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Inverse Analysis of Straw Bale Mechanical Parameters in Load-Bearing Structures Based on a Finite Element Model

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Abstract: Scientific and practical research into alternative building materials is of high importance in terms of sustainability and ecology. Many variables have to be taken into account when using straw bales as load-bearing structures in residential buildings. The main problems are the lack of information on the mechanical properties of this material and its potential high variability. The development of numerical FEM models based on accurate experiments can help to better understand the behaviour of this material. The main objective of this paper is to present a simplified isotropic model of straw bales based on measured data from a laboratory experiment, which will facilitate the preparation and evaluation of further future experiments. Already partially published data of compression tests of load-bearing straw bales were analysed. Using an automated algorithm, an estimate of the elastic modulus of the bale was determined, and inverse analyses were performed using accurate FEM numerical models based on similarity to the force-deformation diagram. In all experiments, it was found that the ideal combination is elastic modulus at 20% load and Poisson's constant of 0.2. From the results, further experimental directions can be determined, mainly considering a larger number of specimens with different properties. These and other findings provide the basis for the ever-expanding field of research on load-bearing straw bales in construction.

Keywords: load-bearing straw bales; mechanical parameters; modelling; FEM; inverse analysis

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1. Introduction

Nowadays, when the ecological footprint and pollution of the planet are becoming bigger and bigger problems, forgotten natural materials are starting to make a comeback in everyday practice. This trend has become evident in the construction industry over the last couple of decades, and materials that were quite common in the past are once again coming to the fore. They are giving rise to new environmentally friendly variants of building elements that are attractive to the public and attract the attention of professionals. This is reflected in the growing popularity of low-energy and passive buildings [1,2].

For some natural materials, a problem is the small database of physical and mechanical properties. Furthermore, compared to industrially produced materials such as concrete, steel, etc., natural materials exhibit higher variability in properties, which may reduce their effective use [3,4]. By natural material, we mean materials of animal or plant origin. This paper presents research on straw as one representative of the group of natural materials of plant origin. The use of straw in construction has several advantages. One of them is the fact that straw is an inherently available and relatively cheap material [5,6]. It can be harvested and processed every year, and its processing is not that difficult. The use of straw can reduce the need to use other, environmentally demanding, materials. Straw provides very good thermal and acoustic insulation [7–9]. One environmental advantage is that straw can be used in places where it is considered an unwanted by-product. In fact, unlike hay, for example, it is not used to feed animals, and its stalks are not adapted to be incorporated into the soil.

One form of straw processing is straw bales. To understand the behaviour of straw bale structures, mechanical properties need to be obtained from testing. One of the main problems in dealing with the properties of straw bales is their inhomogeneity, which makes it difficult to design the element so that its properties are within similar limits [3,4]. Thus, it is important to obtain more data to develop a reliable numerical model, which is needed to facilitate the design of these structures [10]. Further, due to the lack of such data in the Czech Republic, unlike other countries (USA, Denmark, France, etc.), there are no legislative procedures available for these structures, and thus, construction is only guided by previous experience and knowledge [11,12].

1.1. Current Use of Straw Bales

In the case of straw, the so-called Nebraska method (American method) is used. This method is the most commonly used in the United States. It is a method of construction that works using self-supporting straw bales stacked into a wall that is pulled between the foundation and the wreath. They are designed to transfer loads from the ceilings to the foundations. They also have the advantage of acting as a single layer of thermal insulation. They are covered with mesh and stitched with binding wire. They are then most often plastered with clay plaster, both inside and outside. On the outside, however, a fermentation solution or lime plaster must be used. Straw bale buildings are mainly found in the USA, where they have precise regulations for such buildings [12]. Other countries where straw bale construction is permitted are Denmark, France, Great Britain, the Netherlands and Switzerland [13,14].

In the Czech Republic, there are no binding regulations yet. Therefore, most structures are built only following previous experience and knowledge. The construction must therefore be based mainly on the dimensions of the straw bales. The size of the bales then determines the structural height of the storey, the length of walls and the size of openings [15]. Thus, as far as straw bale structures, in general, are concerned, they are straw bales stacked on ties. Both small straw bales and large ones are used for the construction, which, as already mentioned, are used for the construction of load-bearing walls. The small bales have a format of 40 × 50 × 100 cm (see Figure 1), a weight of about 15 kg and a bulk density between 50 and 150 kg/m^3.

Figure 1. Small straw bales.

Large straw bales are usually 70 × 120 × 100 cm. They reach a weight of around 300 kg. They are compressed to a bulk density of between 150 and 200 kg/m^3 [15]. The compression is therefore two times greater than for small bales. Due to the high compressibility, there is then less deformation in the walls under load. The disadvantage is the large thickness of the load-bearing walls, which can vary from 70 to 100 cm, depending on the size of the bales. The advantages are the high heat accumulation, which helps maintain temperature stability, and the high thermal resistance value, which makes it possible to build passive houses from straw.

1.2. Properties of Straw Bales

The physical properties of straw bales are nowadays well known. They have very good thermal, insulating and acoustic properties [8,16]. Straw has also been shown to have very good fire resistance [17,18]. The mechanical properties, however, are still subject to experimental tests and research. Over the last couple of decades, several experiments have been conducted to determine the mechanical properties of straw bales. They were carried out on different types of straw of different densities.

Bou-Ali [3] carried out tests on straw bales placed both on edge and flat and determined the Poisson's constant in the longitudinal direction. His results showed a proportionality between density and stiffness. He also found that the bales return to their original state when the load is removed.. In 2000, Brojan and Clouston [19] conducted cyclic loading tests where bales were subjected to three full cycles of loading and unloading. The stress and strain varied in each cycle. The bales were tested in both positions and were found to have nonlinear behaviour. Later, Vardy and MacDougall [20] carried out testing on two wheat bales with one laid on edge and the other laid flat. Their results confirmed that the bales laid flat exhibited strengthening behaviour. The bales laid on edge showed linear behaviour. Further, Peng et al. [21] presented a very interesting experimental analysis of whole straw bale walls.

1.3. Numerical Modelling in the Straw Analysis

Numerical models of straw bale structures are only a marginal topic. Most often, numerical models are used to investigate heat or moisture transfer [22]. Even though many experimental measurements have been taken, there are very few models, either simple or more complex, dealing with the mechanical behaviour of straw in load-bearing structures. Only a few numerical models can be found in the literature, most of them analysing a combination of wood and straw.

For example, Arnaud and Sallet [23] presented an experimental model of a wall consisting of timber beams and internal load-bearing straw in Consol. From simple compression tests, the basic properties of the materials, both wood and straw, were obtained, and then the compressibility modulus parameters were found. This was therefore a typical example of inverse analysis. Another type of model does not express the mechanical properties of straw but focuses on the durability, sustainability and economics of straw structures [24]. For example, Vanova et al. [25] conducted a detailed life cycle study of a straw-beam building, but the parameters were not based on an underlying numerical model that considered all sides of the material. Thus, the load-bearing straw bale industry is still dependent on empirical observation and previous experience and does not make use of modern numerical approaches.

1.4. Research Significance

The main object of this work was to create a simplified FEM straw bale model, which allows for inverse analysis of the experimentally obtained data, which will facilitate the preparation and evaluation of further future experiments. Ansys Workbench [26] was used to create the model. The inverse analysis was applied to the available strain and load measurement data [14], and subsequently, the best-suited elastic modulus E and Poisson's constant μ were obtained.

1.5. Experimental Program

The presented analysis was prepared based on experiments conducted in the laboratories of VSB-Technical University of Ostrava, Faculty of Civil Engineering. A series of bales without and with side barriers were tested using the UP Formtest 4000 kN testing machine, which is used for testing common materials such as steel and concrete. The experiments were described and evaluated earlier in the study [14].

Four bales with side barriers and four bales without side barriers were tested to specify the behaviour of the bale in the wall. It is not entirely clear whether the bales would form a solid barrier or whether they would interpenetrate each other. Therefore, two series of tests were carried out. In the sidewall tests, threaded rods were added to adjust the distance between the sidewalls according to the dimensions of each bale. Further details of the test are given in another paper [14]; however, the entire set of measured data was not evaluated, only their maximum values. This study, on the other hand, incorporated an evaluation of all measured data over time. It should also be noted that the bales with side barriers (see Figure 2), i.e., the results of four measurements, are numerically analysed here.

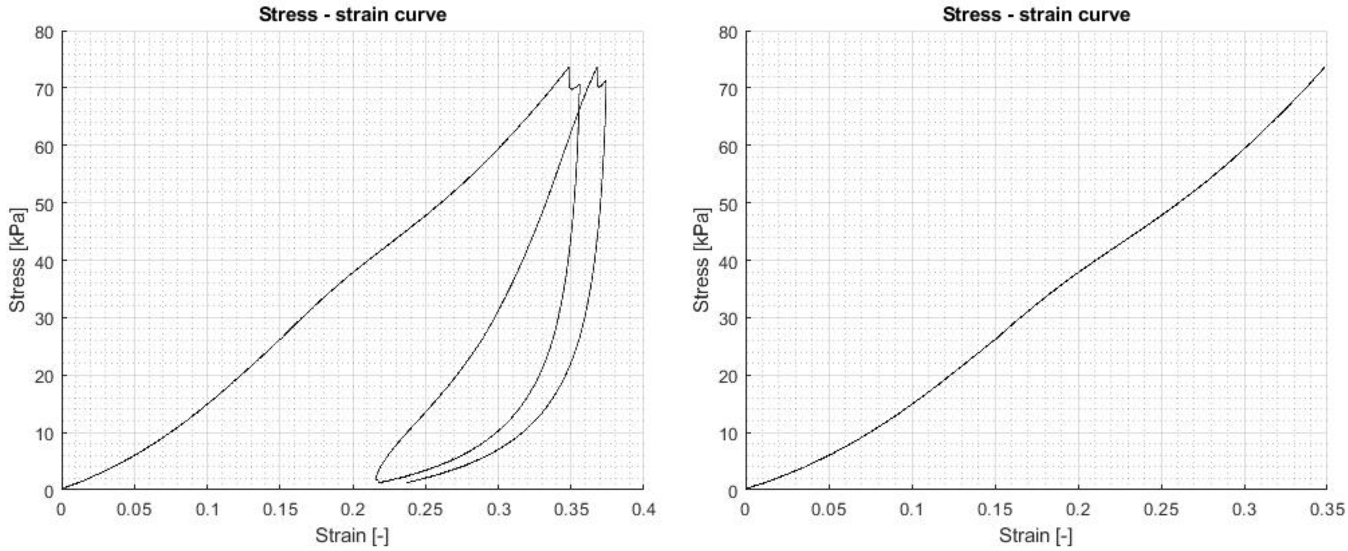
Figure 2. Straw bale bearing capacity evaluation experiment with side panels.

2. Numerical Analysis

The numerical analysis presented here consists of two parts. The first part is used to analyse the experimental measurement data and estimate the material parameters using the prepared algorithm. The second part, based on a finite element model of the bale in the load assembly, is used to conduct an inverse analysis of the two material parameters of the bale.

2.1. Evaluation of Experimental Results

The data analysis was performed in the Matlab programming environment [27]. The input data were obtained directly from the test machine and then, using the readmatrix function, inserted into the script as a matrix of three columns. After the input values were read, the ratio transformation and normal stress were calculated. To obtain the elastic modulus E, it was necessary to restrict the values so that only data from the first loading cycle were considered in the calculation (see Figure 3).



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

Figure 3. Graphical record of the experimental output: (**a**) the entire test period, (**b**) a separate rising cycle for further analysis.

As a criterion for limiting the data, the overstrain values were chosen since the strain was set as a constant increment during testing. The maximum normal strain of the first loading cycle was obtained from the growth and decay limits. From this, the equivalent relative strain was calculated. The normal stress and the relative strain at 20% of the maximum were derived as the next pair of parameters. All these values were then used in the numerical model, which is described in detail below. Relative strain of 20% was chosen as the first representative value. As this is the first critical evaluation, two extreme limits were chosen. Should the results show a need for further refinement, a more in-depth parametric study will be conducted.

2.2. Finite Element Model

The next step of the inverse analysis was to create a simplified model. The model was created in Ansys Workbench [26], where the static structural mode was chosen for the calculation.

The geometry and parameters of the bales were taken from the above experiments, as well as the dimensions of the upper, side and bottom desks made of glulam. The aim of the inverse analysis was to obtain the following material parameters for each experiment: modulus of elasticity E and Poisson's ratio μ. The parameters were introduced sequentially, and the result was confronted with the load-deformation diagram from the experiment and the model. In this way, the comparison of load test progress was monitored.

Two values of the elastic modulus were used: the one at the top of the load diagram (maximum of the first cycle) and the value obtained from the linear part at the beginning of the curve. For each experiment, this was the modulus of elasticity at 20% of the maximum stress value. These values will be used in the future to create multilinear material models. In addition, two values of Poisson's constant were used as per references at 0.1 and 0.2 [28]. Table 1 shows the assumptions for all material setups.

Table 1. Basic assumptions for the distribution of model parameters.

	Mat 1	Mat 2	Mat 3	Mat 4
Modulus of elasticity	maximal	20%	maximal	20%
Poisson's ratio	0.1	0.1	0.2	0.2

Since 4 experiments with different geometries were analysed, and 4 material models were applied to all of them, 16 numerical models were created. Figure 4 shows the first straw bale model from the Ansys software. A 20-node SOLID186 volume element was used. The boundary conditions were set so that the bottom timber desk is supported, gravity is introduced on the whole geometry, and deformation is introduced on the upper deck which is gradually increasing. It must be noted that the loading in the model was nonlinear to make the model stable. The loading curve was divided into three branches so that the first part was gradual, and the other two were faster. This was due to the initial settling of all parts of the model. A friction of 0.2 was set between the parts, and the side plates were connected by a rigid connection simulating tie rods. The aim was to get as close as possible to real behaviour.

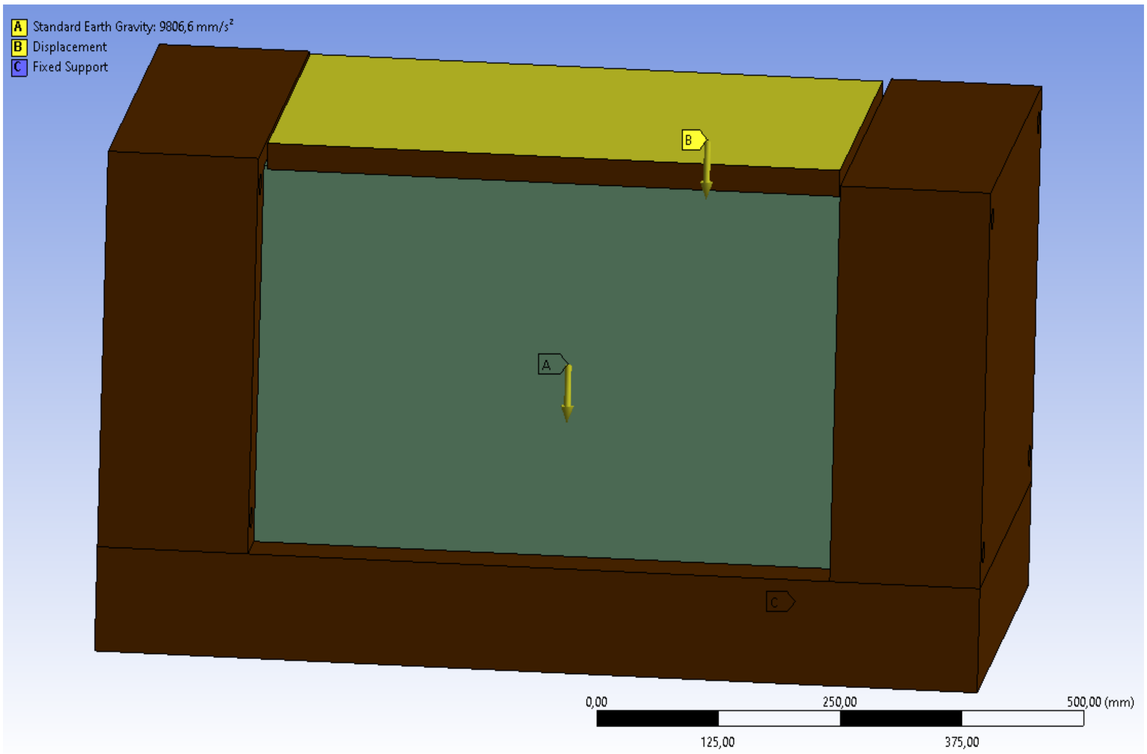


Figure 4. Model of the straw bale in Ansys (green—straw bale, brown—wood, yellows—remote force).

Table 2 shows the combinations of all prepared models. The input information was based on an analysis of experiments and specific geometry. The analysis did not include a search for relationships with density and dimensions. The aim was only to explore the possibilities of statistical advantage of the experimental data and simplified FEM modelling. The beginning of the labelling (S5 to S8) is based on the labelling of samples in the research laboratory, where eight separate tests were performed. The first four tests (S1 to S4) were without side barriers, the next four tests were with side barriers. The experiments with barriers are analysed here. The maximum deformation was the value at which the peak of the load branch was reached in the experiment, and therefore, this was the cut-off value for termination of the numerical calculation.

Table 2. General material model parameters for all calculations.

Mark (L × W × H)	Geometry (m)	Maximal Deformation (mm)	Density (kg/m3)	Modul of Elasticity (MPa)	Poisson's Ratio (-)
S5_mat 1	0.60 × 0.41 × 0.31	107	95.6	0.211	0.1
S5_mat 2	0.60 × 0.41 × 0.31	107	95.6	0.148	0.1
S5_mat 3	0.60 × 0.41 × 0.31	107	95.6	0.211	0.2
S5_mat 4	0.60 × 0.41 × 0.31	107	95.6	0.148	0.2
S6_mat 1	0.76 × 0.44 × 0.34	143	96.7	0.141	0.1
S6_mat 2	0.76 × 0.44 × 0.34	143	96.7	0.072	0.1
S6_mat 3	0.76 × 0.44 × 0.34	143	96.7	0.141	0.2
S6_mat 4	0.76 × 0.44 × 0.34	143	96.7	0.072	0.2
S7_mat 1	0.78 × 0.45 × 0.33	100	96.6	0.186	0.1
S7_mat 2	0.78 × 0.45 × 0.33	100	96.6	0.118	0.1
S7_mat 3	0.78 × 0.45 × 0.33	100	96.6	0.186	0.2
S7_mat 4	0.78 × 0.45 × 0.33	100	96.6	0.118	0.2
S8_mat 1	0.70 × 0.43 × 0.32	113	93.5	0.184	0.1
S8_mat 2	0.70 × 0.43 × 0.32	113	93.5	0.129	0.1
S8_mat 3	0.70 × 0.43 × 0.32	113	93.5	0.184	0.2
S8_mat 4	0.70 × 0.43 × 0.32	113	93.5	0.129	0.2

3. Results of Analysis

A model of bale no. 5 and material 1 was first created. Figure 5 shows the result of deformation on the end. It can be seen that the side plates prevent displacement, and the bale expands to the free sides.

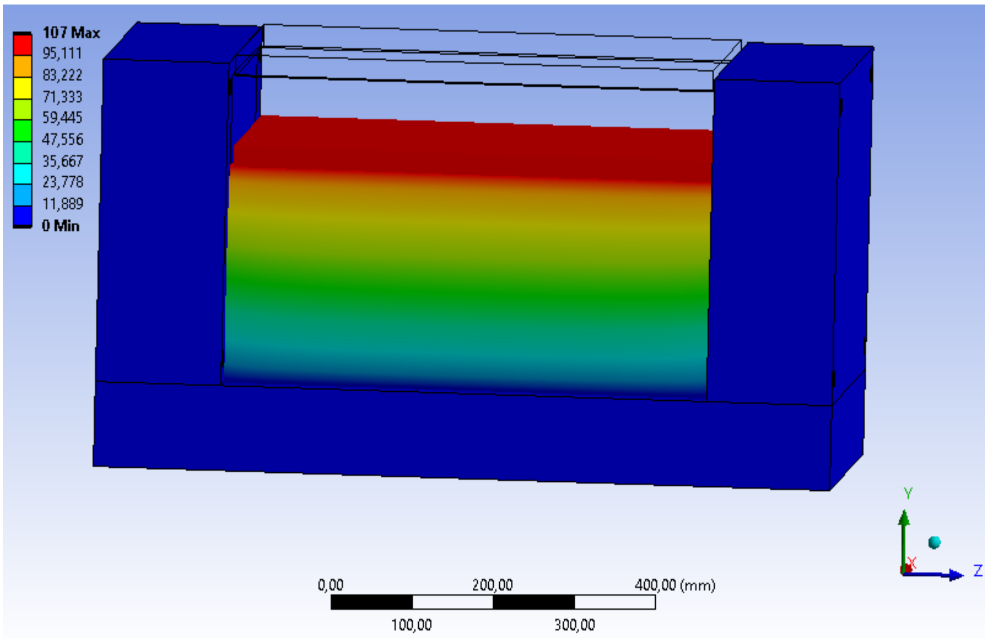


Figure 5. Total deformation of model S5_Mat1 (legend shows the deformation (mm)).

From the models, the values of the loading force and deformation at the location of the upper plate were obtained. The same parameters were also obtained from the experiment. These values can then be used to refine the inverse analysis. Figures 6–9 show the individual curves for load and deformation from the analysed experiment and all available models.

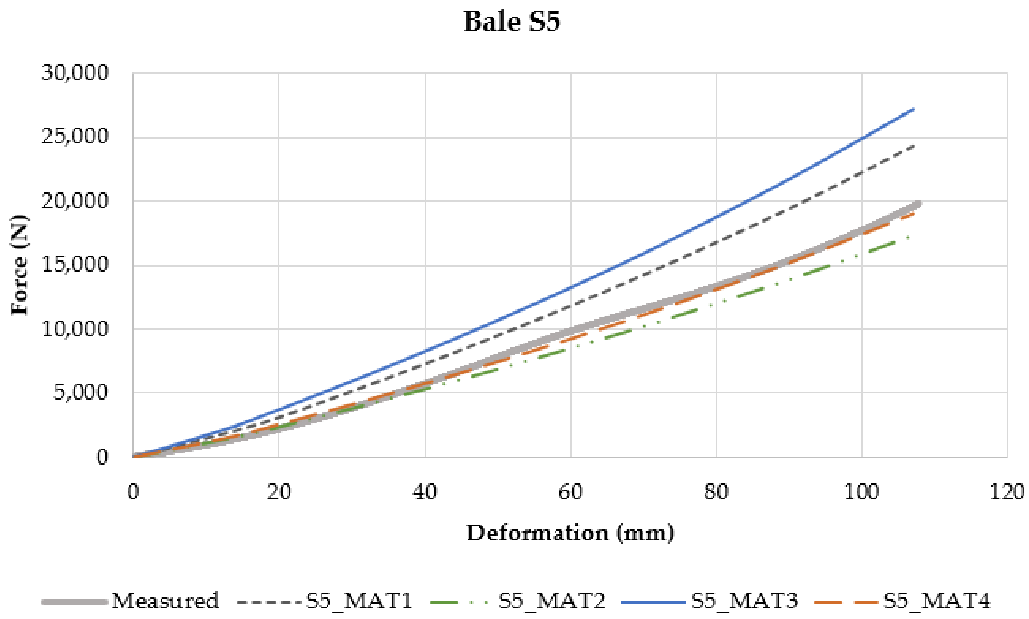


Figure 6. Comparison of load-deformation diagram from the experiment and the models of bale no. 5.

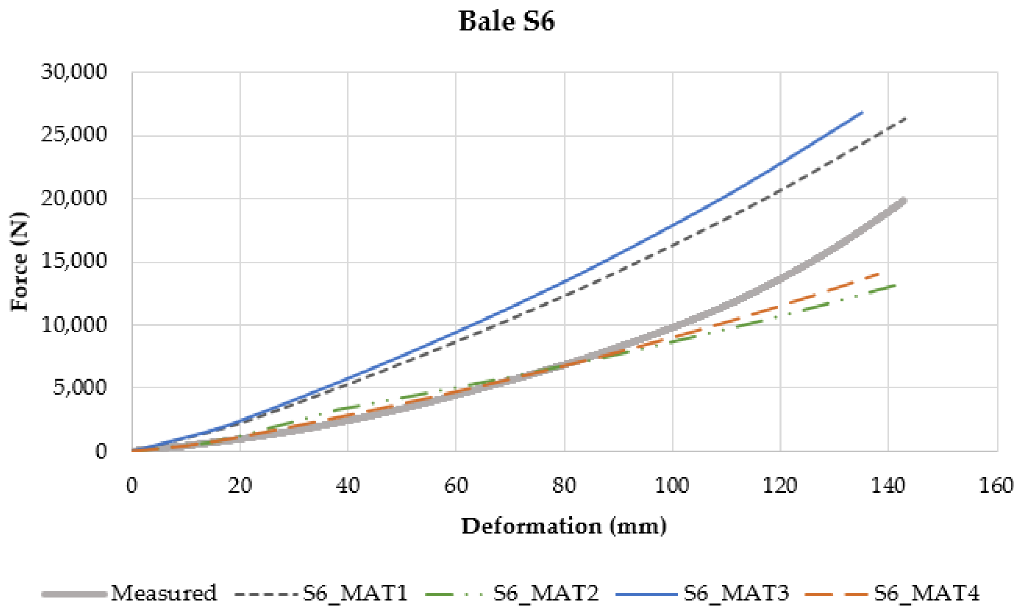


Figure 7. Comparison of load-deformation diagram from the experiment and the models of bale no. 6.

For bale number 5 (Figure 6), there is a good agreement between the curve from the experiment and the S5_Mat4 model. There, a 20% modulus of elasticity and a Poisson constant of 0.2 was applied. On the other hand, for bale number 6 (Figure 7), there is a good agreement at the beginning, but after about 80 mm of deformation, the data from the experiment are significantly nonlinear, which is not accounted for by the numerical model. Bale number 7 (Figure 8) behaves similarly to bale 6, and it cannot be conclusively confirmed that the model is appropriate throughout the experiment. These two bales were longer and taller than bales 5 and 8, and these results must be verified with more experiments and numerical models. Bale 8 (Figure 9) has a good agreement between the experimental data and the S8_Mat4 data, although there is a part of the curve that shows the relaxation of the bale under loading. It must be said that the modelling problem is highly complex, and the approach presented here is one of the basic options. A material such as straw requires more complex material settings (orthotropic, multilinear, etc.), but the results from this initial analysis are necessary and will be used in further research. Similarly, not all model setup options are considered in terms of geometry, friction, etc. It will be important to prepare a large-scale numerical study that will include other types of material models and other material parameter values.

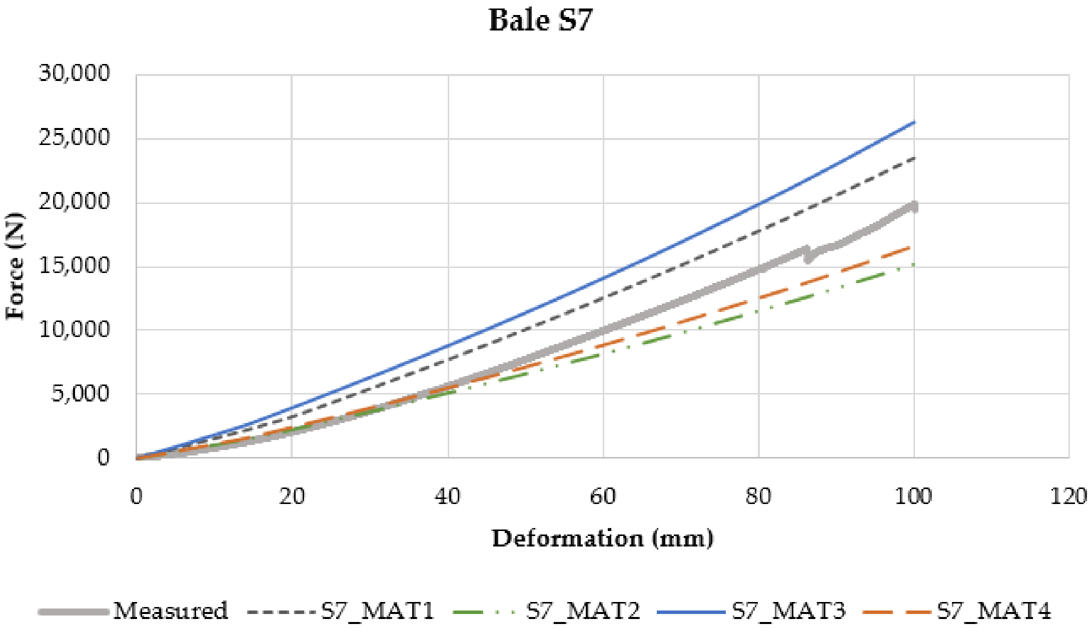


Figure 8. Comparison of load-deformation diagram from the experiment and the models of bale no. 7.

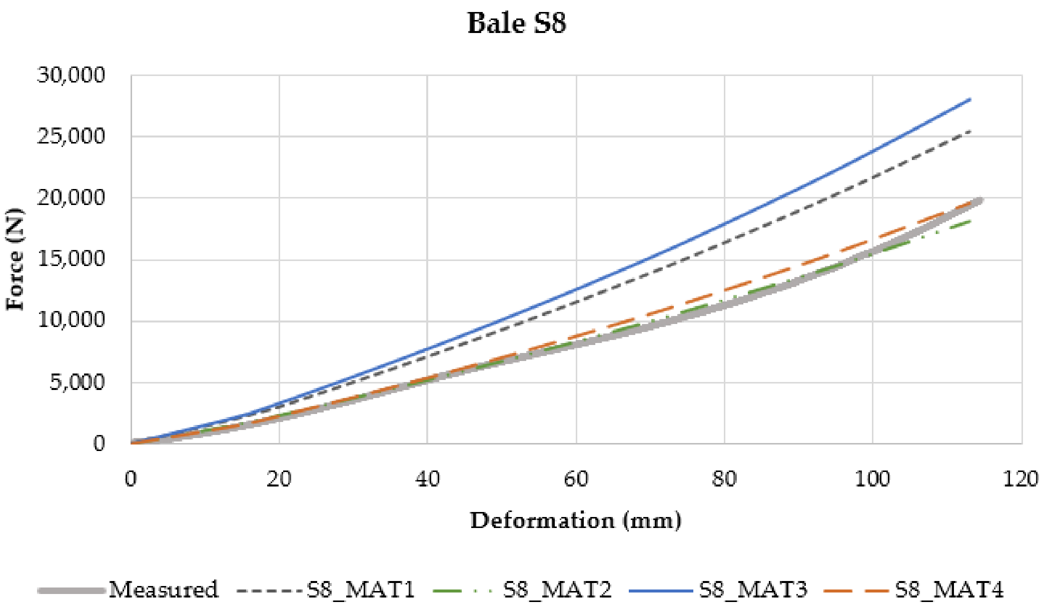


Figure 9. Comparison of load-deformation diagram from the experiment and the models of bale no. 8.

4. Conclusions

This paper presents scientific and practical research on alternative straw-based building materials suitable for promoting sustainability and ecology. Compression test data of straw load-bearing bales were analysed, and then inverse analyses were performed using accurate numerical finite element models based on similarity to the force-deformation diagram. For practically all experiments, probably the most suitable combination of material constants is the modulus of elasticity at 20% load and Poisson's ratio of 0.2. It can be seen from the results that for the experiment with a larger change in material relaxation, the linear modelling approach is inadequate. This is most evident in the results of bales S6 and S7. On the other hand, bales S5 and S8 showed a more linear behaviour in the test and therefore are closer to the model. Further research will be focused on evaluating the correlation between density and material parameters, improving experimental testing (additional numbers for lateral and proportional strain, sidewall pressure, etc.) and, most importantly, improving the efficiency of the numerical model.

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