress σ (Eq. 2):

$$\epsilon = \ln \left(\frac{h}{h_0} \right) \tag{1}$$

where h is the vertical distance between the plates of the press during the test and h_0 is the initial value of h (Fig. 4).

$$\sigma = \frac{\text{Force}}{\text{Contact Area}} \tag{2}$$

The contact area is taken as the actual value of length by height of the bale laid on the edge and as the actual value of length by width of the bale laid flat.

3. Results and interpretation

3.1. Compression behaviour

Globally, the stress-strain curves can be divided into different regions: (i) a narrow curve foot corresponding to the setting of the device to fit the sample, (ii) a quasi-linear elastic phase that continues to around 10% strain, and then (iii) a quasi-linear hardening phase (Fig. 5).

Even if the curves are similar in the edge and flat position, the shape of the specimen shows a very different evolution during compression: bales laid flat keep a rectangle-oblong shape while bales laid on their edge take a deformable parallelogram shape. Bales laid flat undergo intense deformation that can be correlated with the initial string length. In agreement with the observations of [13], these bales maintain a rectangle-oblong shape and, according to the transversal deformation measurements, the sum of height plus length of the bales can be assumed to remain constant. While this appears to be surprising for a material, a bale should be considered rather as a system produced by the packing of straw wisps, which are pre-stressed in the bale-length direction by the strings. In the flat position, the true stress can then be written:

$$\sigma = \frac{F}{w.(l_0 + h_0 - h)} \tag{3}$$



Fig. 4. The compression device and the two different configurations. (left) edge, at the beginning of a test; (right) flat, with a strain of 0.77.

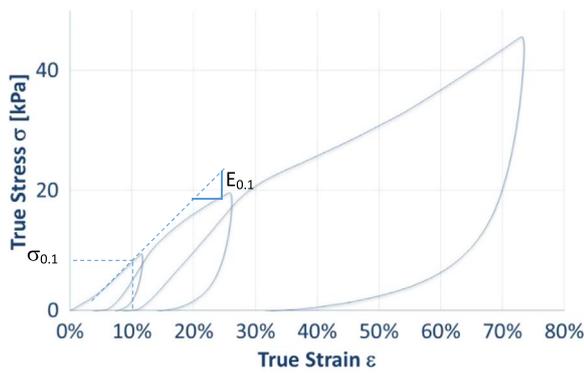


Fig. 5. Typical curve of cyclic compression on a bale, irrespective of loading direction (edge or flat).

where F is the force applied by the press, w and l_0 are resp. the width and the initial length of the bale, h is the distance between the press plates during the compression test and h_0 is the initial value of h , when the upper plate contacts the upper face of the bale.

In the case of bales laid on their edge, the surface area remains constant, so the stress is always equal to the force over the initial area and corresponds to the engineering stress.

From these observations, two parameters are chosen (Fig. 5) to compare the bale properties and investigate a possible correlation between bale density and mechanical characteristics: a stress parameter $\sigma_{0.1}$ corresponding to the stress level when the strain reaches 10%, and a rigidity parameter E representing the elasticity tangent modulus during the initial load. This elasticity modulus is calculated as the maximum slope during the first load. It should be noted that this modulus is representative of the linear part of the curve between at least 6% and 10% of strain for each batch and position. The stress level $\sigma_{0.1}$ is chosen because it is close to the point where the curves switch from a linear to a nonlinear region. This choice also allows to reduce possible perturbations of the device setting. Furthermore, in the case of load-bearing straw bales, the usual approach is to pre-strain the bales by a few percent with pre-tensioning belts to allow a satisfactory setting of the bales. Secondly, it ensures that the wall is stiffer against vertical loading. Thus, operations can be carried out on the roof without causing any critical deflection or differential deformation of the walls. According to this practice, the bales are in a pre-stressed state, and their behaviour should correspond more closely to deformation with a few percent strain.

The straw bales are very ductile and no breakage occurs in the compression directions of the present study, even with true-strain levels near 80% (Figs. 4 and 6). On Fig. 6, the curves of edge and flat loading are compared at two different initial densities: $\approx 62 \text{ kg/m}^3$ and $\approx 98 \text{ kg/m}^3$. The shape of the curves seems independent of the applied

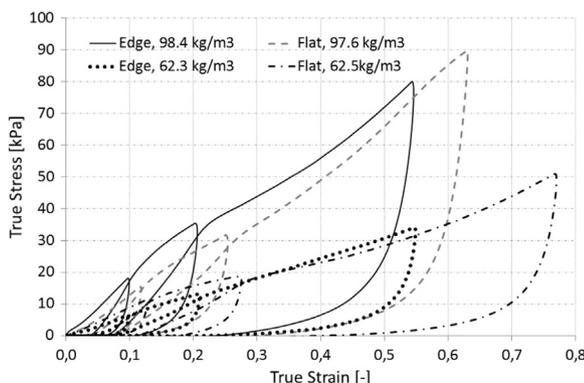
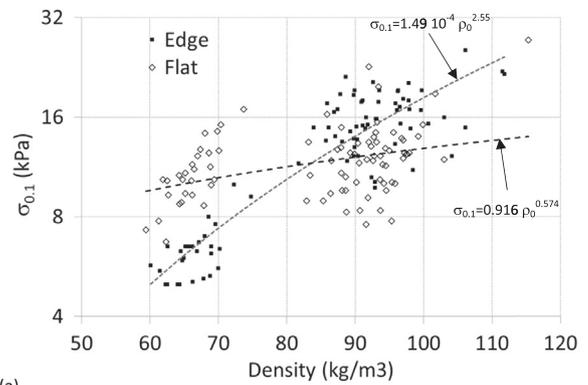
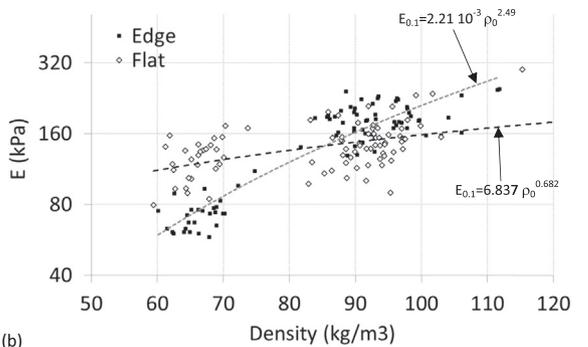


Fig. 6. Compression curves in edge and flat positions, at two different densities: 62 kg/m^3 and 98 kg/m^3 .



(a)



(b)

Fig. 7. (a) Stress at 10% strain and (b) tangent elastic modulus as a function of initial density of the specimens.

loading direction or initial bale density.

Large hysteresis loops are observed, characterizing a highly viscous behaviour. This is a well-known aspect of the behaviour of plant products [17,21], and could be of interest in a para-seismic context, since it enables the storing of deformation energy during an earthquake. However, when the bales are unloaded and kept at rest under ambient conditions, they recover their initial shape after a few minutes, highlighting a time-dependent elastic behaviour as already observed by Ashour et al. [13]. As a result, this composite material, consisting of compressed straw pre-stressed by strings, behaves in an exclusively visco-elastic manner. This behaviour is very unusual in terms of particle compaction, and is probably due to an association of highly elastic straw wisps [16] with the pre-stressing links.

3.2. Compression parameters

Fig. 7a and b show the evolution of stress at 10% strain and the elastic modulus, respectively, as a function of straw bale density for the two configurations (laid on edge and laid flat). In the density-range $80\text{--}100 \text{ kg/m}^3$, these data show that the stiffness and strength in both bale configurations are of the same order. This is advantageous from a thermal point of view: laid on the edge, the thermal flux is perpendicular to the straw wisps, and the thermal conductivity will be lower than in the flat position, as already shown with other agro-resources [22]. This could represent some saving of resources for given thermal and mechanical performances. However, considering the lower density range ($60\text{--}70 \text{ kg/m}^3$), a slight difference can be observed between the two positions pointing out the anisotropic behaviour.

The best model for fitting mechanical parameters versus density is a power law, corresponding to the compaction model proposed by Jones [23]. Table 2 reports the mechanical properties estimated with Jones' compression model. The parameter a (Table 2) is usually called "compressibility". In Jones' model, a material with a higher value of compressibility displays a higher volume reduction under a given pressure. As a comparison, Tronet et al. [24] found a "compressibility"

Table 2
Best fitting models for the mechanical characteristics of straw bale versus initial density. Elastic modulus and strength are expressed in kPa, densities are expressed in kg/m³.

Position	Stress at 0.1% [kPa] $\sigma_{0.1}=\sigma_0\rho^a$		Rigidity [kPa] $E_{0.1}=E_0\rho^b$		R ²
	σ_0 [kPa]	a	E_0 [kPa]	b	
Flat	0.916	0.574	6.837	0.682	0.16
Edge	$1.49\cdot 10^{-4}$	2.55	$2.21\cdot 10^{-3}$	2.49	0.84

of 0.323 on dry hemp shiv in a compression die, a value that corresponds to stiffer packing than in the present study.

The proposed power-law was able to describe the $\sigma_{0.1}$ and $E_{0.1}$ of the bales laid on the edge, while laid flat resulted into low R². It is noteworthy that no data are excluded and that specimen variability is also responsible of the scattering of results. In flat position, the variability of parameters at a given density is much higher than their evolution with density (due to variation between the two batches). The density in itself does not appear as an appropriate variable to explain the variance of mechanical parameters.

Straw bales loaded on their edge have characteristics that are more strongly dependent on density. In fact, in the edge position, straw is mainly loaded parallel to the wisp direction as the baling process tends to orient the wisps and the bale strings maintain a constant cross-section. The wisps have less degrees of freedom than in the flat position. A direct correlation between compactness (i.e. density) and mechanical properties can then be observed because the solid section of the straw wisps is directly loaded. In the case of flat position, the compression is more difficult to relate to the mechanical characteristics and should depend on the stress-strain history of the straw entering the baler and after: as seen on Fig. 2, the straw is compacted along its length at a level of compression that is controlled as it enters the baler. Thus, the stress/strain path depends on this initial compaction, on the nature of the strings and the creep behaviour of the straw wisps in the bale. All of these parameters influence the overall shape of the wisp cross-sections, the initial solid fraction in the packing of wisps and, as a result, the subsequent compression behaviour of the bale in flat position. The results for the flat position configuration are discussed in more detail in Section 3.3.

3.3. Compression mechanisms in flat position

When compressed in the baler, the straw is compacted along the length of the bale in successive layers that are orthogonal to this direction. At the end of the process, the strings maintain a given compaction state in these layers. A certain stress remains, even after relaxation. This phenomenon can be observed when the strings are cut: the bale expands visco-elastically, but only in the long direction. This explains why the strings stay under tension when the pressure is applied in the flat position.

This conformation of wisps in layers perpendicular to the flat loading means that they are able to deform during compression. Actually, this deformation should depend on the inter-wisp voids that exist within the bale. This void space, or inter-particle porosity, represents the volume of the bale minus the place taken by the wisps. This void volume depends not only on the density of the bale, but also on the apparent density of the wisps themselves, conditioned by the original wheat stem properties: density (linked to the core structure [16]), moisture and transverse properties (flattening, ovalization, creep and elasticity). The density of the wisps can be evaluated from the bulk density of the straw when the bale is untied: the denser the wisps, the denser the bulk packing.

Since the bulk density is different for the two batches (Table 1), a compression model is required that considers the bulk state. Cooper and Eaton [25] proposed such a model. Unlike Jones' model [23], the

approach adopted by Cooper and Eaton is not only phenomenological: the compaction of particle beds is known to occur in three steps: rearrangement, deformation of particles, and, in some cases, breakage of particles. From a physical point of view, the Cooper and Eaton model provides pressure levels at which each phenomenon is likely to occur, and can give a density target for straw bales used for load bearing. Above a certain density threshold, the straw particles achieve almost all their deformation by bending of the wisps and ovalization plus compression of their cross section. It means that an optimal number of wisp/wisp contacts into the packing is reached and at the contact points the straw wisps are compressed to a density close to the density of its cell-walls. The stiffness of the bales will then increase more rapidly above this density threshold.

This model leads to good correlations for ground straw [15] and hemp shiv [24]. Here, it is rewritten in terms of density, assuming that no particle breakage occurs, in terms of $\sigma_{0.1}$ versus the density of the bale at 10% strain, $\rho_{0.1}$:

$$\left(1 - \frac{\rho_{bulk}}{\rho_{0.1}}\right)\left(1 - \frac{\rho_{bulk}}{\rho_S}\right) = a \exp\left(-\frac{k_1}{\sigma_{0.1}}\right) + (1 - a) \exp\left(-\frac{k_2}{\sigma_{0.1}}\right) \quad (4)$$

where ρ_{bulk} is the bulk density, i.e the density of the wisps packing when the bale is untied. ρ_S is the specific density of the straw wisp cell-walls, here taken as the cellulose density (1500 kg/m³), while a , k_1 and k_2 are constants; k_1 (resp. k_2), in kPa, is the pressure at which the rearrangement (resp. the particle deformation) is most likely to occur. $\rho_{0.1}$ is the density of the bale at 10% strain, as calculated from Eq. (3):

$$\rho_{0.1}=\rho_0 \frac{l_0 h_0}{(l_0+0.1h_0)(h_0-0.1h_0)} \quad (5)$$

where h_0 and l_0 are initial dimensions of the bale. ρ_0 is the initial density of the bale. Fig. 8a shows the experimental data, taking the bulk densities of Table 1. Some experimental data from the literature

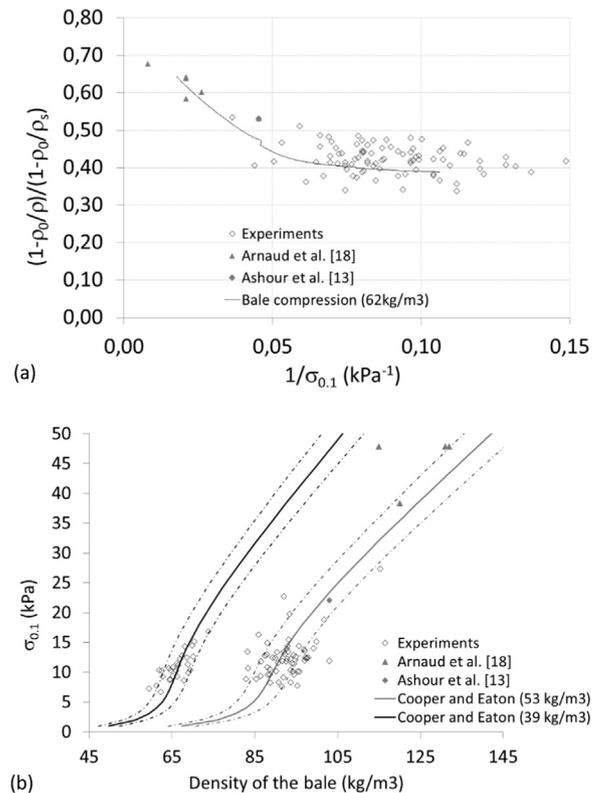


Fig. 8. (a) Experimental data and compression curve of a bale with an initial density of 62 kg/m³, in relation to the Cooper and Eaton modelling parameters; (b) Experimental points and fit with Cooper and Eaton model, using $a=0.42$, $k_1=0.84$ kPa and $k_2=49$ kPa. The dashed curves indicate the model variation due to $\pm 5\%$ scatter in bulk density.

[13,18] are added to enlarge the range of density investigation.

It should be noted that Eq. 4 must also be valid during the compression test on each bale. To validate this assumption, the compression curve of a bale of 62 kg/m³ (batch 1) is drawn on Fig. 6a. To achieve this, the curve is taken above 10% strain, the cycle loops are removed, and ρ is also calculated from Eq. (3):

$$\rho = \rho_0 \frac{l_0}{l_0 + \Delta h} \frac{h_0}{h_0 - \Delta h} \quad (6)$$

where Δh is the displacement of the press during the compression test: $\Delta h = h_0 - h$.

This curve fits the experimental data (Fig. 8a). The parameters used in Cooper and Eaton's model are computed from this curve with the least squares method. Values of $a=0.42$, $k_1=0.84$ kPa and $k_2=49$ kPa are found, giving a correlation coefficient $R^2=0.83$ for batch 1 and $R^2=0.55$ for batch 2. The value of parameter k_2 obtained from the experimental data implies that around 49kPa, most of the wisps will undergo deformations. It is difficult to correlate this value with the strength of straw stems. From a mechanical study of single specimens [16], the mean flexural yield stress of the cell-wall can be estimated at between 17 MPa and 66 MPa, depending on the stem source area. In a bale, the stress is distributed within the packing, and the loading on each single wisp is very different. Furthermore, the straw wisps themselves are already subject to strain in the baler and at rest. Therefore, it is very difficult to relate these two studies. The value of 49 kPa corresponds to a density ratio ρ_0/ρ_{bulk} of around 2.15. Therefore, with a bulk density of 53 kg/m³, the target value of density for straw bales should be 118 kg/m³ to minimize deflection under loading. This value is consistent with the density currently advised for load bearing by self-builders, i.e.: about 120 kg/m³. The parameter k_1 of Cooper and Eaton's model is very low compared to the usual values for bio-based materials [15,24]. It may correspond to the pressure value at which the rearrangement step is likely to occur. This rearrangement is actually achieved during the baling process.

The experimental points of Fig. 8a and b are supplemented with the data of Ashour et al. [13] and Arnaud et al. [18]. It can be observed that the model with a bulk density of 53 kg/m³ yields results close to the literature data points, except for one point. Other studies should be carried out on higher bale densities to confirm this trend. Fig. 8b also shows a high sensitivity to the bulk density of the straw. The model curves for a bulk density variation of $\pm 5\%$ are drawn on Fig. 8b. These curves cover 86% of batch 1% and 73% of batch 2, suggesting that controlling the stress/strain path of the straw is a very important lever for conditioning its subsequent mechanical behaviour.

3.4. Correlation between rigidity and $\sigma_{0.1}$

From the experimental data, we can observe a correlation between rigidity and strength (Fig. 9).

The best correlations between these two parameters for flat and

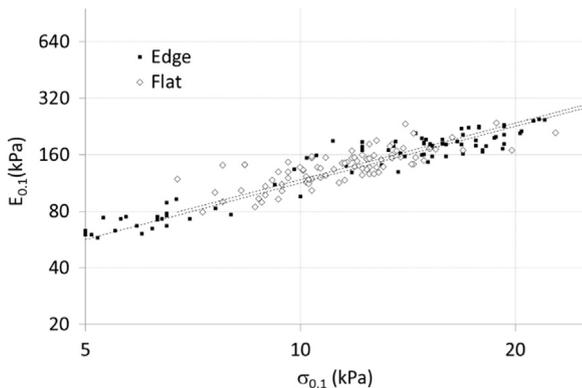


Fig. 9. Elasticity modulus versus stress at 10% strain.

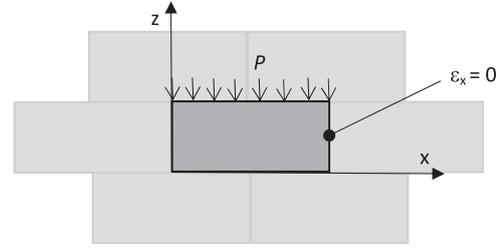


Fig. 10. A bale contained in a wall and its boundary conditions.

edge positions are:

$$E_{0.1,flat} = 11.8 \sigma_{0.1,flat} \quad (7)$$

$$E_{0.1,edge} = 11.4 \sigma_{0.1,edge} \quad (8)$$

Eqs. (7) and (8) are very close to Hooke's law (i.e. $\sigma_{0.1} = 0.1 E$), showing a slight increase of rigidity between the initial state and the linear behaviour region, between 6% and 10% strain.

3.5. Vertical behaviour in a wall, the case of self-bearing constructions

The most common orientation of bales in self-bearing wall is on its flat position. Doing so, each bale is confined by its neighbours, leading to the boundary conditions given in Fig. 10. In the case of a small-scale ground floor house with 6x6 m² floor space and a light roof (zinc or stainless steel), the linear load q can be assumed to be around 2 kN/m.

Under these conditions, we can write the 2D elastic problem as follows:

$$\bar{\sigma} = 2\mu \bar{\epsilon} + \lambda tr(\bar{\epsilon}) \bar{I} \quad (9)$$

$$\text{With } \bar{\sigma} = \begin{bmatrix} \sigma_{xx} & 0 \\ 0 & -P \end{bmatrix}, \bar{\epsilon} = \begin{bmatrix} 0 & 0 \\ 0 & \epsilon_z \end{bmatrix}$$

And:

$$-P = (2\mu + \lambda) \epsilon_z \quad (10)$$

where P is the vertical pressure on the wall, while λ and μ are the first and second Lamé coefficients, respectively. In the transverse plane of the bale (x, z), the Poisson ratio in compression is derived from Eq. (3) or Eq. (6), considering small displacements. As the perimeter of a bale laid in flat position remains constant, the Poisson ratio of the transverse (x, z)-plane (Fig. 10) can be calculated as follows:

$$\nu_{xz} = -\frac{\epsilon_x}{\epsilon_z} = -\frac{\Delta h}{l_0} \left(-\frac{h_0}{\Delta h} \right) = h/l_0 \quad (11)$$

This parameter is correlated with the bale shape. Thus, it is not an intrinsic parameter of the material. In fact, each bale must be considered as a system, composed of more or less pre-stressed straw and the links that maintain this stress.

The relation between pressure on the wall and vertical deformation of bales can be derived from (10), (11) and the relation of the Lamé parameters with the Young's modulus and the Poisson coefficient $\mu = E/[2(1+\nu)]$ and $\lambda = E\nu/[(1+\nu)(1-2\nu)]$:

$$\frac{P}{\epsilon_z} = -E \frac{r(r-1)}{(r+1)(r-2)} \text{ and } \frac{q}{\epsilon_z} = -wE \frac{r(r-1)}{(r+1)(r-2)} \quad (12)$$

where r is the aspect ratio of the bale ($r=l_0/h_0$), w the width of the bales and q the linear load on the wall (kN/linear metre). Eq. (12) results in the expression of the apparent Young modulus in the wall. It shows that the bale shape is a parameter that plays a role in controlling the wall stiffness: when the bale is in the flat position, a high aspect ratio gives a stiffer wall. Then, using Eqs. (4), (5), (7) and (12), it is possible to estimate the vertical deformation of a wall submitted to a linear load q.

For example, let us assume straw bales with an initial density of

around 100 kg/m^3 , and a bulk density of 53 kg/m^3 with dimensions $w.h.l=0.48 \times 0.38 \times 0.9 \text{ m}^3$. As pointed out in the introduction, load-bearing straw walls are pre-stressed by belts, to improve the cohesion and vertical stiffness of the bales. Let us consider a pre-stressing of 1% strain. Ignoring the dead weight of the straw bales making up the wall, the load required to reach 1% strain can be approximated by considering a linear behaviour for the first loading of the bales until 10% strain. For bales of 100 kg/m^3 , the density and stress at 10% strain can be calculated with Eq. (4) and Eq. (5): $\rho_{0.1}=106.6 \text{ kg/m}^3$ and $\sigma_{0.1}=29.9 \text{ kPa}$. The pressure P and the linear load q that must be applied by the pre-stressing belts follow from Eq. (12), i.e.: $P=15.6 \text{ kPa}$ and $q=7.58 \text{ kN/m}$.

Now, considering the dead load of a light roof to be around 2 kN/m (zinc or stainless steel), it is possible to estimate the vertical strain of the wall under this load, by assuming that the elastic modulus is close to $E_{0.1}$ (here 270 kPa). In this case, we find a strain $\epsilon_z=-2.95 \cdot 10^{-3} q$ (q in kN/linear metre), leading to a permanent strain of 0.6% which does not exceed the limit for loss of linearity of straw material (Fig. 6). This calculation does not take into account the eventual presence of wood in the corners or the contribution due to coatings.

4. Conclusion

The aim of the present study is to gain a better understanding of the mechanical behaviour of small straw bales, and identify the levers that might improve their use as a building material. For this purpose, an experimental study was carried out. The behaviour of the straw bales is found to be different if the bale is loaded on its edge or laid flat. For low densities, the bales laid flat are clearly stiffer than on their edge. Around $90\text{--}110 \text{ kg/m}^3$, the stiffness is equivalent in both configurations. When laid flat and loaded in uniaxial compression, the shape of a bale under deformation is controlled by the string length: the perimeter of the bale remains constant.

The density of straw bales laid flat is not the only key parameter and we should also take the wisp density as well as the bulk density into account. The key parameter is then the ratio of bulk density over straw bale density, which characterizes the overall compaction state and solid volume fraction of the wisps.

The shape of the bales, more particularly their slenderness, will influence the stiffness of a load-bearing wall made of straw: a high aspect ratio gives a greater stiffness.

By using the Cooper-Eaton model, a critical compaction state could be identified for which the applied pressure in the baler ensures sufficient stiffness of the produced bales. This critical state could be identified by the ratio of initial to bulk density $\rho_o/\rho_{\text{bulk}}$ of 2.15. This value corresponds to a critical compaction state, for which the applied pressure in the baler ensures a proper stiffness of the bale.

The interaction between the baling process, the mechanics of straw packing and bales needs to be investigated further, particularly by developing the approaches of Leblcq et al. [16] applied to individual stems and Nona et al. [17] who worked on straw packing compaction and relaxation. These approaches should allow us to determine the

entire loading path of the straw, from the crop field to the wall, by studying its compressive and relaxation behaviour.

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