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Experimental Investigation of Two Test Setups on Straw Bales Used as Load-Bearing Elements of Buildings

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Abstract: The importance of green and sustainable materials in civil engineering is undeniable. Alongside modern practices that improve the properties of standard building materials, there are ways to revive forgotten techniques, including straw bale buildings. Straw bales are load-bearing structures, which are applied based on handed-down experience and lack standard approaches in testing, design, and application. Therefore, a goal ahead is to describe every aspect of the process in technical detail. The objective of this paper is to highlight practical ideas for testing straw bales on a hydraulic press machine and to provide a basic statistical investigation of the results obtained. Two basic series were prepared, one without a side barrier and the other with a side barrier. The reason for this was to delineate the limits of the real behaviour of the straw bale on the load bearing wall of the house. Due to the assumed slight embedment of adjacent bales, the real result were within these limits. The experimental plan, basic results, simplified correlations, and statistical evaluation are presented. Recommendations for a further testing and evaluation are provided. As expected, the results with and without the lateral barrier differ by almost 18% for the true strain.

Keywords: straw bales; building; experimental; mechanical parameters; lateral barrier

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1. Introduction

Straw as a component of buildings (roofs, insulation, and load bearing elements) appeared in the Middle Ages but was also used in the early 20th century [1]. Straw bales, as a main load-bearing element or part of a load-bearing structure [2–4], have undeniable advantages in terms of low environmental load [5], minimal energy consumption in production [6], and advantageous thermal engineering properties [7]. The use of straw in the construction industry is in line with the principles of sustainable development due to the use of the material as a secondary raw material [8]. A large amount of straw is burned in the field [9] or used in incinerators for energy production [10], which entails a certain increase in environmental burden that can be counteracted by the alternative use of a straw. We must not forget the increasing interest in green building due to the unenviable need to further reduce the impact of human activity on the environment and global phenomena [11,12].

1.1. Straw Bales in the Civil Engineering

Straw can be used in the construction industry as blown insulation [13], prefabricated straw wall panels [14,15], or self-supporting straw bales [16,17]. Another possible application of straw in the construction industry can be various composite structural elements, for example, in the form of straw-fibre cement composite [18,19]. It should be noted here that each type of straw use has different economic and ecological impacts, and in particular, different principles of behaviour of the whole structure and individual elements. We intend to primarily explore the raw materials available in the area to reduce the impact of transport. The thermal insulation, acoustic, and moisture properties of straw are relatively well studied around the world, but in the knowledge of the mechanical and physical parameters of straw structures, the knowledge is negligible [20–23]. A separate and extensive chapter is the research on the properties of straw bales that can be used as self-supporting elements of the external walls of houses.

1.2. Load-Bearing Wall from Straw Bale

In general, a load-bearing wall (in the Czech Republic) that carries the load of a roof can be built up to a height of 3.0 m with a thickness of 50 cm [24]. However, this does not mean that there are no ways to overcome these limitations. In the US, which is a leader in straw buildings, the potential for straw construction is proving to be high and has undeniable potential due to its ecology and sustainability [25,26]. Several basic standard practices in the world deal with straw-based construction in terms of thermal and moisture mechanical behaviour [27,28]. However, these practices are methods tied to local natural resources, which in contrast do not exist in the Czech Republic, and there are a lack of data for the materials available.

Importantly, the design process of straw-bale structures is associated with several unknowns. For the construction of load-bearing walls, straw bales are used as classical building material, which is reinforced with a perpendicular wreath at the ceiling level. This allows the introduction of primary deformation utilizing prestressing strips or reinforcement. The shear interaction of the individual bales is further ensured by employing pins that connect the individual straw bales across the entire surface of the load-bearing wall. Currently, only empirical experience and knowledge, especially from foreign projects, is used in the design and construction of straw bales.

The straw in the bales is arranged mechanically so that orthotropic behaviour analogous to timber elements can be assumed [29,30]. It is necessary to prove this hypothesis and obtain mathematical models related to the orthotropic behaviour of bales. On the other hand, the rheological properties, especially shrinkage and creep of straw bales, can be described theoretically, such as the rheological properties of concrete [31,32] or the rheological behaviour of wooden structures [33]. The dispersion of bulk mass, stability and compressibility can be a problem for straw bales and their use for load-bearing structures. Therefore, it is difficult to define the mechanical and physical properties of individual straw bales and consequently of the whole load-bearing structure.

1.3. Motivation and Research Significant

A major problem in the research and development of structural tools is the fact that straw bales are inhomogeneous. In principle, it is thus difficult to design a load-bearing element in repeatable quantities within tolerable limits. Therefore, it is necessary to provide more input information (test results) and establish consistency with computational models. Using current tools, numerical modelling is one of the possibilities to globally analyse the behaviour of the whole structure and the individual load-bearing parts of straw houses. There have been attempts to numerically model straw structures using a simplified view based on empirical relationships and a phenomenological approach [25,30]. Therefore, it is necessary to thoroughly investigate the possibility of testing straw bale as the first type of load-bearing structure of houses [34], then evaluate the data obtained, analyse them using regression analysis, and use inverse analysis and numerical models to obtain unmeasurable parameters. The present research investigated two limiting testing situations—straw bale without side barrier and straw bale with side barrier. In reality, the straw bale in the wall will behave within the limits of these situations as the bales will tend to embed slightly into each other. The second reason for the choice is to look for the percentage difference in true strain allowed in two directions (for a straw bale without a barrier) or in one direction (for a straw bale with a barrier). These and other aspects are evaluated in the present paper. Research has its assumptions and there are limits that should not be ignored; this paper is initial and basic yet important research at the level of the wheat material presented from the Czech Republic. Based on the findings and results presented here, it is possible to pursue broader research both in terms of the number of straw bales tested and of other approaches that will be highly relevant in modelling structures made of this material. Suitable and working numerical models are then a future goal.

2. Preparation and Properties of Straw Bales

2.1. Straw Bales Harvesting

The straw bales used in this research were purchased directly from a supplier in Znojmo, Czech Republic. Wheat straw was used to produce the bales. Straw baling was carried out using standard technology with mechanical balers. In agricultural production, straw balers are used to press straw into bales (see example in Figure 1). The task of the balers is to smoothly pick up the dry straw material from the rows. The straw is then pressed and tied into dimensionally identical bales. The baled bales can be left in the field or loaded onto a transport vehicle and transported to a place of further use or storage. The dry bulk weight of the baled raw material is usually 50 to 250 kg/m^3 depending on the type of cereal.

Figure 1. Example of mechanical straw balers.

2.2. Moisture Measurements

If the moisture content of the straw is higher during baling, the straw must be allowed to dry. Drying in the field at the harvesting site is optimal. The straw can also be dried industrially using dryers. However, this method is energy demanding and costly. Drying straw in the field depends on weather conditions. In general, straw should be pressed in the same weather as the grain harvest. This should ensure optimum moisture content without the need for further drying. The ideal moisture content is around 14% as stated in a study [27]. The moisture content of the straw bales can be checked after baling and during storage, for example, by using ground-agricultural moisture meters. Moisture control is crucial not only to protect against rot and mould but also because of the risk of spontaneous combustion.

2.3. General Information and Properties

The straw bales were produced in 2020 and were stored in covered warehouses. Before the actual measurement, the straw bales were wrapped with stretch film to prevent excessive contamination of the test centre area. The stretch film was wrapped loosely so as not to affect the measured quantities. Before the measurements, the moisture content of the individual straw bales was measured using a GMH 3830 resistance moisture meter equipped with needle probes for measuring the moisture content of bulk materials. The moisture content of the straw bales ranged from 10 to 13%. The moisture content of the straw bales corresponds to their intended use for the envelope construction, i.e., exterior placement. A total of 12 bales were purchased for the first series of tests. Four pieces were discarded due to irregular shapes or unsuitable density. The aim was to find bales with an average density between 90 and 100 kg/m^3. Another criterion was a height between 30 and 35 cm. The other dimensions had no set limits.

It should be noted here that straw bales show large variations in quality, and this must always be taken into account. The straw bales were divided into two series—four were tested without a side barrier and four were tested with a side barrier. The bales were weighed, and three basic dimensions were measured before testing. Subsequently, the average package density was calculated using Equation (1):

$$\rho = \frac{h \times l \times w}{m}, \quad (1)$$

where ρ is density [kg/m^3], h is height [m], l is length [m], w is width [m], m is mass [kg], of the straw bale. All values and statistical results are presented in Section 4, Tables 1 and 2.

3. Experimental Program and Analysis

3.1. Assumptions for the Experiment

The straw in the bales behaves as a highly elastic material and is therefore expected to expand to all free sides when compressed. In preparing the experimental program, a hypothesis was put forward on the potential behaviour of straw bales in the wall. The straw bale is expected to be enclosed on the sides to prevent stretching by other bales (see Figure 2).

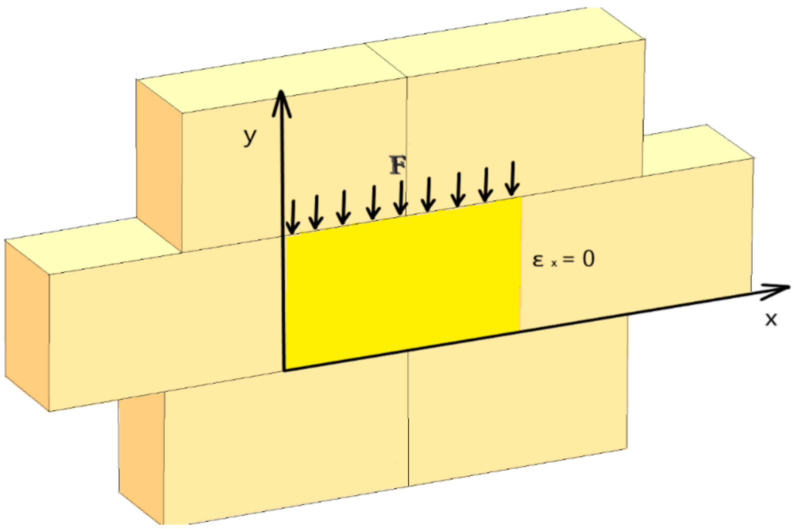
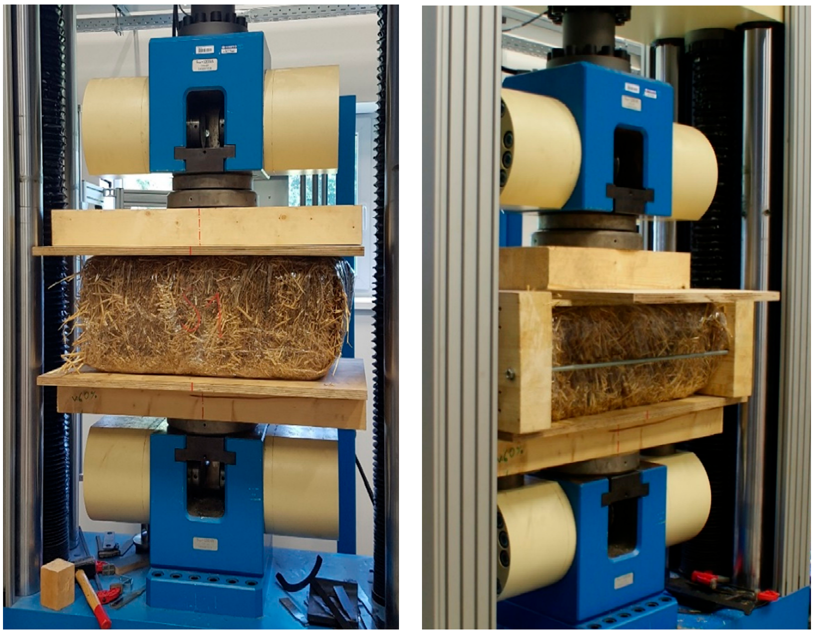


Figure 2. Illustrative model of a straw bale in the load-bearing wall of a building.

On the other hand, these barriers may not be perfect, as adjacent bales could theoretically become embedded in each other. As well as bales at the corners of the building will exhibit different behaviour. That is why two series were prepared—one series of straw bales was loaded without a barrier (see Figure 3a) and the other series of straw bales was loaded with a fixed barrier (see Figure 3b).



(**a**) (**b**)

Figure 3. Position of straw bale in hydraulic press machine without barrier (**a**) and with side barrier (**b**).

The barrier consisted of two glued laminated timbers connected by four 10 mm diameter threaded rods. Using bolting, the barriers were positioned a distance the width of the straw bales before each test.

3.2. Testing Setup

The experiments were carried out on the universal testing machine UP Formtest 4000 kN, which is used for standard testing of building materials such as concrete or steel. A high rigidity glued laminated slat board and a particleboard spreader plate were placed on the support head. Similarly, a spreader plate and a glued laminated board were placed on the bale.

The loading rate was set to a constant strain rate of 0.175 mm per second. The loading was stopped at approximately 20 kN. Only for the first specimen, the loading was stopped at 25 kN due to the initial behaviour of the experiment. Time, deformation, and loading force were recorded from the testing machine directly.

3.3. Testing Setup

After subtracting the maximum force, the stress as the true stress σ was calculated using the load area according to Equation (2):

$$\sigma = \frac{F}{l \times w} \tag{2}$$

where σ is true stress [MPa], F is maximum force [kN], l is length [m], w is width [m] of straw bale after the end of testing.

The deformation at maximum force was then determined and the true strain ε was calculated according to Equation (3):

$$\varepsilon = \ln\left(\frac{h}{h_0}\right), \tag{3}$$

where ε is true strain [-], F is maximum force [kN], h is length [m], h_0 is height after deformation [m] of straw bale. Note here that the calculation of true strain was proceeded to because the straw bale shows elastic-plastic behaviour.

Means and standard deviations (*STD*) were calculated for all values obtained to compare the results between the series without barrier and with barrier next to straw bales. The mean is considered as the arithmetic average of the four values of each parameter. The coefficient of variation (*CV*) as the ratio of the standard deviation to the mean was also added based on Equation (4):

$$CV = \frac{STD}{mean}, \quad (4)$$

where *CV* is coefficient of variation, *STD* is standard deviation and *mean* is arithmetic average.

4. Results and Discussion

The obtained results are divided according to the process of the experimental program, where the basic measured geometric and material parameters are first presented together with statistical values of the mean, standard deviation, and coefficient of variation. Then, the mechanical properties are presented with important statistical evaluation and last but not least, the differences between the two series are pointed out. The results are always separated for the series of tests with and without the lateral barrier.

4.1. Basic Parameters

According to the data and procedure presented in chapter two, the basic properties of each package were obtained. Table 1 shows the straw bales for testing without lateral barrier and Table 2 shows the straw bales for testing with the lateral barrier.

Table 1. Basic parameters of the tested straw bales used in the test without barrier.

No. of Bale	S1	S2	S3	S4	Mean	STD	CV
Mass [kg]	10.40	9.60	10.01	10.30	10.08	0.31	0.03
Length [m]	0.80	0.71	0.77	0.73	0.75	0.03	0.05
Width [m]	0.43	0.44	0.43	0.43	0.43	0.00	0.01
Height [m]	0.33	0.34	0.32	0.33	0.33	0.01	0.02
Density [kg/m^3]	91.614	90.382	94.382	96.537	94.000	3.487	0.04
Contact area [m^2]	0.344	0.312	0.331	0.314	0.325	0.013	0.04

From the coefficient of variation results in Table 1, it can be concluded that no parameter deviates significantly from the mean. On the other hand, in Table 2, we see that mass and length have a higher variation due to sample S5, which was light and narrow. In the future, the series needs to be prepared not only with respect to density but also to other parameters, or to evaluate whether this significantly affects the statistical variation. At this point, it can be concluded that all parameters are within the extremes.

Table 2. Basic parameters of the tested straw bales used in the test with a barrier.

No. of Bale	S5	S6	S7	S8	Mean	STD	CV
Mass [kg]	8.00	11.00	11.20	9.00	9.80	1.35	0.14
Length [m]	0.60	0.76	0.78	0.70	0.71	0.07	0.10
Width [m]	0.45	0.44	0.45	0.43	0.44	0.01	0.02
Height [m]	0.31	0.34	0.33	0.32	0.33	0.01	0.03
Density [kg/m^3]	95.579	96.749	96.693	93.439	95.615	1.340	0.01
Contact area [m^2]	0.270	0.334	0.351	0.301	0.314	0.031	0.10

4.2. Mechanical Properties

The logic of the above hypothesis shows different results after testing straw bales without lateral barrier and with the lateral barrier. The results of the experiments are shown in Tables 3 and 4.

Table 3. Results of mechanical properties when tested without barrier.

No. of Bale	S1	S2	S3	S4	Mean	STD	CV
Force [kN]	25.11	19.89	19.88	19.89	21.19	2.26	0.11
True stress [MPa]	72.99	63.66	60.05	63.38	65.02	4.82	0.07
Deformation [mm]	0.137	0.158	0.142	0.133	0.142	0.010	0.07
True strain [-]	0.414	0.465	0.444	0.402	0.431	0.025	0.06

Table 4. Results of mechanical properties when tested with barrier.

No. of Bale	S5	S6	S7	S8	Mean	STD	CV
Force [kN]	19.88	19.89	19.89	19.87	19.88	0.01	0.00
True stress [MPa]	73.63	59.47	56.66	66.03	63.948	6.543	0.10
Deformation [mm]	0.109	0.140	0.100	0.116	0.116	0.015	0.13
True strain [-]	0.352	0.412	0.303	0.361	0.357	0.039	0.11

As stated earlier, the first test was terminated with a force of 25 kN and all subsequent tests were terminated with a force of 20 kN. The calculated true stress corresponds to the fact that the bales had different contact areas (see Tables 1 and 2). However, the coefficient of variation is not extreme. The comparison between the groups is shown below, but it is interesting to put the results into a graph showing true stress and true strain (see Figure 4). The scatter plot may reveal correlation behaviour. For the first series, a large polynomial correlation can be observed, but this is small for the second series.

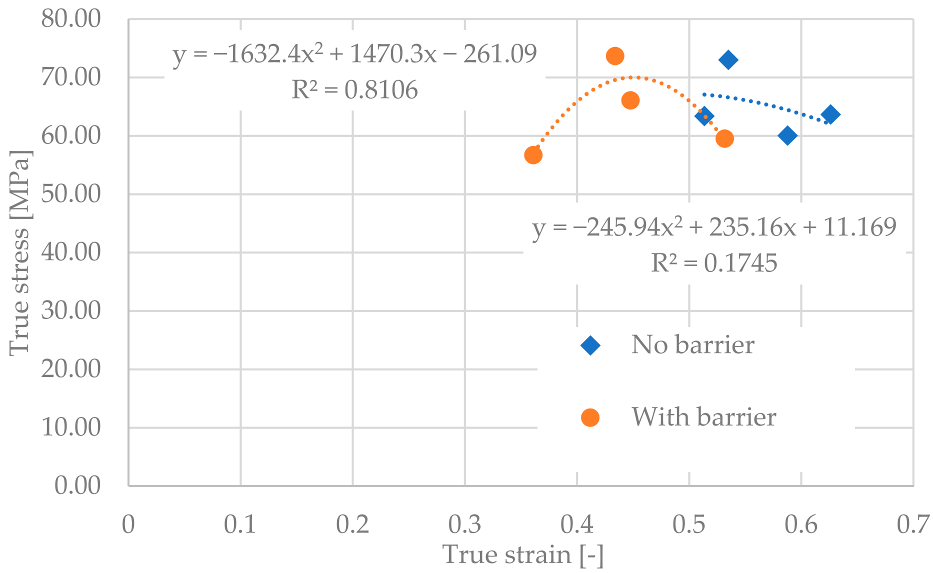


Figure 4. Results of true stress and true strain from straw bales experiment.

4.3. Comparison of the Results of Two Series

The main and most important result of the research is the comparison of the two series. For this purpose, Table 5 shows the average values for all measured and derived parameters and properties from both series. Furthermore, the table shows the percentage difference for each value.

Table 5. Statistical evaluation of the results of the experimental program.

	Mean—No Barriers	Mean—With Barriers	Difference of the Means
Mass [kg]	10.08	9.80	3%
Length [m]	0.75	0.71	6%
Width [m]	0.43	0.44	2%
Height [m]	0.33	0.33	2%
Density [kg/m^3]	94.000	95.615	2%
Contact area [m^2]	0.325	0.314	3%
Force [kN]	21.19	19.88	6%
True stress [MPa]	65.02	63.948	2%
Deformation [mm]	0.142	0.116	18%
True strain [-]	0.431	0.357	17%

The maximum measured strain and the actual stress for the maximum load for the experiment without a lateral barrier are much larger than that of the experiment with a lateral barrier (by 18% and 17% respectively). This is as expected since the straw bale cannot stretch in two directions.

The results should be taken in the context that the straw bales were not accurately compressed beforehand. This was the reason for the higher force values of up to 20 kN. For example, Ashour et al. [35] loaded the straw bales progressively from 2 kN to 10 kN and the stresses ranged from 7 MPa to 45 MPa. The stress results presented here at a force of 20 kN averaged 65 MPa. The true strain value in the paper [35] was around 0.25. On the other hand, in our case, where the load was up to at least twice as high, it averaged 0.39. Studies of stress and strain during compression of straw bales have shown that nonlinear behaviour can be observed with a narrow curve at the beginning followed by a nearly linear elastic curve [36–38] But, in our experience, the differences between restricted side-barrier and unrestricted straw bales have not been analysed. Other studies have pointed out the high scatter of results for straw bales; therefore, the evaluation needs to be extended to a larger number of experiments to further increase the knowledge in this area.

5. Conclusions

The paper presented the practical procedures of testing straw bales in a hydraulic press and the basic statistical investigation of the results obtained. Two basic series were prepared, one without lateral barrier and the other with the lateral barrier. The experimental design, basic results, simplified correlations, and statistical evaluation were presented. As expected, the results with and without lateral barriers differ by almost 18% for true strain. These findings contribute significantly to the understanding of the foundation behaviour of straw bales in the bearing wall of residential buildings and will help lay the foundation for further research. Based on the results, we conclude there is a need to extend the experimental program to include a larger number of tests as well as experimental evaluation of the behaviour under cyclic loading as well as the rheological behaviour of straw bales. Nevertheless, the results presented here are important precisely because of the basic evaluation of the difference between the behaviour of straw bales with and without a lateral barrier. This is important for the path to efficient numerical modelling of the entire structure of an object made of load-bearing straw bales.

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