A new human powered press for producing straw bales for load bearing constructions (Anpilpay 2.0)

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Abstract: This paper provides the design method to realize a human-powered press for continuous production of high-density straw bales, necessary for the realization of load bearing housing moules. Particular attention is directed to the simplicity of the press mechanical structure in order to make possible its construction in developing countries. The design process is fully described, then the use of a prototype press for the realization, with high-density rice straw bales, of a load bearing housing module is presented and the results are commented.

Keywords: straw bale construction, human powered baler, slider crank, mechanism synthesis, apropriate building, humanitarian engineering

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1 Introduction

At least 11% of the global population does not have an appropriate house, i.e. live in slums (United Nations, 2017). This condition is even more dramatic in particular post-emergency condition areas, where may suffer the effects of tsunami, earthquakes or hurricanes for several years. The improvement of housing conditions of the citizen can take place using appropriate construction techniques, which should use local materials and follow local traditions as well. Furthermore, they should be suitable for self-production, in order to reduce costs.

Some of the construction techniques that follow these purposes are based on raw soil (Ferraresi et al., 2011; Sassu et al., 2016; Ferraresi et al., 2017b), while others on straw (Piemonte, 2013; Bonoli et al., 2015; Franco and Iarussi et al., 2016; Franco and Quaglia et al., 2016; Ferraresi et al., 2017a; Kean, 2010).

Generally speaking, straw is very suitable for constructions due to its insulation properties and its fire resistance when plastered (Ashour et al., 2011; Jones, 2009). Moreover, a proper design of the construction will allow it to be also earthquake-resistant (Kean, 2010). In addiction straw is a low-cost sustainable building material, renewable and reachable. There are two basic styles of straw bale construction: load-bearing or Nebraska-style in which the bale wall carries vertical load; non-load-bearing, or post-and-beam, or infill style, in which bales are used as infill panels between or around a structural frame (King, 2006).

The load bearing technique has been proved to be more efficient in developing countries, or for emergency post-disaster housing for different reasons: these conditions very often make it difficult and expensive to find wood necessary for the construction of the structural frames; a load-bearing structure is often simpler and faster to erect; a load-bearing structure will generally

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perform more effectively under dynamic seismic loads (King, 2006).

Furthermore, motorized hay balers for agricultural use are often unavailable in such conditions, fossil fuels are expensive and limited, and electricity is often provided in a discontinuous way. All these elements suggest that the production of the straw bale has to be conducted manually.

The solutions presently available derive from traditional agricultural machines and are the result of empirical studies and progressive adjustments on the field. For example, in the Pakistan Straw Bale and Appropriate Building project (Khan and Donovan, 2012), straw bales were made with self-fabricated compression moulds using manually operated farm jacks. In this case, the pushing mechanism of the pressing plate has a constant transmission ratio which is disadvantageous because the compression pressure required by the straw increases according to its density.

In other cases, different articulated mechanisms were applied for the motion and force transmission, but in none of these cases a dimensioning methodology was introduced.

The authors of this paper have already dealt with such a problem, yielding to the design and the prototype of a manual press, called Anpilpay 1.0, able to produce straw bales for non-load bearing constructions (Franco and Iarussi et al., 2016; Franco and Quaglia et al., 2016). Although the press Anpilpay 1.0 was able to realise straw bales suitable for a warehouse in Haiti (A.S.F Piemonte, 2013; Cottino et al., 2017), some weaknesses in its usage have been discovered. The most important of these are the fixed geometry of the compression chamber, and the need of re-positioning of the sliding/lockable end during the process of compacting the straw bale.

Furthermore, the only way to control the density of the bale was to weigh the straw before the compression, and the extraction of the bale, once produced, was quite difficult.

In order to improve these weaknesses, the authors designed a new press that is able to produce rice straw bales in a continuous way and with the possibility to regulate its density. The final bales are suitable for constructions in straw load-bearing.

This work aims to define a methodology for design this kind of press, starting from the measurement of the mechanical properties of the used straw. The solutions adopted must guarantee that people who live in that background can build itself a similar press.

First, the design specifications of the press are defined and listed, and the concept design of the press is presented. Then an energy-based calculation method for the main functional parameters of the press with continuous bale production and density control is introduced. Further experimental tests, aimed to characterise the mechanical behaviour of the rice straw are described and used to analyse the dynamic behaviour of the press. The mechanical architecture of the press and the detailed design of the slider crank mechanism are defined; all the technical data of the machine are listed. Finally, a prototype of the press is presented. This prototype has been used to build a post-emergency housing module in load-bearing straw, realised during a student workshop called Anpil Pay 2.0 at Politecnico di Torino.

2 Design specifications

The press must be able to produce straw bales in a continuous way and must be provided with a device capable of regulating the density of the straw.

Starting from rice straw with initial density of about ρ_o=30 kg m^{-3}, the press has to produce straw bales with final dimensions of 0.36×0.45×0.9 m and a density of ρ_f = 120 kg m^{-3}. Such final density is needed for utilising the bales in load bearing straw bale construction (King, 2006). The main characteristics of the bale are summarized in Table 1.

Table 1 Main straw bale characteristics

Straw initial density ρ_o (kg m^{-3})	30
Bale final density ρ_f (kg m^{-3})	120
Bale dimensions (m)	0.36×0.45×0.9
Total bale mass m_{tot} (kg)	17.5

The press must also be able to work in rural areas of developing countries, even for emergency post-disaster housing. For this reason it is therefore necessary to opt for a hand-powered actuating mechanism.

3 The concept of the press

Each straw bale is produced in n_c consecutive compaction cycles, each one having a certain mass of straw m_c to be put in a compression chamber with section A and length l_o (Figure 1a). The being formed straw bale, whose density ρ_f has been obtained during the precedent cycle, takes place in the final part of the compression chamber, and constitutes its end. After this, a complete formed bale is forced to pass through a vertically restricted opening that crushes the bale of an entity equal to h (Figure 2). Calling N the net vertical force acting on the bale, this quantity, neglecting the straw weight force, can be supposed to be proportional to the transverse crushing of the bale:

$$N=N(h) \tag{1}$$

As a direct consequence, once the vertical crushing h has been defined and considering the bale homogeneous, the force N is known and constant.

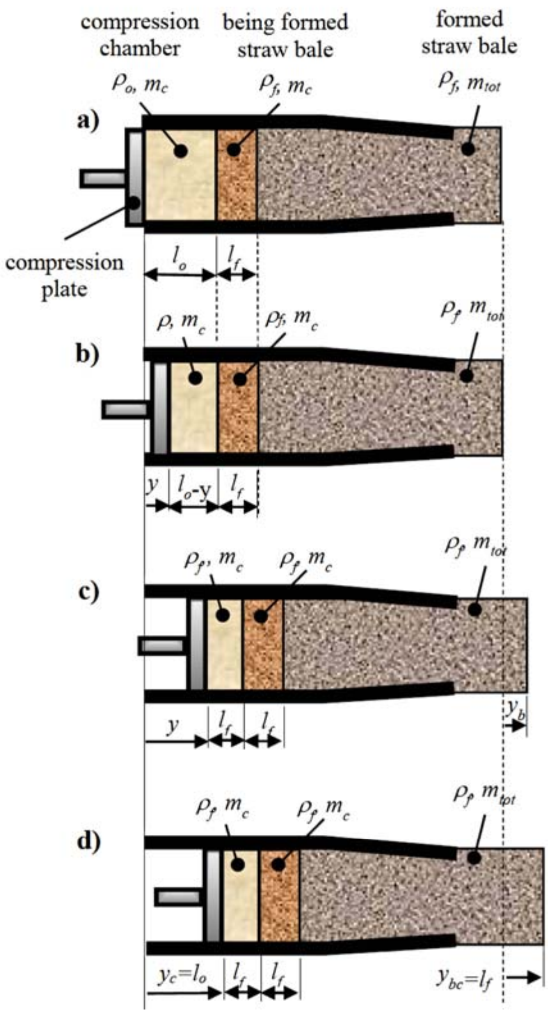


Figure 1 Schematic of the steps needed in a compression cycle with a continuous production of bales

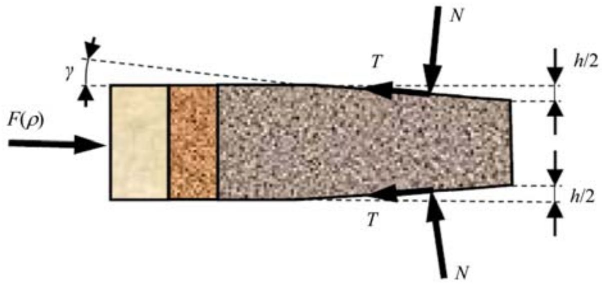


Figure 2 Mechanism to regulate the density of the bale

When the compression plate moves of a quantity y, it produces a force $F=F(\rho)$ acting on the ongoing bale that increases with increasing density. If the transversal forces that act on the straw inside the compression chamber are considered negligible, which means that the friction on the ongoing bale is negligible too, the force F is balanced only by the longitudinal components of the friction forces T acting on the formed bale due to the restricted opening. Furthermore, Equation (2) is obtained if the inclination of the narrowing plane is considered small:

$$F\approx 2T \tag{2}$$

In the initial phase, calling f_s the static friction coefficient between straw and steel, the forming bale remains in adhesion (stick) condition until the increasing compression force F is less than the limit value:

$$F\leq 2f_sN(h) \tag{3}$$

Thus, the end of the compression chamber remains stationary while the compression plate moves, compressing the straw and increasing its density (Figure 1b).

Once the adhesion limit is exceeded, the bale starts moving and the compaction force is balanced by the dynamic friction acting on the formed bale. Calling f the dynamic friction coefficient between straw and steel, the compaction force F is then:

$$F=2fN(h) \tag{4}$$

And it remains constant as the vertical crushing h has been fixed. The value of h can then be regulated so that the force exerted by the compression plate on the straw in dynamic condition, according to Equation 4, is the one that allows the mass m_c inside the compression chamber to reach the final density ρ_f. An additional movement of the compression plate causes then a translation of the entire straw inside the press, whose density is homogeneous and constant and equal to ρ_f (Figure 1c).

Once the compression plate returns to its initial position, it is straightforward that its total stroke should be equal to the initial length of the compression chamber, so that this latter recovers its initial geometry (Figure 1d):

$$y_c = l_o \tag{5}$$

At the end of the compaction cycle a new layer of straw having density ρ_f and length l_f takes the place of the one compressed in the previous cycle, and the entire formed bale moves of a quantity:

$$y_{bc} = l_f = \frac{m_c}{A\rho_f} \tag{6}$$

4 The functional design

Knowing the maximum work L_{opmax} that an operator is able to perform during every compaction cycle, calling η the efficiency of the mechanism, the total work required to execute a compaction cycle L_{tot} should be

$$L_{tot} \leq \eta L_{op\max} \tag{7}$$

The total work is the sum of the compression work L_c related to the mass of the straw m_c and the translation work L_t to expel the bale.

$$L_{tot} = L_c + L_t = \int_0^{l_o - l_f} p(\rho)A\,dy + p(\rho_f)A\,l_f \tag{8}$$

Equation (8) clearly shows that the total work L_{tot} depends on the mechanical behaviour of the straw. The authors have already proved in a previous work (Franco and Iarussi et al., 2016) that in the design of this kind of presses a simplified linear model of the mechanical behaviour of the straw can be assumed:

$$p = k(\rho - \rho_o) \tag{9}$$

where, k is the constant stiffness of the straw, and can be experimentally obtained:

$$k = \frac{p_f}{\rho_f - \rho_o} \tag{10}$$

Taking into account Equation (9), the compression work L_c can be expressed as:

$$L_c = km_c\left(\ln\left(\frac{\rho_f}{\rho_o}\right) + \frac{\rho_o}{\rho_f} - 1\right) \tag{11}$$

Recalling Equation (6) it is possible to obtain the work L_t required to translate the formed bale thus restoring the initial geometry of the compression chamber:

$$L_t = km_c\left(1 - \frac{\rho_o}{\rho_f}\right) \tag{12}$$

From Equations (11) and (12), remembering Equation (8), it is possible to calculate the ratio between the translation work L_t and the total work per cycle L_{tot}:

$$\frac{L_t}{L_{tot}} = \frac{1 - \frac{\rho_o}{\rho_f}}{\ln\left(\frac{\rho_f}{\rho_o}\right)} \tag{13}$$

This ratio is equal to 0.54 in the present case. Therefore, the choice of producing the bale continuously, so allowing the regulation of the density and the automatic ejection of the formed bale, on the other hand requires the operator to effectuate more than twice the work for each formed bale with respect to a press having a fixed compression chamber.

From Equations (8), (11) and (12) the mass loaded at every compaction cycle can be derived as a function of the total work per cycle L_{tot}:

$$m_c = \frac{L_{tot}}{k\ln\left(\frac{\rho_f}{\rho_o}\right)} \tag{14}$$

Thus, the number of compaction cycles required to form a bale is:

$$n_c = \frac{m_{tot}}{m_c} = \frac{m_{tot}k\ln\left(\frac{\rho_f}{\rho_o}\right)}{L_{tot}} \tag{15}$$

Furthermore, considering the relation $m_c=\rho_o A l_o$ and recalling Equation (5), it is possible to calculate the stroke that the compression plate covers during every cycle as a function of the total work per cycle L_{tot}:

$$y_c = l_o = \frac{L_{tot}}{kA\rho_o\ln\left(\frac{\rho_f}{\rho_o}\right)} \tag{16}$$

Figure 3 shows the trend of the piston stroke y_c per cycle related to the total work for each cycle L_{tot}, i.e. the compression work and the translation work, for different straw stiffness constants k. The curves are obtained considering a straw bale of transverse sectional area A = 0.36×0.45 m^2, initial density ρ_o=30 kg m^{-3}, and a final density ρ_f= 120 kg m^{-3}.

Fixing the total work L_{tot} available at every cycle according to Equation (7), and knowing the stiffness constant of the straw k, it is possible to calculate the stroke of the compression plate y_c requested to the mechanism.

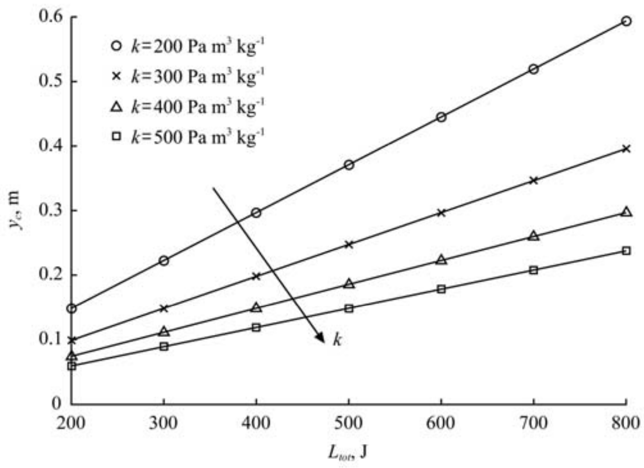


Figure 3 Piston stroke y_c per cycle related to the total work for each cycle L_{tot} (straw stiffness constant k, m_{tot} = 17.5 kg, ρ_o=30 kg m^{-3}, ρ_f = 120 kg m^{-3})

For sake of simplicity, the transmission of the motion is entrusted to a centred slider crank mechanism (Figure 4). Thus, the operator applies a force F_{op} to the end of a lever of length l, rigidly connected to a crank of length m. The angle α_o defines the initial position of the crank. A connecting rod of length b is then hinged to the crank, and its initial inclination on the horizontal is defined by the angle β_o.

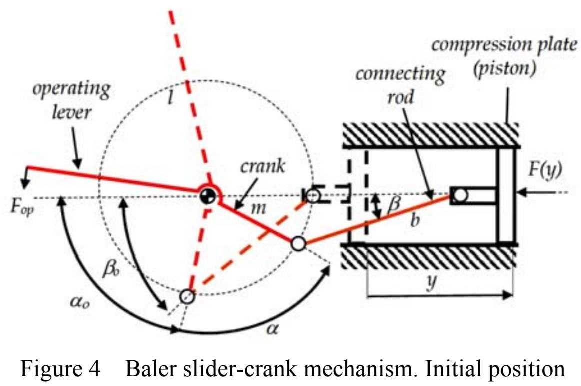


Figure 4 Baler slider-crank mechanism. Initial position (hatched line); generic position (continuous line)

A rotation α of the crank causes a translation y of the compression plate. During every compaction cycle the crank rotates of an angle equal to α_c ($0<\alpha<\alpha_c$), at which the compression plate reaches the final stroke y_c, according to Equation (16).

The design of the actuating mechanism requires to define the length of the operating lever l, the initial crank angle α_o, the rotation angle of the crank for one complete compaction cycle α_c, the crank length m and the connecting rod length b in order to obtain the desired stroke y_c according to Equation (16) and to maintain the operating force F_{op} within adequate limits.

Referring to Figure 4, it is possible to express the length of the crank as a function of the piston stroke y_c, once the initial crank angle α_o, the rotation angle of the crank for one complete compaction cycle α_c, and the ratio between the length of the crank and the length of the connecting rod $m/b=\lambda$ have been chosen:

$$m = \frac{y_c}{1/\lambda(\cos\beta_c - \cos\beta_o) + \cos\alpha_o - \cos(\alpha_o + \alpha_c)} \quad (17)$$

where,

$$\beta_o = \arcsin(\lambda \sin(\alpha_o)), \quad \beta_c = \arcsin(\lambda \sin(\alpha_o + \alpha_c)) \quad (18)$$

Actually, the choice of parameter λ affects the minimum transmission angle and it has to be as high as possible in order to reduce the normal component of the force applied to the frame.

In order to optimize the trend of the force applied by the operator at the lever end, we can consider that:

$$F_{op} = \frac{p(\rho)A}{\eta l}\frac{dy}{d\alpha} = \frac{p(\rho)A}{\eta l} m\left[1/\lambda \cos\beta - \cos(\alpha_o + \alpha)\right]\tan\beta \quad (19)$$

where, η is the efficiency of the transmission, and $dy/d\alpha$ the geometrical speed of the output link, and m can be calculated using Equation (17).

Being the operating force depending on the straw mechanical characteristic, the latter has been experimentally determined.

5 Experimental characterisation of the straw

In literature, there are many straw and hay mechanical characteristic models (Afzalinia and Roberge, 2013; Ferrero et al., 1991; Galedar et al., 2008; Kaliyan and Morey, 2009; Nona et al., 2014; Watts and Bilanski, 1991). Unfortunately, each of these data refers to a particular kind of straw tested in different loading conditions, which makes them extremely heterogeneous. Thus, it has been considered appropriate to execute specific measurements in order to seek for an experimental relation between compression and density of rice straw.

A steel box having cross section of 0.36×0.45 m (Figure 5) has been assembled inside a universal testing machine for materials (Baldwin Zwick-B_1058 MA), equipped with a load-cell TMT, WB series, linearity ± 0.15% and with a LVDT (linearity ± 0.3%). A mass of straw equal to 0.8 kg has been loaded into the steel box, having initial density of approximately 35 kg m^{-3}. The compression plate has been moved at velocity of 3 mm s^{-1}, and both displacement and applied force have been recorded. The entire test has been repeated three times.

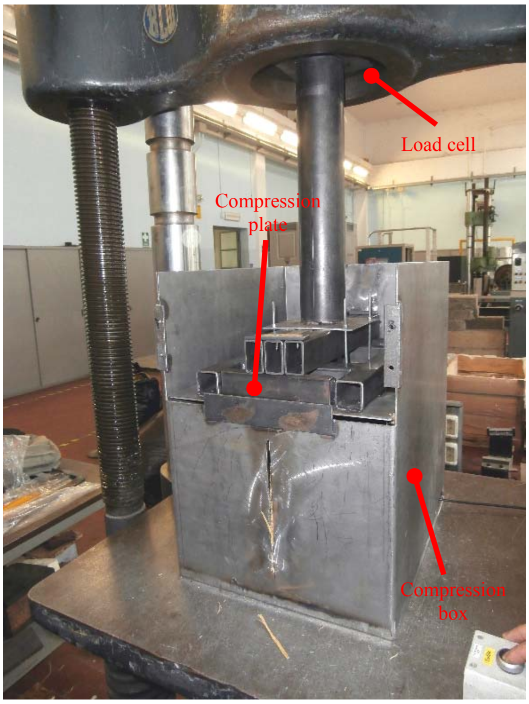


Figure 5 Straw mechanical characterisation setup

Elaborating the data of each test, a set of experimental mechanical curves that relate the compression pressure to the density have been obtained. The three curves are reported in Figure 6, and show a fair repeatability. Using Equation (10), the mean stiffness constant of the tested rice straw was calculated k=463 Pa m^3 kg^{-1}.

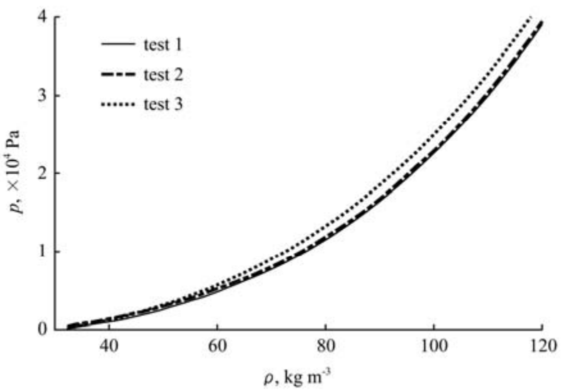


Figure 6 Straw mechanical characteristic

6 Choice of design parameters

Known the mechanical behaviour of the straw, from Equation (19), it is possible to plot the operating force F_{op} as a function of the rotation angle of the lever α.

Considering the stiffness constant of the straw obtained by the experimental measurements (k = 463 Pa m^3 kg^{-1}), assuming that the operator performs a work L_{opmax}≈600 J (i.e. the work obtained applying a constant force of 200 N at the end of the lever for a rotation angle equal to 85°) and assuming also an efficiency η=0.95, a piston stroke equal to y_c=0.18 m is derived from Equations (7) and (16).

The length of the lever has been limited to l=2 m so that it can be easily grabbed when it is in vertical position. Concerning the ergonomics of the mechanism, it is considered appropriate that the compaction cycle starts with a nearly vertical lever, and ends with the lever having a horizontal position. Thus, the rotation angle of the crank for one complete compaction cycle has been set to α_c=85°. Finally, the ratio between length of the crank and length of the connecting rod has been set to m/b=λ=0.2 in order to limit the transversal force exchanged between the piston and the frame.

Figure 7 shows different curves representing the applied force at the end of the lever in the mentioned conditions, for different initial crank angles α_o and with the precautionary assumption that the mechanical behaviour of the straw is defined by the “test 3” curve in Figure 6. The first part of the curves corresponds to the compression stage of the straw, while the second part

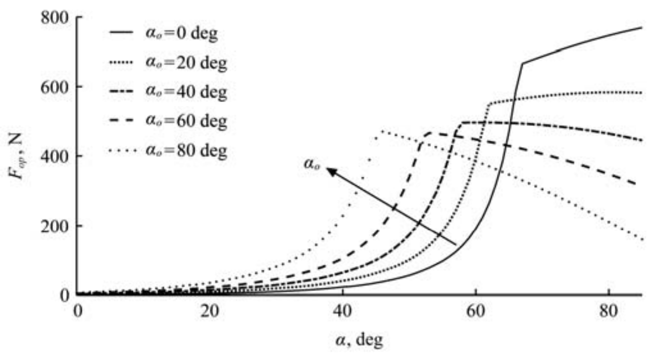


Figure 7 Operating force F_{op} versus the lever angle α, for different initial values α_o

(ρ_o≈30 kg m^{-3}; ρ_f = 120 kg m^{-3}; α_c = 85°; m/b = λ = 0.2; l = 2 m; y_c =0.18 m; η = 0.95) corresponds to the translation stage of the formed bale. In order to minimize the peak of the operating force, it is appropriate to choose an initial crank angle α_o>40°. In the presented case, aiming to limit the peak force at nearly 450 N and to limit the operating force in the last translation part of the compaction cycle, an initial crank angle α_o=80° has been chosen.

The main design parameters of the press are summarized in Table 2.

Table 2 Design parameters assumed and calculated

assumed design parameters	
Actuating lever length (m)	$l = 2$
Rotation angle of the lever per cycle (deg)	$\alpha_c = 85$
Compression work per cycle (J)	$L_{tot} \approx 550$
Ratio between crank and rod lengths	$\lambda = 0.2$
calculated design parameters	
Straw stiffness constant (Pa m^3 kg^{-1})	$k = 463$
Piston stroke (m)	y_c =0.180
Number of compaction cycles	$n_c \approx 20$
Initial angle of the operating lever (deg)	α_o=80
Crank length (m)	$m = 0.146$
Connecting rod length (m)	$b = 0.731$

7 The detailed design

Starting from the functional parameters that have been defined by means of the design method previously described, a detailed project of the new press, called Anpilpay 2.0, has been developed. A 3D scheme of the designed press is shown in Figure 8.

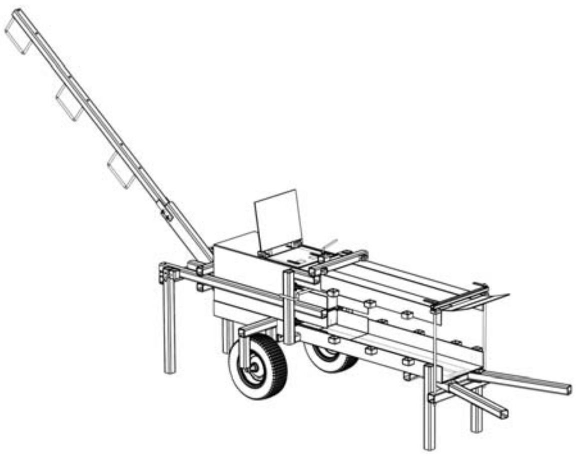
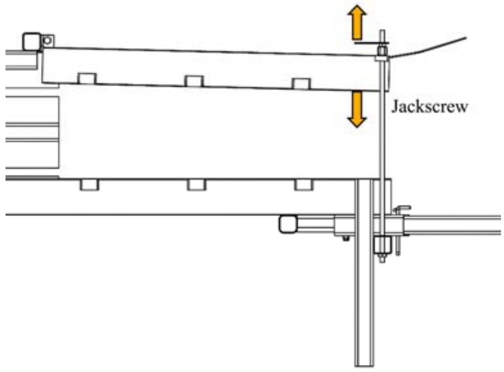
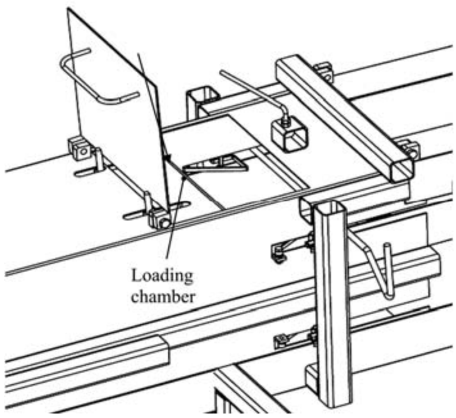


Figure 8 Detailed design of the press

The operator modifies the transverse crushing h on the ongoing bale acting on the specific jackscrew (Figure 9a). The straw to be pressed for each cycle is charged into the loading chamber (Figure 9b). Then the operator grasps the handles and rotates the lever that makes the piston move forward by mean of the sliding-crank mechanism (Figure 10).

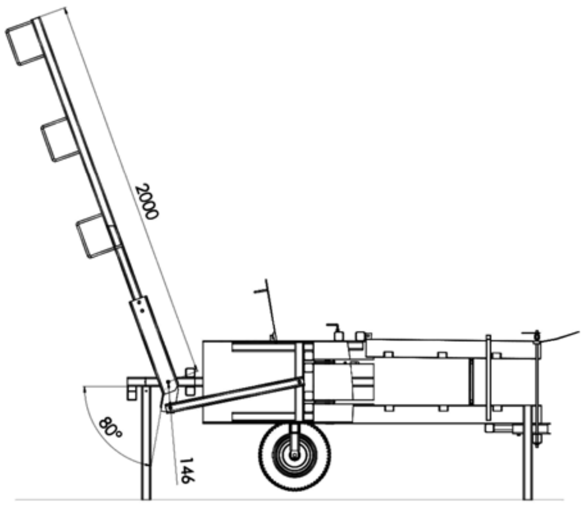


a. The density regulation system

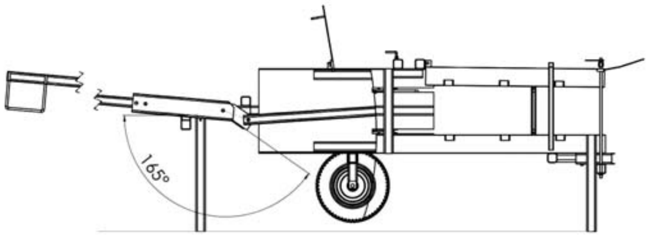


b. The compression chamber

Figure 9 Details of the density regulation system and of the compression chamber



a. Initial of the operating lever



b. Final position of the operating lever

Figure 10 Initial and final position of the operating lever

During the first stage of the cycle the density of the straw increases until the desired value is reached, then all the straw inside the mechanism translates. A specific non-return system (Figure 9b) prevents the compressed straw to re-expand once the lever returns to the initial position, and the compression chamber is then ready to start the next cycle. Once the bale reaches the desired length, it can be tied using specific needles. During the next compaction cycles the formed bale is forced to move towards the exit and then ejected, being replaced by ongoing bale.

8 The prototype

A prototype of the press Anpil Pay 2.0 was realised based on the above described design (Figure 11). The revolute joints and the prismatic joint of the compression plate are plain bearings. In order to reduce the friction force, lubricating grease was used.

Figure 11 The prototype of the Anpilpay 2.0 press

This prototype press has been tested and used to realise the straw bales needed to build a "Nebraska style" prototype of housing module, in the frame of the student project Anpilpay 2.0 at Politecnico di Torino (Figure 12).

Figure 12 Housing module with bearing straw bales, realized with the Anpilpay 2.0 press

The Anpilpay 2.0 press has improved several weak points of its predecessor Anpilpay 1.0 (Franco and Iarussi et al., 2016). In particular, the following considerations should be noted: Just a few adjustments to the density regulation mechanism allow the density of the bale to be efficiently regulated within a range of 90 to 120 kg m^{-3}. The system for the density regulation is able to maintain it constant regardless the quantity of the straw that is loaded at each compaction cycle; depending on the amount of loaded straw, the formed bale will translate of a greater or lesser quantity. The actuating force of the lever, as perceived by the operator, is contained within an acceptable range (F_{opmax}≈450 N for a nominal mass of loaded straw). The continuous production process of the machine allows to obtain bales having different lengths, for instance half-bales. The automatic ejection of the bale has proved to be more efficient than the process of manually extracting the bale from the compression chamber.

9 Conclusions

A concept of a manual press able to continuously produce straw bales with regulation of the density has been developed. Moreover, a rigorous design method valid for this kind of presses has been elaborated, and used to find the optimal functional parameters for a specific prototype within an experimental validation.

In particular: The slider-crank mechanism has proved to be effective in the actuation of the compression plate, both in the compaction stage of the ongoing bale and in the translation stage of the formed bale. The design method has made it possible to choose the best functional parameters of the press in order to minimize the peak of the force as perceived by the operator; thus, a rotation of the lever equal to α_c=85° has been chosen, starting from an initial angle of the crank equal to α_o=80°. The system for the density regulation has proved to be efficient, allowing a regulation between 90 and 120 kg m^{-3}. The prototype as a whole, built in accordance with the design method, has proved to be adequate in producing a lot of straw bales with 120 kg m^{-3} density, used to build a prototype of a housing module within the student project Anpilpay 2.0 at Politecnico di Torino.

However, the slider-crank mechanism, which has been chosen due to its simplicity, has shown some intrinsic weaknesses. In particular, the transmission ratio is not conveniently adapted to the mechanical behaviour of the straw. Thus, even if the peak of the operating force is limited, the trend of the operating force is highly variable along the compaction cycle, making it non-optimized from an ergonomic point of view. Further researches are indeed necessary in the field of mechanisms science, intended to seek for a device that, maintaining a certain simplicity, develops more adequate transmission ratio shapes.

Furthermore, the system for the density regulation has the considerable drawback of requiring a substantial amount of energy to realise a bale, more than twice the energy required for a fixed-chamber press. This weakness should be also solved with a more in-depth study of this system.

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Nomenclature

Symbol	Meaning	units
A	compression plate area	m^2
b	connecting rod length	m
f_s	straw-steel static coefficient of friction	
f	straw-steel kinetic coefficient of friction	
F	compression force	N
F_{op}	operating force	N
k	stiffness constant of the straw	Pa m^3 kg^{-1}
h	transverse crushing of the bale	m
l	operating lever length	m
l_f	final length of the straw mass m_c	m
l_o	initial length of the compression chamber	m
L_c	compression work per cycle	J
L_{opmax}	maximum mechanical work that an operator can do in one compacting cycle	J
L_t	ejecting bale translation work per cycle	J
L_{tot}	total work per cycle	J
m	crank length	m
m_c	mass of straw loaded in each compaction cycle	kg
m_{tot}	total bale mass	kg
N	transverse crushing force	N

Symbol	Meaning	units
n_c	number of compaction cycles to produce a bale	
p	compression pressure	Pa
p_f	straw compression pressure at final density ρ_f	Pa
T	friction force on the bale	N
y	compression plate (piston) displacement	m
y_b	displacement of forming bale	m
y_{bc}	bale displacement in one compaction cycle	m
y_c	compression plate (piston) stroke in one compaction cycle	m
α	rotation angle of crank (operating lever)	rad
α_c	rotation angle of crank (operating lever) in one complete compaction cycle	rad
α_o	initial crank (operating lever) angle	rad
γ	inclination of output neck	rad
λ	m/b, dimensionless parameter, mechanism's proportions	
ρ	density of the straw	kg m^{-3}
ρ_f	final density of the straw bale	kg m^{-3}
ρ_o	initial density of the straw	kg m^{-3}
ASF	Architettura Senza Frontiere (*Architecture Without Borders*)	