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Human powered press for producing straw bales for use in construction during post-emergency conditions

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Abstract

The straw bale construction technique is considered one of the most appropriate for the improvement of housing conditions in developing countries and for the reconstruction in post-emergency situations. In this environment, no electricity or other energy sources are available; for this reason, straw bales have to be produced by means of a human powered press. This paper presents the designing process of a manual press, that is a key tool for the objectives introduced above. Following definition of the machine architecture and the actuating mechanism (slider-crank), a design method based on energy considerations is introduced. Given the mechanical properties of straw, described by a simplified linear model, and the maximum work that a human operator can do, applying the designing method, it was possible to obtain the main functional parameters of the machine, such as the pressing piston stroke, and the length both of the connecting rod and of the crank. The method was experimentally validated and a prototype assembled and used for the production of infill bales in the construction of a warehouse in Haiti.

Keywords:

Straw bale construction; slider crank mechanism synthesis; human powered baler; hand-operated machine

Nomenclature

Symbol	Meaning	units
A	compression plate area	m^2
b	connecting rod length	m
C	operating torque	Nm
F	compression force	N
F_{op}	operating force	N
F_{opmax}	maximum force that is exerted by the operator	N
$F_{op\ peak}$	peak of the operating force	N
k	stiffness constant of the straw	Pa m^3 kg^{-1}
l	operating lever length	m
l_f	final length of the compression chamber	m
l_o	initial length of the compression chamber	m
L_c	compression work per cycle	J
L_{opmax}	maximum input mechanical work that an operator can do in one compacting cycle	J
m	crank length	m
m_c	mass of the straw loaded in the loading chamber between each compaction cycle	kg
m_{tot}	total bale mass	kg
n_c	number of compaction cycles necessary to produce a bale	

p	compression pressure	Pa
p_f	straw compression pressure at final density ρ_f	Pa
y	compression plate (piston) displacement	m
y_c	compression plate (piston) stroke in one compaction cycle	m
α	rotation angle of the crank (operating lever)	rad
α_c	rotation angle of the crank (operating lever) for one complete compaction cycle	rad
α_0	initial crank (operating lever) angle	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_0	initial density of the straw	kg m^{-3}
ASF	Architettura Senza Frontiere (*Architects Without Borders*)	

1. Introduction

The earliest straw bale constructions were built in Nebraska, USA, towards the end of the 19th century (Jones, 2009; King, 1996; Magwood, 2000). Those were temporary constructions, built while waiting for the wood supplies needed for the producing permanent constructions. Only later straw bales were applied as the main building material for permanent constructions (Jones, 2009) and some of these are still in use today (Lerner, 2000).

Around 1970, with the increase in awareness of the green building technology, there was renewed interest in this construction technique. Straw is a sustainable naturally renewable material, which is widespread, cheap and with good insulating properties. Building with straw bales can provide energy-efficient, durable, attractive, fire-resistant, and comfortable accommodation (Ashour 2011, Jones 2009).

Thanks to these characteristics, particularly availability, the low cost of straw and the easy implementation in self-construction projects, straw bale building is considered one of the most appropriate techniques for providing improved housing in developing countries and for reconstruction in post-emergency situations (earthquakes, tsunami etc.) (ASF, 2013; Bonoli, 2015; Kean, 2010). To apply this construction technique, it is necessary to have bale production equipment, and where there is no availability of motorised balers for agricultural use, or the cost to handle this kind of equipment is too high, the application of a manual pressing machine can be a very effective alternative.

There appears to be no scientific literature regarding manual straw bales pressing. The solutions currently available are the result of empirical studies and progressive adjustments on the field. For example, the Pakistan Straw Bale and Appropriate Building (PAKSAB) reported by Khan and Donovan (2012), a project of Builders Without Borders (http://www.builderswithoutborders.org/), straw bales were made with locally 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 resistance applied 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 was a dimensioning methodology introduced (The Appropedia Foundation, http://www.appropedia.org/).

To address this shortcoming, in our study the aim was to produce a rigorous methodology for the functional synthesis of a slider crank mechanism applied to a manual straw bale press. The concept was to produce a dimensioning method for optimising the performance of bailing mechanisms based on a simplified straw mechanical characteristic model developed for the purpose; making it possible, even in areas with a low availability of instrumentation, to conduct tests.

The methodology proposed is applied to the design of a hand-powered rice straw press that can produce bales for use as infill material for construction. The authors developed the design method for the *Architettura Senza Frontiere Piemonte (ASF, Architects Without Borders)* project for building a straw warehouse for a rice farmers cooperative in Saint Marc, Artibonite Valley, Haiti (ASF Piemonte, 2013). Artibonite Valley is the main rice production area in Haiti, and the farmers' cooperative is a local partner of an international cooperation project, aimed at enhancing the rice supply chain and also enabling the straw to be used as a construction material.

In this paper the design specification of the press is defined and listed, and an energy-based calculation method for the functional parameters of the press, in particular the number of compaction cycles required by the hand-powered mechanism, is introduced, described and validated. The mechanical architecture of the press, the functional and detailed design of the slider crank mechanism are described, and all the technical data of the machine are listed. The mechanism synthesis method is validated by means of experimental tests and the end prototype that was built is presented and conclusions provided.

2. Goal statements and design specifications

Starting from rice straw with initial density of ρ_0 = 30 kg m^{-3}, the press has to produce straw bales with final dimensions of 0.3x0.45x0.9 m and a density of ρ_f = 90 kg m^{-3}. The final density needs to be sufficient for utilising the bales as an infill material in construction (King, 2006). The main characteristics of the bale are listed in Table1.

Table 1. Main straw bale characteristics

Straw initial density ρ_0	30 kg m^{-3}
Bale final density ρ_f	90 kg m^{-3}
Bale dimensions	0.3x0.45x 0.9 m
Total bale mass m_{tot}	10.9 kg

The press must be able to work in rural areas of developing countries, even in post emergency conditions, for example during the re-building phase following an earthquake. For this reasons any press must be capable of operation without electricity or fuel. To cope with this situation, it is therefore necessary to opt for a hand-powered actuating mechanism.

Since one of the aims of the project was to involve local communities and to engage a self-constructing and sustainable technology process at a local level, the press has to be simple, ergonomic and easy to build; it has to be made using metal products and other materials that can be found directly on site. An objective was not only to build a hand-powered press for producing straw bales, but to transmit knowledge to local people, so that in the future they could build, use and maintain other presses. During the designing phase it is therefore necessary to take into account the limits imposed by the technical means that the destination territory can offer, in this case the community of Bocozelle, Saint Marc, Artibonite Valley, Haiti.

3. Human powered press design: an energy method

Apart from the architecture and the transmission mechanism, the press can be seen as a black box machine. The operator moves the actuating lever (i.e. the input link) through an angle α, obtaining the displacement y from the compressing plate (i.e. the output link, Fig. 1). The goal of the design phase is to build a machine that transforms the rotation of the lever into the translation movement of the compression plate, by mean of instantaneously variable transmission ratios defined considering the force slope needed for compression and the range of the torque applied by the operator. The compressed straw applies a resistant force F to the compression plate that requires the operator to apply an input torque C to the lever.

Defined F_{opmax} the maximum force that a human operator can apply at the end of the lever of length l, and α_c the angular rotation of the lever that corresponds to one single compaction cycle, the maximum mechanical work that an operator can do in one compaction cycle is given by:

$$L_{op\max} = F_{op\max} l \cdot \alpha_c \tag{1}$$

The work needed, for each compaction cycle, in order to compress the straw is:

$$L_c = \int_0^{y_c} F \, dy = \int_0^{y_c} p(\rho) A \, dy \tag{2}$$

where y_c is the compression plate stroke, p is the compression pressure that the plate of area A exerts on the straw, dependent on the straw density ρ.

The compression work L_c has to be assumed equal to a fraction of the maximum work L_{opmax} that the operator can do in one compacting cycle, expressed in Eq. (1). However, the force that the operator exerts on the lever depends on the mechanical characteristics of the straw, on the instantaneous transmission ratio, and on the efficiency of the mechanism. For this reason, the applied force cannot be considered constant and equal to the maximum force that can be exerted F_{opmax} for all the range of the lever rotation.

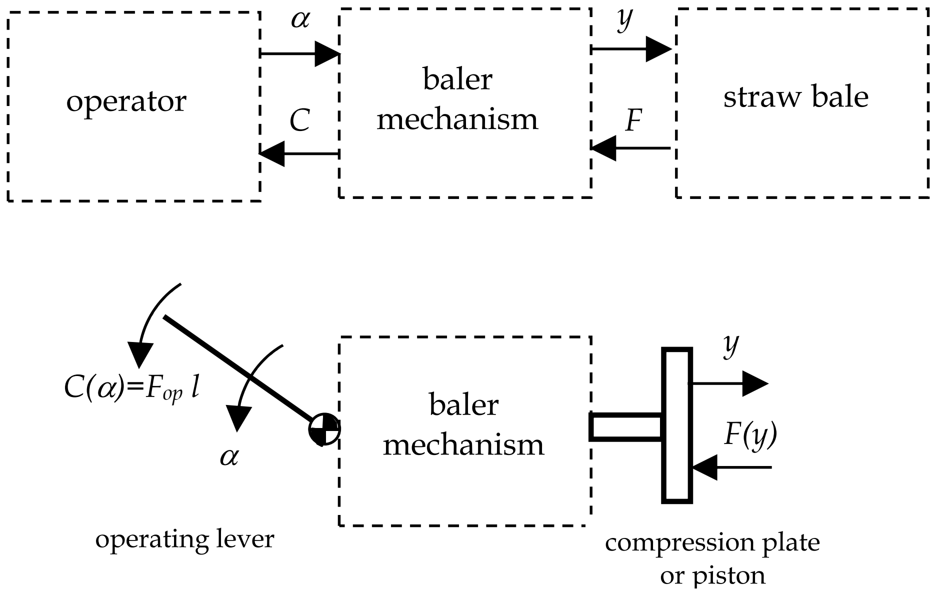

Fig. 1. Black box baler model

In literature there are many straw and hay mechanical characteristics models (Afzalinia 2013; Bilanski 1985; Faborode, 1986; Ferrero 1990; Galedar, 2008; Kaliyan, 2009; Mewes, 1958; Nona 2014; Watts, 1991). Since each model has been developed with straw in different initial conditions, the trends that correlate compression pressure p and straw density ρ, are heterogeneous, and are not applicable to this case of study. Also, at the Haiti site, during construction activities, it was not possible to execute complete compression tests in order to identify a mechanical model of the straw behaviour, and in general in these contexts, the problem of the mechanical characterisation of the straw to be compressed is common. The ASF operators could only measure the straw initial density ρ_o (30 kg m^{-3}) and the required pressure p_f (0.3 $\times 10^5$ Pa) to reach the final density of ρ_f (90 kg m^{-3}. Not having sufficient data, it was necessary to opt for a linear model for the straw mechanical behaviour (Fig. 2):

$$p = k(\rho - \rho_o) \tag{3}$$

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

$$k = \frac{p_f}{\rho_f - \rho_o} \tag{4}$$

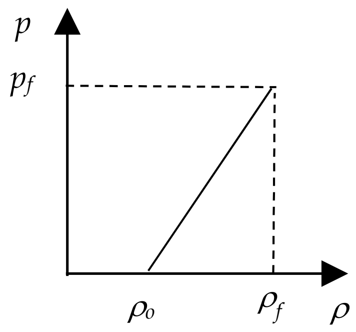

Fig. 2. Straw mechanical characteristic

Merging Eq. (3) in Eq. (2), taking into account that ρ is the ratio between the straw mass m_c and its true volume, and integrating, it is possible to obtain the straw mass m_c that is need to load the press in between each pressing cycle and relate it to the compression work L_c:

$$m_c = \frac{L_c}{k\left(\ln\left(\frac{\rho_f}{\rho_o}\right) + \frac{\rho_o}{\rho_f} - 1\right)} \tag{5}$$

Defining m_{tot} as the total mass of the straw bale, and assuming the compression work L_c is available for each pressing cycle as a fraction of the maximum input mechanical work, it is possible to obtain the number of pressing cycles (n_c) needed for the bale production:

$$n_c = \frac{m_{tot}}{m_c} = \frac{m_{tot} k\left(\ln\left(\frac{\rho_f}{\rho_o}\right) + \frac{\rho_o}{\rho_f} - 1\right)}{L_c} \tag{6}$$

The trend of the number of compression cycles n_c, related to the compression work for each cycle, needed to obtain a bale of total mass m_{tot} of 10.9 kg and a final density ρ_f of 90 kg m^{-3}, starting from straw with an initial density ρ_o of 30 kg m^{-3} is shown in Fig. 3. The curve parameter is the stiffness constant of the straw k that can be obtained experimentally using Eq. (4).

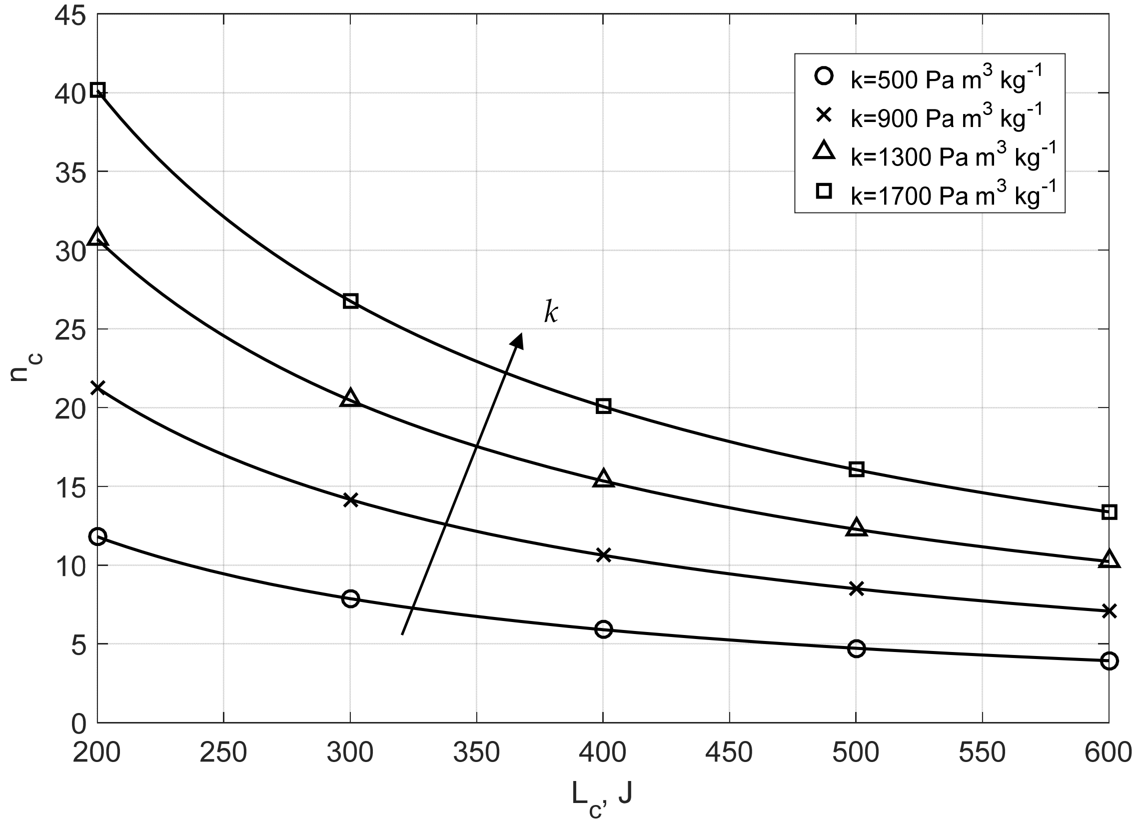

Fig. 3. Number of compaction cycles n_c related to the compression work for each cycle L_c (straw stiffness constant k, m_{tot} = 10.9 kg, ρ_o = 30 kg m^{-3}, ρ_f = 90 kg m^{-3})

In order to guide the reader, and indicate how the parameters k and L_c are evaluated, it is useful to consider a specific case: If an operator applies a constant force F_{op} = 200 N, to a lever of length 1.5 m, which is always normal to the level itself for a rotation of 80°, it provides work of about 400 J (Eq. 1). For the straw stiffness, using the straw initial density ρ_o = 30 kg m^{-3} and the required pressure p_f = 0.3 ×10^5 Pa, to reach the final density of ρ_f = 90 kg m^{-3}, Eq. 4 provides a value of k = 500 Pa m^3 kg^{-1}.

Each of the n_c compaction cycles consists of putting a mass of straw m_c as for Eq. (5), with an initial nominal density of ρ_o = 30 kg m^{-3}, in the compression chamber with section A and initial length l_o (Fig. 4), compressing the straw up to a density of ρ_f = 90 kg m^{-3} and reducing the compression chamber length to l_f, i.e. imposing the piston stroke of y_c, then:

$$y_c = l_o - l_f = \frac{1}{\rho_o A} m_c \left(1 - \frac{\rho_o}{\rho_f}\right) = \left(\frac{1}{\rho_o} - \frac{1}{\rho_f}\right) \frac{L_c}{Ak\left(\ln\left(\frac{\rho_f}{\rho_o}\right) + \frac{\rho_o}{\rho_f} - 1\right)} \tag{7}$$

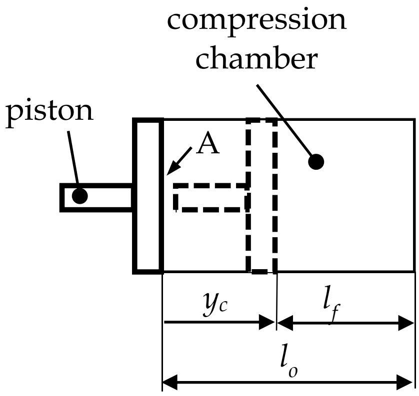

Fig. 4. Compression chamber scheme

The piston stroke y_c , for each compaction cycle is expressed by Eq. (7) and related to the compression work per cycle L_c, as shown in Fig. 5. This curves are again obtained by using the parameters needed for a straw bale of total mass m_{tot} = 10.9 kg and transverse sectional area A = 0.3x0.45 m^2, initial density ρ_o=30 kg m^{-3}, and a final density ρ_f = 90 kg m^{-3}. The curve parameter remains the stiffness constant of the straw k.

Equation (7) allows the piston stroke for each compaction cycle y_c to be calculated, fixing the compression work per cycle L_c as a percentage of L_{opmax}, i.e. the maximum work that the operator can do, and knowing the straw stiffness constant k. This value y_c is used as input for the next designing step of the transmission mechanism.

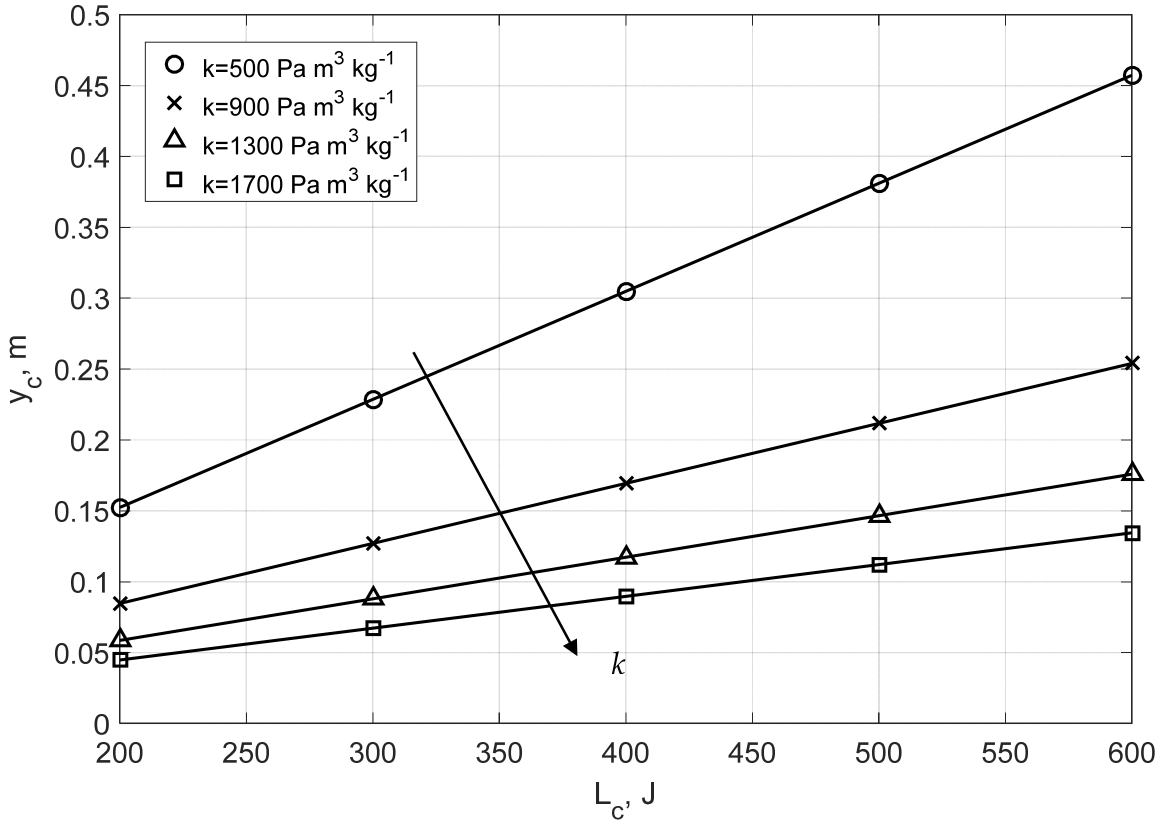

Fig. 5. Piston stroke y_c for cycle related to the compression work for each cycle L_c (straw stiffness constant k, m_{tot} = 10.9 kg, ρ_o=30 kg m^{-3}, ρ_f = 90 kg m^{-3})

4. The functional design

Considering the design specifications introduced in section 2, in particular the need for a simple manufacturing process of the machine, a centred slider crank mechanism was chosen as the transmission mechanism for the press. The operating lever is rigidly connected to the crank (Fig. 6). In this section the dimensioning process of the mechanism will be described. It is assumed that the operating lever length is l , the crank length m, and the connecting rod length is b.

The crank has an initial angular position α_o, and it rotates at an angle α, until reaching a maximum value α_c ($0<\alpha<\alpha_c$) corresponding to the translation y_c of the piston. The aim of the functional model is to choose the optimum lengths of the crank m, and the rod b, and the initial angle of the lever α_o, in order to reach a desired stroke of the piston y_c and reduce the peak of the operating force. The lever length l and its rotation angle for one compaction cycle α_c, were chosen taking into account ergonomic reasons that will be clarified later.

Referring to Fig. 6, it is possible to obtain the piston displacement y starting from the initial position:

$$y = b(\cos\beta - \cos\beta_o) + m(\cos\alpha_o - \cos(\alpha_o + \alpha)) \tag{8}$$

with:

$$\lambda = m/b \qquad \beta_o = \arcsin(\lambda \sin(\alpha_o)) \qquad \beta = \arcsin(\lambda \sin(\alpha_o + \alpha)) \tag{9}$$

The stroke of the compression plate for one compaction cycle is thus:

$$y_c = b(\cos\beta_c - \cos\beta_o) + m(\cos\alpha_o - \cos(\alpha_o + \alpha_c)) \tag{10}$$

being:

$$\beta_c = \arcsin(\lambda \sin(\alpha_o + \alpha_c)) \tag{11}$$

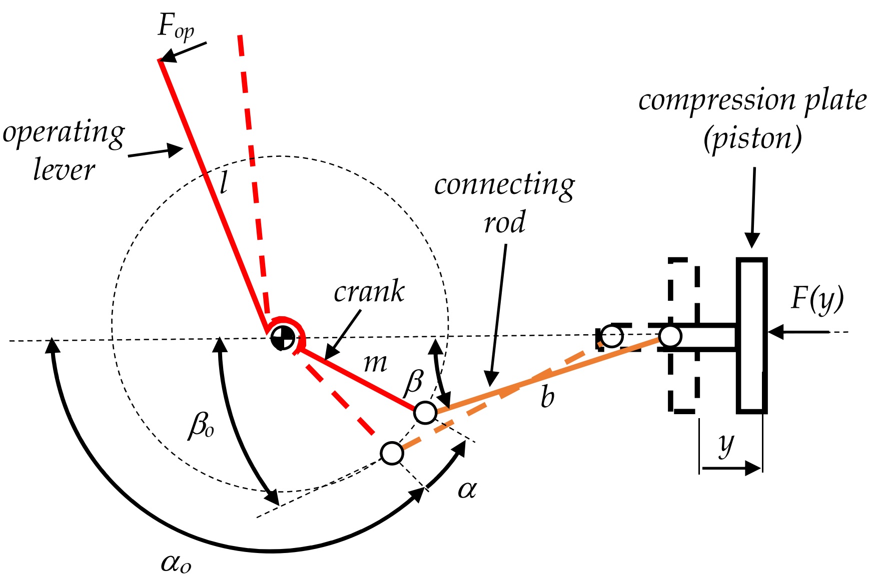

Fig. 6. Baler slider-crank mechanism. Initial position (hatched line); generic position (continuous line).

Dividing Eq. (10) by the crank length m, and bearing in mind that $\lambda = m/b$ is the ratio between the crank length m and the connecting rod length b, it is possible to obtain:

$$\frac{m}{y_c} = \frac{1}{1/\lambda(\cos\beta_c - \cos\beta_o) + \cos\alpha_o - \cos(\alpha_o + \alpha_c)} \tag{12}$$

The Eqs. (9), (11) and (12), allow the ratio between the crank length and the piston stroke m/y_c to be calculated as a function of the initial crank angle α_o, once the parameter λ and the maximum rotating angle of the lever α_c are chosen. 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. The choice of the rotation angle α_c of the lever, that corresponds to one compacting cycle, can be based on ergonomic considerations. Even with a centred sliding crank mechanism this angle can be 180°, usually, in the manual mechanism it is fixed in the range 80-90° so that the operator can easily hold the suitably shaped lever, and rotate it from an almost vertical position to a horizontal one, optimising the applied force application. In Fig. 7 the trend of the Eq. (12) is shown for different λ values (λ = 0.14, 0.28, 0.42), with a fixed value of α_c = 80°.

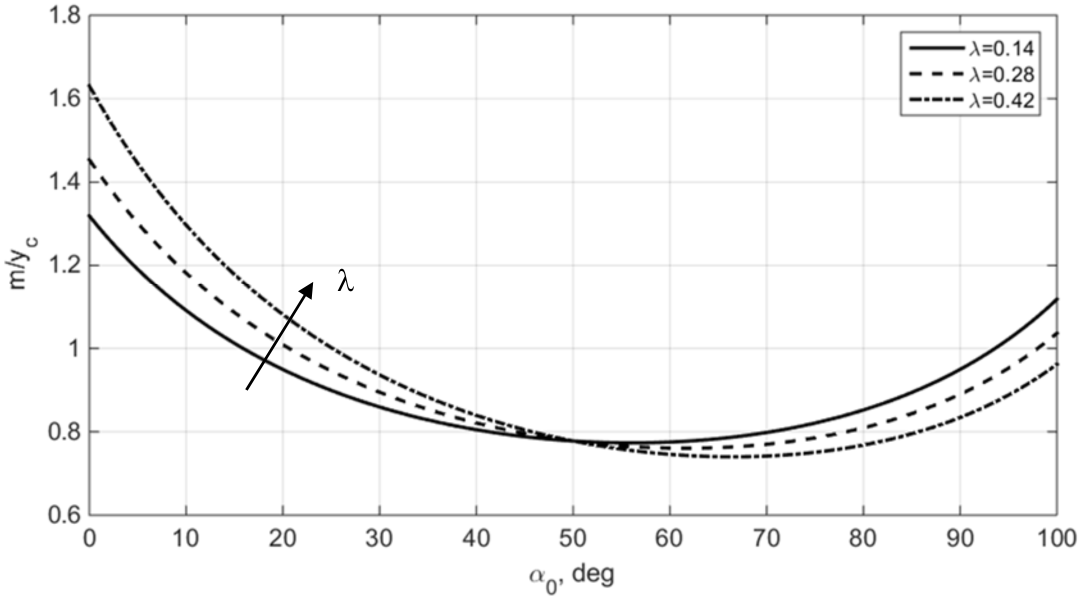

Fig. 7. Trend of the ratio of the crank length and the piston stroke m/y_c related to the initial rotation angle of the lever α_o (α_c =80°)

In order to calculate the force applied by the operator at the lever end, we can write:

$$F_{op} l \cdot d\alpha = \frac{F dy}{\eta} \tag{13}$$

where η is the total efficiency of the transmission and recalling Eq. (3)

$$F_{op} = \frac{F}{\eta l}\frac{dy}{d\alpha} = \frac{pA}{\eta l}\frac{dy}{d\alpha} = \frac{k(\rho - \rho_o)A}{\eta l}y' \tag{14}$$

where y' is the geometrical speed $dy/d\alpha$ of the output link

$$y' = [b\cos\beta - m\cos(\alpha_o + \alpha)]\tan\beta \tag{15}$$

Considering that:

$$\rho = \frac{m_c}{A(l_o - y)} \tag{16}$$

$$\rho_o = \frac{m_c}{Al_o} \tag{17}$$

$$l_o = \frac{y_c}{1 - \frac{\rho_o}{\rho_f}} \tag{18}$$

and considering Eq. (8), it is possible to obtain the trend of the force applied by the operator F_{op} versus the rotation angle of the lever α:

$$F_{op} = \frac{L_c}{\eta l\left(\ln\left(\frac{\rho_f}{\rho_o}\right) + \frac{\rho_o}{\rho_f} - 1\right)}\left(\frac{1}{\frac{1}{1-\frac{\rho_o}{\rho_f}} - \frac{m}{y_c}\left(\frac{1}{\lambda}(\cos\beta - \cos\beta_o) + \cos\alpha_o - \cos(\alpha_o + \alpha)\right)} - \left(1 - \frac{\rho_o}{\rho_f}\right)\right) \bullet$$
$$\bullet \frac{m}{y_c}\left(\frac{1}{\lambda}\cos\beta - \cos(\alpha_o + \alpha)\right)\tan\beta \tag{19}$$

where m/y_c is expressed by Eq. (12).

The lever length l can be chosen based on ergonomic considerations. Even if a longer lever is better from a force reduction point of view, the operator has to be able to grab it even, when it is in a vertical position. For this reason, the maximum lever length is around 2 m.

Equation (19) shows that the operator force trend related to the rotation angle of the lever is defined once that the initial density of the straw ρ_o, the final density of the bale ρ_f, the lever length l, the rotation angle of the lever for one compacting cycle α_c, the compression work per cycle L_c, and the ratio λ are all known. It does not depend from the straw stiffness constant k because, according to the mechanical characteristic of the straw and to the compression work L_c, the piston stroke y_c will change on a case to case basis based on Eq. (7) (Fig. 5). For example, fixed the compression work L_c, and λ, is possible to compress straw to high stiffness, reducing the stroke of the piston.

Equation (19) (with $\rho_o = 30$ kg m^{-3}; $\rho_f = 90$ kg m^{-3}; $\alpha_c = 80°$; $l = 2$m; $Lc = 400$ J; $\eta = 0.95$) is plotted in Fig. 8 considering $m/b = \lambda = 0.14$, considering $m/b = \lambda = 0.28$ in Fig. 9, and considering $m/b = \lambda = 0.42$ in Fig. 10. Figures 8, 9 and 10 show the actuating force related to the lever rotation angle of the lever, for different initial angles of the lever. The trend for the operating force peak $F_{op\ peak}$ related to the starting angle of the operating lever α_o, calculated in the same conditions and fixed the ratio $m/b{=}\lambda$, is showed in Fig. 13.

Equations (5), (7), (12) and (19) are valid for the manual press dimensioning and a useful tool. Assuming that we want to produce a straw bale with known geometry and known final and initial densities, knowing the straw stiffness constant k, and choosing a compression work per cycle L_c, from Eq.(5) it is possible to obtain the straw mass that is needed to load between each cycle m_c, and from Eq. (7) the piston stroke y_c. Chosing the lever length l and the lever rotation angle α_c, based on the ergonomic considerations discussed above, and fixed the appropriate value of λ in order to have acceptable forces discharged by the piston on the frame, from Eq. (19) it is then possible to obtain the operating force F_{op} trend and in particular the operator force peak F_{oppeak} (Fig. 11). From Fig. 11 it is possible to see that, in order to minimise the peak operating force, it is convenient to choose initial rotation angles in the range of 80 -100°. Fixed α_o, based on these considerations , using Eq. (12), showed in Fig. 7 that it is possible to obtain the ratio m/y_c, or rather, if y_c and l are known, it is possible to calculate the crank length m and the connecting rod length b of the slider-crank mechanism that best satisfies the design requirements.

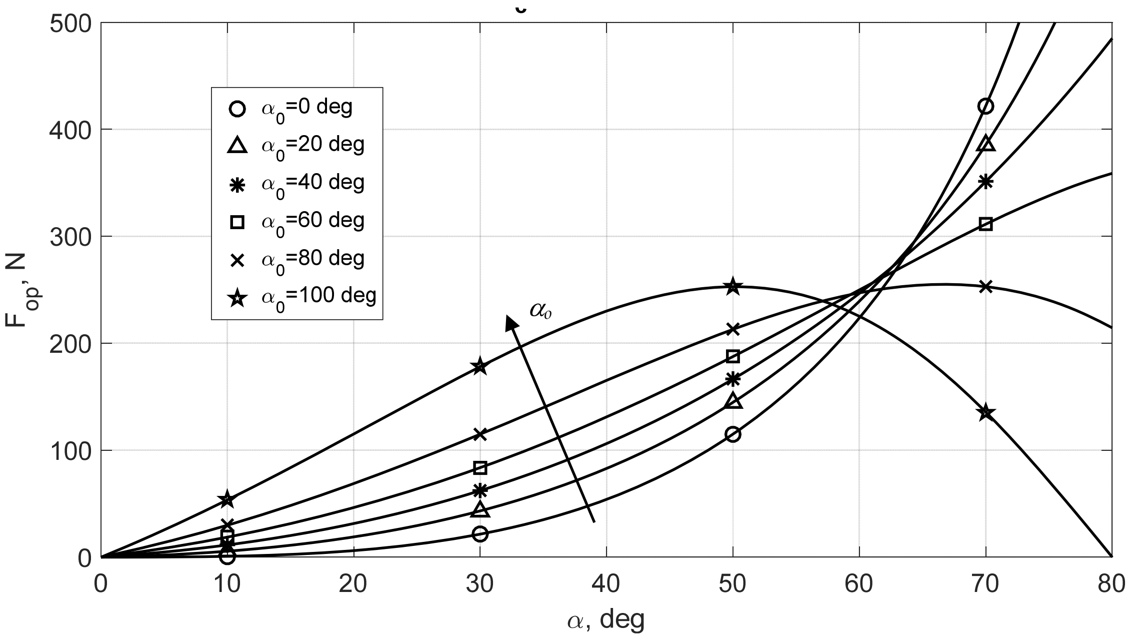

Fig. 8. Operating force F_{op} related to the rotation angle of the lever α for different initial angles of the lever α_o
(ρ_o = 30 kg m^{-3}; ρ_f = 90 kg m^{-3};α_c = 80°; $m/b = \lambda$ = 0.14; l = 2m; L_c = 400 J; η = 0.95)

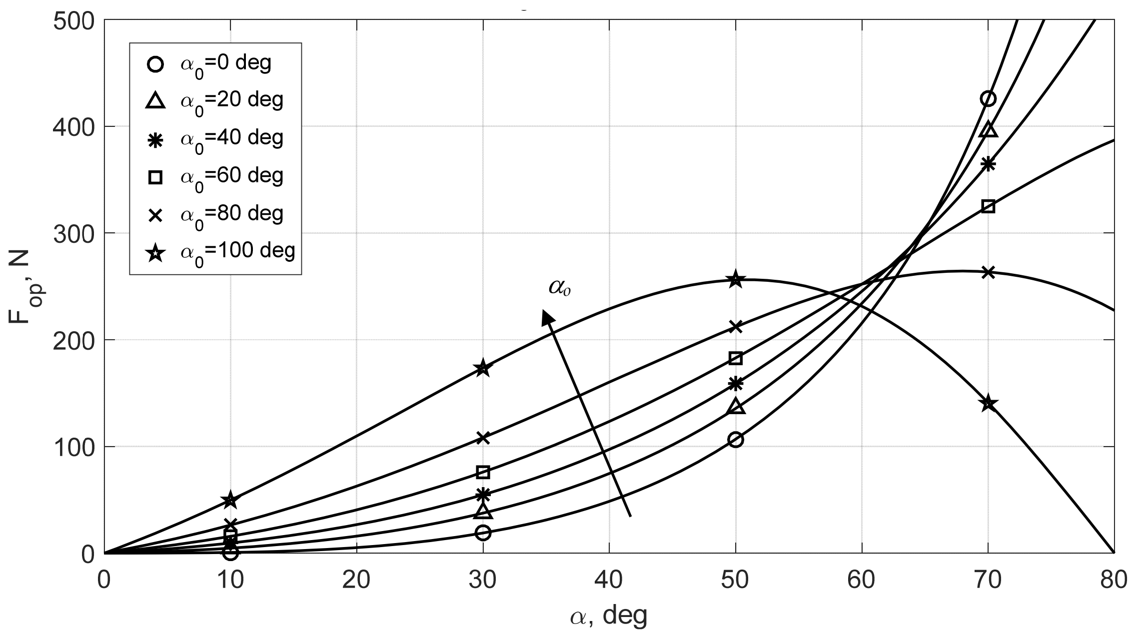

Fig. 9. Operating force F_{op} related to the rotation angle of the lever α for different initial angles of the lever α_o
(ρ_o=30 kg m^{-3}; ρ_f = 90 kg m^{-3}; α_c = 80°; $m/b = \lambda$ = 0.28; l = 2m; L_c =400 J; η = 0.95)

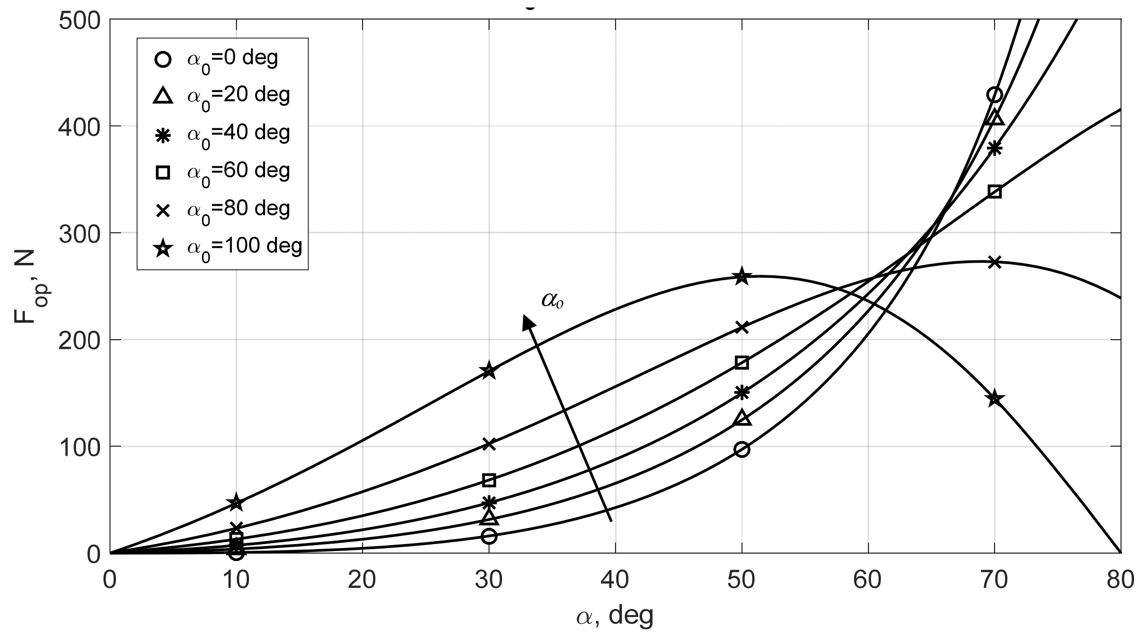

Fig. 10. Operating force F_{op} related to the rotation angle of the lever α for different initial angles of the lever α_o
(ρ_o=30 kg m^{-3}; ρ_f= 90 kg m^{-3}; α_c=80°; m/b =λ = 0.42; l = 2m; L$_c$= 400 J; η= 0.95)

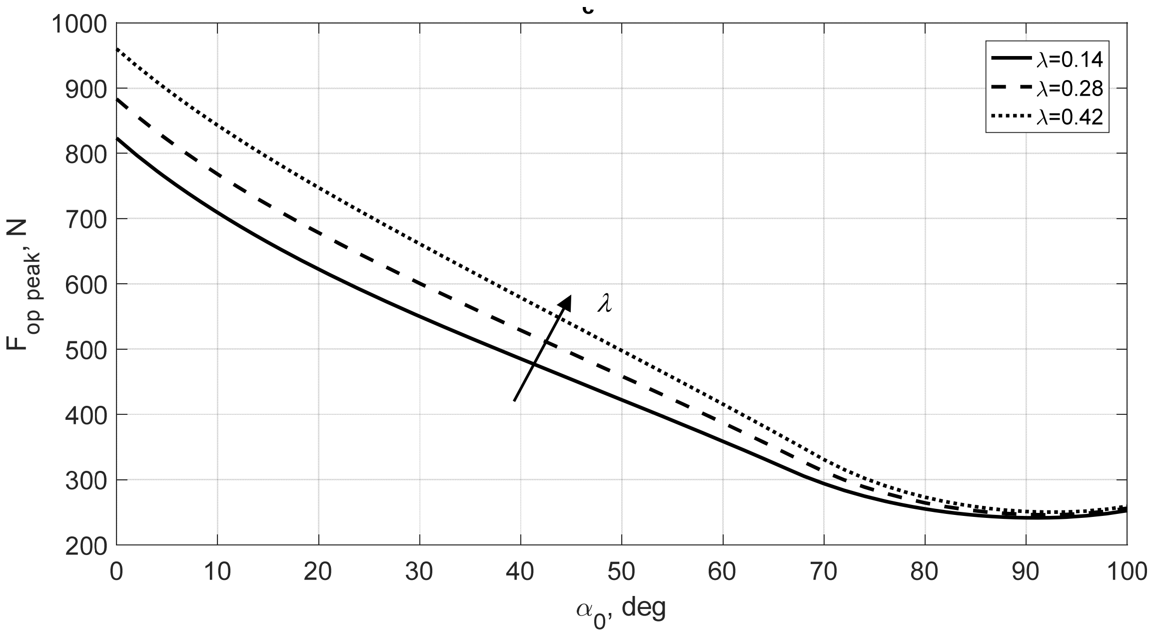

Fig. 11. Peak of the operating force $F_{op\ peak}$ related to the initial rotation angle of the lever α_o for different ratios m/b=λ
(ρ_o=30 kg m^{-3}; ρ_f= 90 kg m^{-3}; α_c=80°; l = 2m; L$_c$= 400 J; η= 0.95)

5. Validation of the synthesis methodology

In order to validate the functional designing methodology, introduced in the previous paragraphs, a synthesis of the actuation mechanism of a press able to compress rice straw on which an accurate experimental mechanical characterisation was conducted.

A total mass of 1.720 kg of straw was introduced into the compressing chamber of section 0.36 x 0.45 m. The compression plate displacement was controlled at the speed of 3 mm s^{-1} until it reached the 90 kg m^{-3} final density required. The compression force and the position plate data were elaborated in order to obtain the pressure – density characteristic of the straw. The experimental trend was linearised based on Eq. (3) evaluating the stiffness coefficient of the straw using Eq.(4) (k = 246 Pa m^3 kg^{-1}). Applying the synthesis methodology, considering a compression work per cycle Lc = 400 J, an actuating lever length l = 2m, a rotation angle of the lever per cycle α_c = 80°, an initial angle of the operating lever α_o=100°, λ = 0.42, it showed that the plate stroke must be y_c = 0.63 m (Eq. (7)), and this can be obtained using a crank length of m = 0.60 m and a shaft length of b = 1.44m (Eq. (12)).

In Fig. 12 the operating force trends related to the rotating angle are shown, based both on the linear and on the experimental relation between straw density and compression pressure. The trends of the operating forces are comparable. The maximum operating force obtained with the experimental curve is lower, around 11%, than the one calculated using a linear trend. In general, therefore, it is possible to state that the linear model can be used to design the mechanism in a conservative way, with a limited and acceptable for the application error.

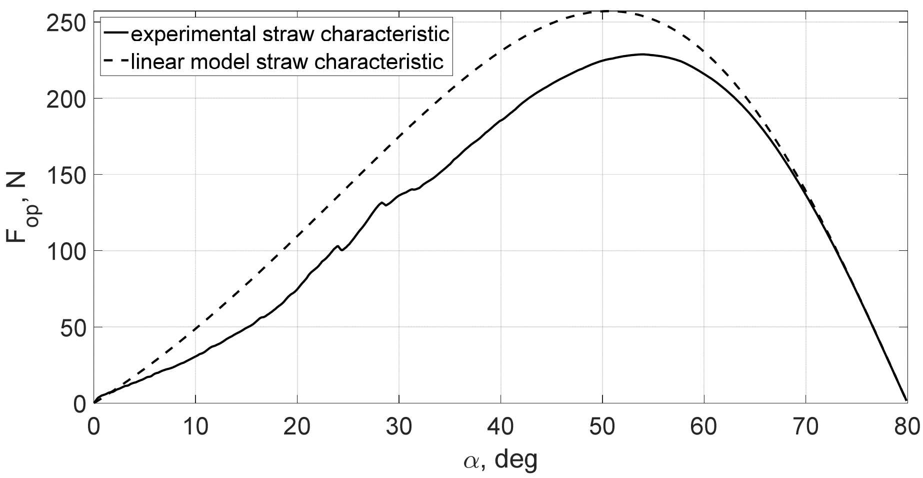

Fig. 12. Operating force F_{op} related to the lever rotation angle α, calculated using the linear model of the straw characteristic (dashed line), and the experimental characteristic (continuous line).

6. The detailed design

The synthesis methodology was used to define the functional parameters of the press. The design parameters assumed and calculated using the methodology described in the sections 3 and 4 are listed in Table 2.

The stiffness constant of the straw was calculated by means of Eq. (4), being measured, in experimental tests done on the Haiti site, the values of the compression pressure p_f= 0.3 ×10^5 Pa needed to reach the final bale density of ρ_f= 90 kg m^{-3} starting from an initial density of ρ_o=30 kg m^{-3}. The lever length l and its rotation angle for the compaction cycle α_c were fixed based on the ergonomic considerations, as discussed in section 4. The compression work L_c was fixed, in a conservatively, to equal the half of the maximum work that can be done by a single operator and considering an efficiency of the all transmission η:

$$L_c = \frac{1}{2}\eta L_{op\max} = \frac{1}{2}\eta F_{op\max} l \cdot \alpha_c \qquad (20)$$

assuming $F_{op\ max}$=300 N and η=0.95.

Table 2. Design parameters assumed and calculated

Design parameters assumed	
Actuating lever length	l = 2 m
Rotation angle of the lever per cycle	α_c = 80°
Compression work per cycle	L_c = 400 J
Ratio between crank and rod lengths	λ = 0.42
Design parameters calculated	
Straw stiffness constant	k = 500 Pa m^3 kg^{-1}
Piston stroke	y_c =0.31 m
Number of compaction cycles	n_c = 6
Initial angle of the operating lever	α_o=100°
Ratio between crank length and piston stroke	m/y_c = 0.96
Crank length	m = 0.3 m
Connecting rod length	b = 0.7 m

In Fig. 13 a 3D scheme of the designed press is shown. The straw to be pressed for each cycle is charged into the loading chamber. The operator rotates the lever that makes the piston move forward by mean of the sliding-crank mechanism. The sliding/lockable end of the pressing chamber is adjustable, and can be moved cycle after cycle, from a position that is near the pressing chamber to the other end of it. In this way, while the bale is being pressed, the geometry of the pressing chamber, represented in Fig. 4, is restored. The extraction of the bale, manually tied, is done by means of the unloading door.

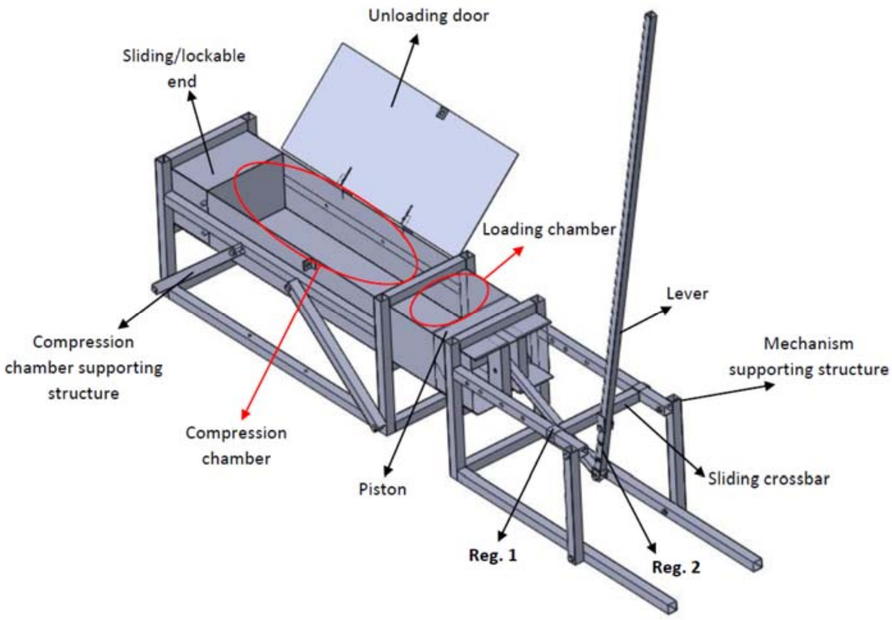

Fig. 13. Detailed design of the press

Because of the uncertainty concerning straw mechanical characteristics, and in order to produce straw bales even in the case in which the straw stiffness constant is higher than expected, a regulation of the slider-crank mechanism has been introduced (Fig. 14). Moving the lever fixed hinge O, it is possible to obtain different length of the crank m_1 = 0.3 m (design length), m_2 = 0.2 m, m_3 = 0.1 m, maintaining the connecting rod length equal to b = 0.7 m. Thanks to this, i.e. reducing the piston stroke to 0.09 m with 20 cycles of compression maintaining the compression work L_c=400 J, it is possible to press straws with a stiffness constant k up to 1700 Pa m^3 kg^{-1} (Table 3).

Table 3. Functional parameters in the three press configurations

Project assumptions			
Straw stiffness constant	k = 500 Pa m^3 kg^{-1}	k = 800 Pa m^3 kg^{-1}	k = 1700 Pa m^3 kg^{-1}
Lever length	l =2 m	l = 2 m	l = 2 m
Rotation angle of the lever per cycle	α_c = 80°	α_c = 80°	α_c = 80°
Compacting work	L_c = 400 J	L_c = 400 J	L_c= 400 J
Crank/rod ratio	λ = 0.42	λ = 0.28	λ = 0.14
Calculated data			
Piston stroke	y_c = 0.31 m	y_c= 0.19 m	y_c = 0.09 m
Number of cycles per bale	nc =6	nc = 10	nc = 20
Initial angle of rotation of the lever	α_o = 100°	α_o = 100°	α_o = 100°
Crank length/piston stroke ratio	m/y_c = 0.96	m/y_c = 1.04	m/y_c = 1.12
Crank length	m = 0.3 m	m = 0.2 m	m = 0.1 m
Rod length	b = 0.7 m	b = 0.7 m	b = 0.7 m

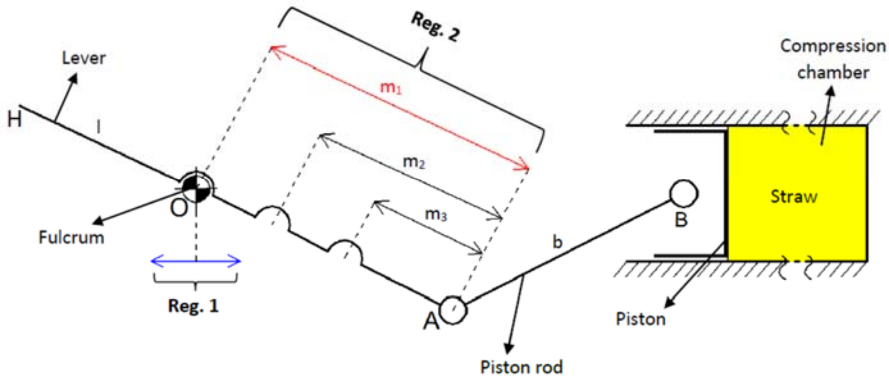

Fig. 14. Regulation of the sliding-crank mechanism

7. The prototype

Based on the design made, a prototype of the press, called Anpil Pay 1.0, was constructed by the mechanical workshop of the Salesian school of Port-au-Prince, Haiti (Fig.15). The prototype was constructed using simple equipment: a circular saw, a drill press and a welding machine. 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. The prototype press was used to produce the straw bales required as infill for the construction of the lateral walls of the warehouse (Fig.16).

Fig. 15. The prototype of the press

Fig. 16. A typical straw bale obtained by using the prototype press and the background the warehouse built by ASF in Haiti using the bales.

Although the press was able to produce the 240 bales needed to build the warehouse some weaknesses were identified:

- the re-positioning of the sliding/lockable end during the compacting of the straw bale was not really effective;
- the need to weigh the straw that was put into the loading chamber between each compression cycle was an uncomfortable operation;
- the tying operations of the bale were difficult and took a very long time, up to 10 m.

8. Conclusions

A rigorous design method for a hand-powered press used for producing straw bales was developed. The method was validated experimentally and used to calculate the main functional parameters of a specific prototype press.

In particular:

- The method showed that the slider crank mechanism is able to actuate a human powered straw press, allowing variable transmission ratios as the resistance force applied by the straw increases.
- It is possible to optimise the functional parameters of the mechanism starting from a simplified linear straw mechanical model, that can be identified knowing the initial density of the straw and the pressure that is needed in order to reach the desired final density.
- In order to minimise the peak operating force it is recommended to choose an initial angle of the operating lever α_0 in the range 80-100°.

The prototype press had some limitations, especially in the repositioning of the sliding/lockable end and in the tying operations. These limits require a re-examination of the machine architecture, for example introducing a density regulation system that enables a continuous production of the bales and some measures to simplify the bale tying operation.

Overall the technology was appropriate for the objective of completing the rice cultivation chain in the Artibonite Valley by means of using the straw that normally was considered as waste as material for self-construction.

Based on the results obtained of the first Haiti Project, the authors are confident that the press is attractive and appropriate device that is easily constructed from materials that are available by the local blacksmiths, has low cost, is easily replicable and is easy to maintain and use.

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Figure Captions

Fig. 1. Black box baler model

Fig. 2. Straw mechanical characteristic

Fig. 3. Number of compaction cycles n_c related to the compression work for each cycle L_c (straw stiffness constant k, m_{tot} = 10.9 kg, ρ_o = 30 kg m^{-3}, ρ_f = 90 kg m^{-3})

Fig. 4. Compression chamber scheme

Fig. 5. Piston stroke y_c for cycle related to the compression work for each cycle L_c (straw stiffness constant k, m_{tot} = 10.9 kg, ρ_o = 30 kg m^{-3}, ρ_f = 90 kg m^{-3})

Fig. 6. Baler slider-crank mechanism. Initial position (hatched line); generic position (continuous line).

Fig. 7. Trend of the ratio of the crank length and the piston stroke m/y_c related to the initial rotation angle of the lever α_o (α_c = 80°)

Fig. 8. Operating force F_{op} related to the rotation angle of the lever α for different initial angles of the lever α_o (ρ_o = 30 kg m^{-3}; ρ_f = 90 kg m^{-3}; α_c = 80°; $m/b = \lambda$ = 0.14; l = 2m; L_c = 400 J; η = 0.95)

Fig. 9. Operating force F_{op} related to the rotation angle of the lever α for different initial angles of the lever α_o (ρ_o = 30 kg m^{-3}; ρ_f = 90 kg m^{-3}; α_c = 80°; $m/b = \lambda$ = 0.28; l = 2m; L_c = 400 J; η = 0.95)

Fig. 10. Operating force F_{op} related to the rotation angle of the lever α for different initial angles of the lever α_o (ρ_o = 30 kg m^{-3}; ρ_f = 90 kg m^{-3}; α_c = 80°; $m/b = \lambda$ = 0.42; l = 2m; L_c = 400 J; η = 0.95)

Fig. 11. Peak of the operating force $F_{op\ peak}$ related to the initial rotation angle of the lever α_o for different ratios $m/b=\lambda$ (ρ_o=30 kg m^{-3}; ρ_f = 90 kg m^{-3}; α_c = 80°; l = 2m; Lc = 400 J; η = 0.95)

Fig. 12. Operating force F_{op} related to the lever rotation angle α calculated using the linear model of the straw characteristic (dashed line), and the experimental characteristic (continuous line).

Fig. 13. Detailed design of the press

Fig. 14. Regulation of the slider-crank mechanism

Fig. 15. The prototype of the press

Fig. 16. A typical straw bale obtained by using the prototype press and the background the warehouse built by ASF in Haiti using the bales.