AIR TIGHTNESS OF STRAW BALE CONSTRUCTION

Larisa Brojan[1], Ben Weil[2], Peggi L. Clouston[3]

ABSTRACT

Straw bale construction offers a renewable, sustainable and proven alternative to mainstream building methods; still, little is known about its airflow characteristics. To this end, the intent of this paper is to evaluate airtightness of fully constructed and plastered straw bale walls as well as individual plain straw bales. The first experiment entailed measuring the influence of straw bale orientation on airflow characteristics with the finding that straw bale considered alone has poor air flow-retarding characteristics and that plaster is the primary air barrier. A second experiment involved thirty plastered straw bale specimens using three different plaster types. From this experiment, a crack grading system was developed and is herein proposed as a tool to evaluate plaster performance as an air barrier. A third experiment validated the crack grade system through application on four fully constructed straw bale walls. Practical use of the crack grading system was demonstrated on a case study straw bale house in Radomlje, Slovenia, where the predicted air tightness results were validated through comparison to results of blower door tests.

KEYWORDS

Straw bale, air tightness, edge, flat, plaster material, crack grading system

1. INTRODUCTION AND HYPOTHESIS

Straw bale building is considered to be an environmentally friendly construction technology because of its low embodied energy and use of a rapidly renewable resource (Atkinson 2008). Straw bale building may also be an efficient way to sequester large amounts of carbon. Because scientific research on straw bale buildings has been limited to date, many potential investors hesitate to build with straw bales. Building codes in many jurisdictions do not accommodate straw bale construction due to the lack of reliable and standardized evaluation procedures.

Part of straw bale construction's appeal is the perception that the techniques and materials involved do not require skilled labor. However, poorly executed or conceived construction

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1. PhD student at University of Ljubljana, Faculty of Architecture, Zoisova 12, SI-1000 Ljubljana,
2. Assistant Professor, Dept. of Environmental Conservation, University of Massachusetts, Amherst MA 01003.
3. Associate Professor, Dept. of Environmental Conservation, University of Massachusetts, Amherst MA 01003.

details may lead to poor performance, unhealthy indoor environmental conditions, and eventual building failure. Therefore planning straw bale structure details concerning moisture transmission, fire safety and air tightness is crucial.

The role of the building envelope is to maintain comfortable interior conditions by controlling heat, moisture and air transfer (Cosmulescu 1997). Previous research has characterized thermal and moisture transmission through straw bale wall and straw bale buildings (Ashour et al. 2011); however, research on the air tightness of straw bale construction has been limited and has not isolated the various air leakage pathways through the assembly.

Controlling air flow through the building enclosures systems is not only important for controlling energy losses for space conditioning, but can also significantly impact the durability of buildings (ASHRAE, 2013). Over a single heating season, air leakage through a hole with an area of less than 1 cm^2 could allow up to approx. 4.7 liters of water to pass through a wall (Magwood et al. 2005). Thus, cracks and other degradation of the air barrier are not only a source of heat loss but also a way for moisture to penetrate a wall. This is particularly critical for straw bale construction, as straw can start to decompose as moisture content rises above 20% (Jones, 2009). Air tightness of straw bale buildings is under-researched in the scientific literature, though data on whole building envelope air leakage are available (Racusin et al. 2011).

This paper investigates air flow characteristics of straw bale construction through three experimental studies considering: 1) plain straw bales, 2) plastered straw bale composites, and 3) fully constructed straw bale wall systems. In an additional fourth step, iterative blower door testing was performed on a straw bale house in Slovenia to evaluate vulnerability of air leakage and cracking at construction joints such as those between framing member and bale and plaster infill.

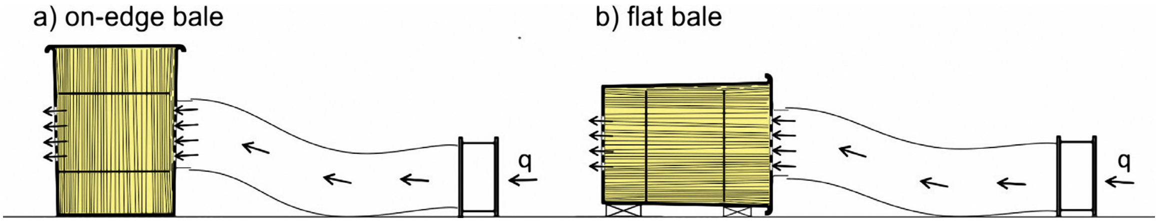
2. EXPERIMENTAL STUDIES

All three experiments were performed using two pieces of equipment: an Energy Conservatory (2012) Duct Blaster and a DG700 dual pressure gauge. For each bale and wall specimen, eight readings of air flow, q, at different pressures (between 20 Pa and 100 Pa) were collected according to ASTM air leakage measurement standards (ASTM E779 2010). The duct blaster and the pressure gauge provided all pressure and flow measurements. Test data were collected and analyzed using the computer program "TECBLAST Duct Airtightness".

2.1. Air tightness of plain bales

The first experiment focused on the effects of bale orientation and density on air tightness of individual plain straw bales. Orientation was considered because, in practice, straw bale walls may be stacked "flat" or "on edge" (see Figure 1). Bales that are stacked flat are loaded perpendicular to their largest face — parallel to the plane of the tie hoops and generally perpendicular to the straw fibers. Bales loaded on edge are loaded parallel to their largest face — perpendicular to the plane of the tie hoops and generally parallel to the straw fibers (King 2003). Though straw bales are known to be highly air permeable, it was hypothesized that, due to the anisotropic nature of straw, the ability of plain straw bales to retard airflow would vary depending on bale orientation and density.

Figure 1: Schematic of measuring air flow through plain bales, (a) on-edge and (b) flat.



2.1.1. Plain bale test procedure

Two-string rye straw bales were placed into a plastic container with dimensions 50 x 40 x 84 cm. The basic physical properties of the bales are provided in Table 1. The straw bale occupied the majority of the container volume and small gaps were also filled with straw so that airflow across the volume of the container would have to pass through straw material. The container served the purpose of keeping the specimen in the same position throughout the process to eliminate interference from investigators shifting the bales. The moisture content of the bales was measured using a Greisinger GMH 3810 moisture meter.

Holes were drilled on four sides of the container to allow connection of pressurization testing equipment (see Figure 2). Twelve holes with diameter of 2.54 cm were made on each side. Depending on the orientation being tested, one pair of holes (on opposite sides of the container) were sealed with tape. The tape was also placed around the circumference of the container lid to ensure complete air tightness. Connections were tested for each specimen with depressurization and smoke to assure no air leaks occurred except through the holes on the opposite side of the container where testing equipment was attached. To change bale orientation, the container was simply rotated and the internal pressure tube and flex-duct connection was repositioned on the other side.

The air flow rate at a standard air pressure difference of 50 Pa was determined using the computer program "TECBLAST Duct Airtightness"which incorporates calibration of the particular fan apparatus used. The calibrated variable flow fan apparatus is the Energy Conservatory Minneapolis Duct Blaster. The TECBLAST software is designed to be used with the Duct Blaster and simply provides a convenient data input and curve-fitting platform. A multipoint test is conducted by collecting flow readings at multiple pressures. A "best fit" regression line is plotted through the flow/pressure readings data to determine the Leakage Curve. The leakage curve follows the Power Law, which has been shown to reliably model actual leakage in buildings and assemblies (ASHRAE 1989, Etheridge 1977, Walker et al 1997). The leakage curve is defined by the following equation:

$$q = C \times P^{n}$$

where:

- q is airflow into (or out of) the tested assembly.
- C is the Coefficient.
- P is the pressure difference between inside and outside of the duct system
- n is the Exponent.

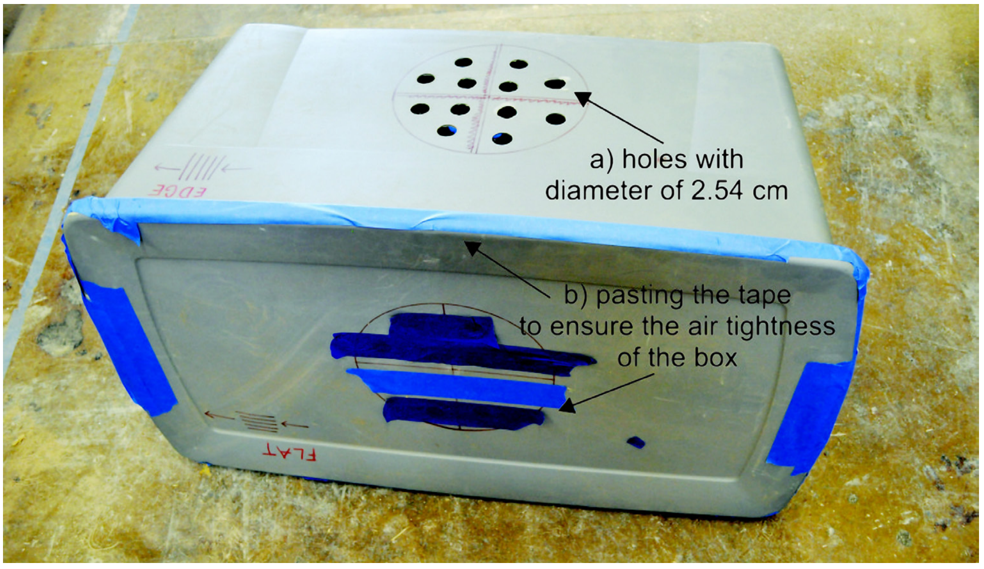
For each specimen tested, the calculated leakage curve also generates a correlation coefficient (r), which can be interpreted as a measure of the precision and repeatability of the test. Taking together all of the tested specimens in all three of the experimental procedures described below, the mean correlation coefficient was 0.9987 with a standard deviation of 0.0011, indicating a very high level of precision and reliability for the air flow testing apparatus and procedure used.

Collected test data were analyzed and 50 Pa was established as an appropriate reference pressure difference, conforming to standard practice.

TABLE 1. Basic properties of plain straw bale specimens:

Descriptive statistic	Width (cm)	Height (cm)	Length (cm)	Density (kg/m^3)	Moisture (%)
Mean	49.5	36.4	84.9	93.9	5.6
Standard deviation	1.0	1.0	1.7	6.8	0.4
Count	18	18	18	18	18
Minimum	47.5	35.1	82.4	86	4.9
Maximum	50.5	38.1	87.4	106	6.2

Figure 2: Plastic container showing a) holes for connection of pressurization testing equipment and (b)tape to ensure complete airtightness of the box circumference



2.1.2. Plain bale test results

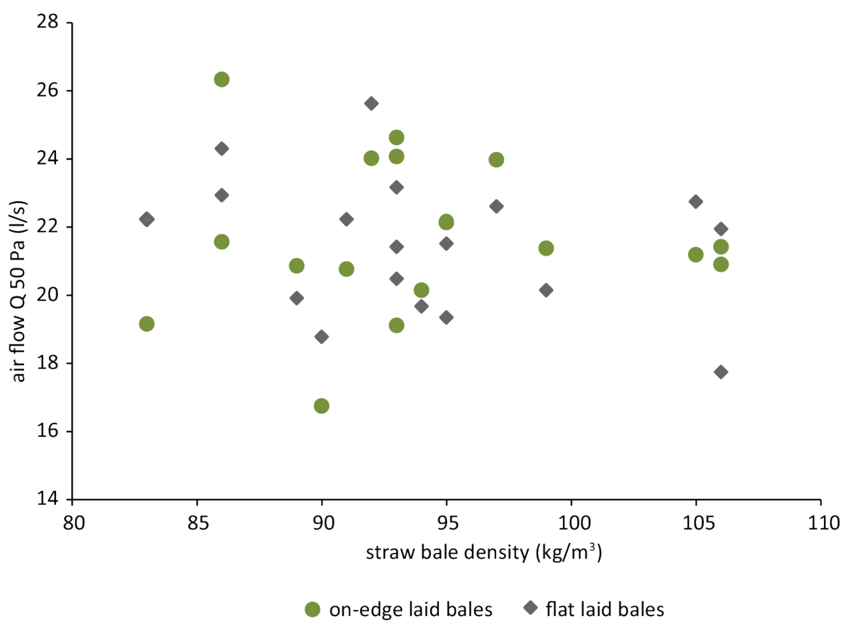
The results show clearly that the straw bale material itself is highly air permeable: the air flow rates are almost as high as for unimpeded openings. An Analysis of Variance (ANOVA) indicated that no statistically significant difference exists between the mean values of air flow for the two bale orientations at a 5 % level of significance.

TABLE 2. Air flow (q) at pressure 50 Pa and comparison between flat and on-edge orientated plain bales.

Descriptive Statistics	Density (kg/m³)	q (l/s) flat	q (l/s) edge	Δ q (l/s)
Mean	94.1	21.5	21.7	-0.2
Standard deviation	6.6	2	2.3	2.2
Count	18	18	18	18
Minimum	86	17.7	16.8	-3.7
Maximum	106	25.6	26.3	3.1

It was also found that there was no statistically significant relationship between air flow and straw bale density either, as illustrated in Figure 3, by the degree of random scatter of the data points.

Figure 3: Air flow through straw bales with different orientations and densities.



2.2 AIR TIGHTNESS OF PLASTERED BALES

A second experiment measured the air tightness of plastered straw bale surfaces. Thirty bales were coated on two opposing surfaces with plaster - 15 bales in the flat orientation and 15 in the on-edge orientation. Therefore, 60 plastered surfaces were measured in total.

2.2.1 Plastered bale preparation

Plaster material selection was based on practical guidelines presented in several studies (Morrison and Kefee 2012, Lacinski 2001). Since straw bales are extremely sensitive to moisture, careful selection of material is needed particularly in a cold and wet climate where both exterior bulk moisture and condensation from within threaten the durability of walls. It is important to insure a vapor-permeable wall system that allows for drying potential to both sides of the wall assembly (Dérome and Saneinejad 2010).

In practice, lime plaster is the most commonly used material for both interior and exterior finishes because of its higher durability in comparison to clay-based plaster (Racusin et al. 2011). For the purposes of this research, three different material types of plaster were used; clay, lime and lime-cement plaster. Plasters recipes and their application were applied on straw bales in accordance to straw bale building guides (Morrison and Kefee 2012, Lacinski 2001). Plasters were manually stirred until a uniform mixture was obtained. Plaster was applied in two layers with surface moistening between applications to assure good adhesion. The average layer thickness of each specimen was measured to be 30.6±0.57 mm (COV 19%) where layer thickness was defined as the difference between manually measured width of the bale and plastered bale.

The lime plaster mixture was prepared by following the ratio of 1:3, lime: sand. The ratio for the lime-cement plaster was 1:1:6 lime: cement: sand. In both cases, Dolomitic Hydrate Hydrated type S lime was used and in the second case, sand and Portland cement was incorporated. For the clay mixture, clay, sand and chopped straw (approx. 5 cm long) was mixed in the ratio of 1:1:0.25 where the straw acts as a binder. Local clay (as opposed to a bagged clay mixture) was used for consistency with common practice as many builders utilize clay directly from the construction site to save money and use material that would otherwise be taken away. Before the plaster was mixed, the clay was cleaned and filtered; bigger aggregates (such as stones, leaves and roots) were removed but many smaller parts such as seeds remained.

2.2.1.1 Crack grade measurement

Before air tightness was measured and after curing for over 40 days, the surfaces were evaluated for crack severity and compared visually to establish what the authors have termed a "crack grade". The purpose of this crack grade is to quantitatively describe and categorize the bale surface condition with the intention that a crack grade categorization will become a useful tool in practice to enable a fast, efficient, economic and easy way to evaluate the air-tightness of the building envelope.

Currently, the air tightness diagnostic is delivered by using expensive specialized equipment that are operated and interpreted by experts. For this reason, air tightness test results are usually supplied after most of the construction is completed. However, the authors contend that because the plaster has the critical function of being the primary air barrier, air tightness should be evaluated periodically throughout the construction process. Thus, the simple, visual crack grade system was developed.

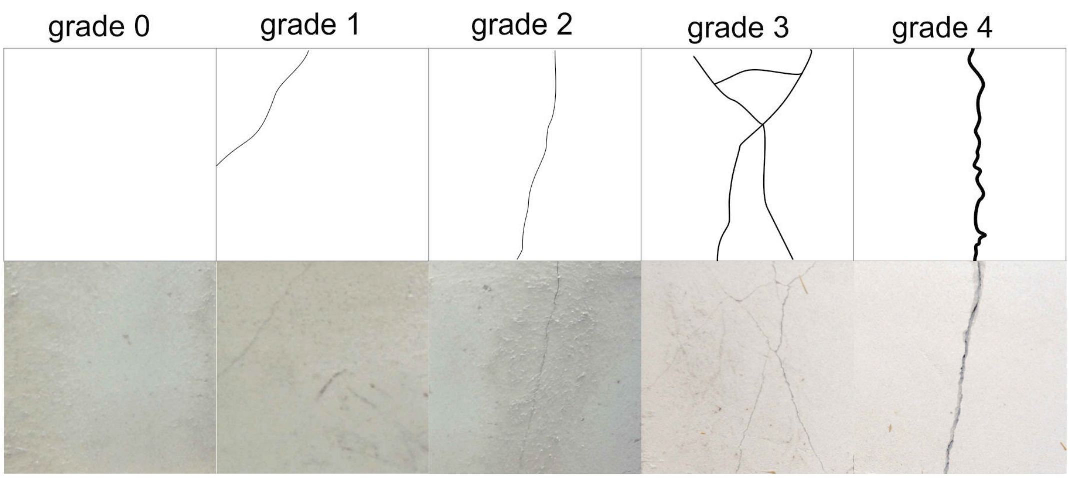
The crack grade system was devised after collecting detailed crack information (size and severity) on each of the 60 specimen surfaces. Five distinct crack grades were established. Although the boundaries drawn between grades are somewhat subjective, the results reinforce the veracity of the system. Corresponding crack grade and crack type are described in Table 3. Typical cracks for each crack grade are visually depicted in Figure 4. The images show only part of the surface evaluated because it is not possible to see the cracks in the image without using magnification.

It is important to note that for crack grade 0, although there are 'no visible cracks', there may still be some air leakage. This is because the system is based on visual inspection for a material that is not a perfect air barrier; that is to say, that air will flow through cracks that are too small for the naked eye as well as through diffuse airflow networks, which is confirmed by differential pressure testing.

TABLE 3. Specimen surface categorization.

Crack grade	Crack type
0	no visible cracks
1	no more than 3 short surface cracks of maximum 3 cm long
2	more than 3 short surface cracks of maximum 3 cm long
3	more than 3 longer and deeper surface cracks of 3 cm long
4	Any number of deep (through the plaster) cracks more than 3 cm long

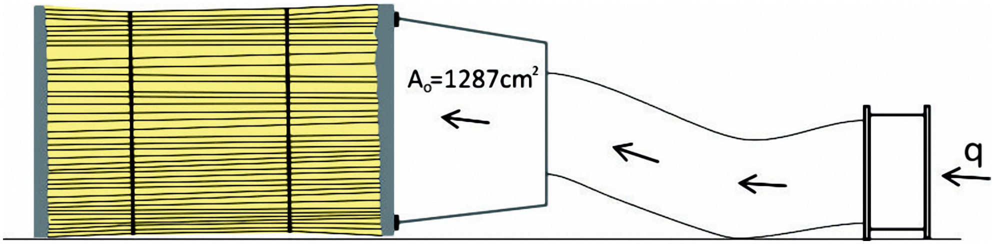
Figure 4: Typical cracks for each crack grade.



2.2.2. Plastered bales results

As in the first experiment, all pressure and flow measurements were made with the duct blaster and the dual pressure gauge. Tests were performed by pressing the gasketed open face of the flow-calibrated plastic container (Ao=1287 cm^2) against the plaster of each specimen as shown in Figure 5. For each specimen, eight readings of air flow were collected according to ASTM E779.

Figure 5: Schematic of second experiment – container pressed against plastered specimen.



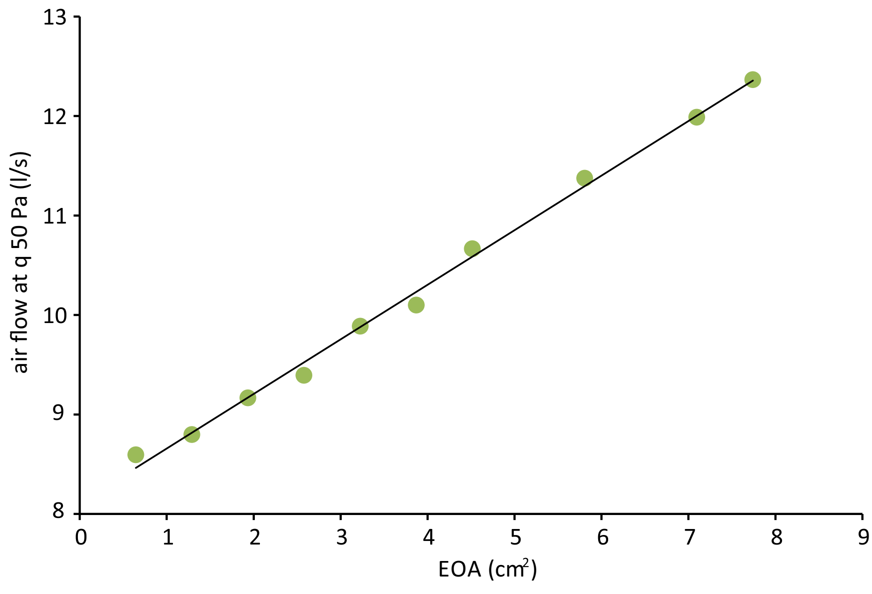
The theoretical collective area of cracks (Ac)[1] on the surface of the tested specimens was calculated using the computer program "TECBLAST Duct Airtightness" which incorporates calibration of the particular fan apparatus used. Table 4 summarizes the results according to each crack grade.

TABLE 4. Crack Area (A_c).

Descriptive Statistic	0	1	2	3	4
Mean A_c	1.0	1.48	2.48	5.38	7.42
COV	0.33	0.30	0.87	0.74	0.46
Count	26	24	5	3	2
Minimum	0.65	1.29	1.94	4.52	7.10
Maximum	1.29	1.94	3.87	5.81	7.74
Crack ratio area (%)	0.08	0.12	0.22	0.42	0.58

Figure 6 illustrates that air flow pressure increases linearly with crack size. These results indicate a significant impact of crack size on air tightness of the specimen's surface. It should be noted that no statistically significant difference was found between bale orientations or plaster type. It was, however, observed that more cracks occurred on lime and clay plastered bales.

Figure 6: Air flow pressure at 50 Pa increases with the size of crack area (A_c).



1. The TECBLAST software and other documentation from the Energy Conservatory use the nomenclature of "effective orifice area" (EOA) for what is referred to here as crack area (A_c).

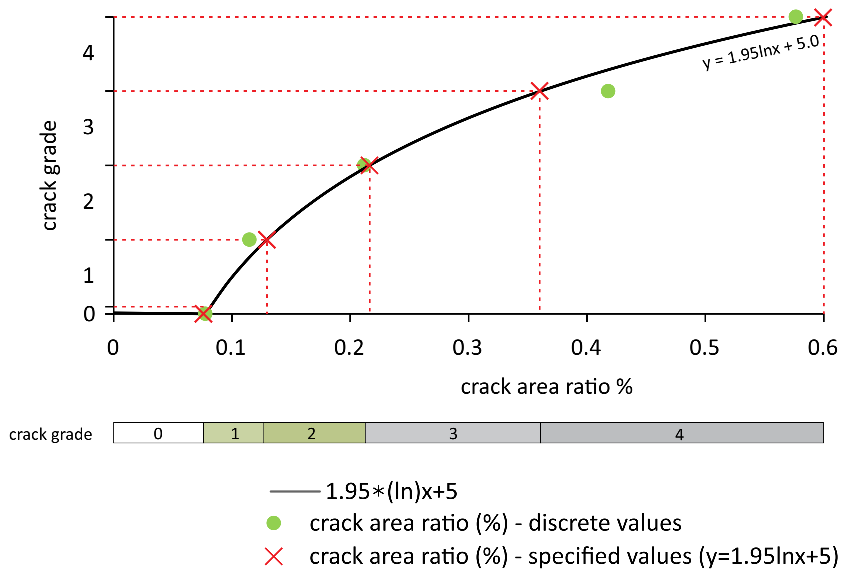
2.2.2.1 Crack area ratio calculation

Based on the average crack area, A_c, for each established grade (Table 4), the crack area ratio, Ω, (i.e. the ratio between crack area, A_c, and tested surface area, A_o, where A_o= 1287 cm^2 is the gasketed face of the plastic box pressed against the plaster) was calculated and expressed in percentage (%):

$$(A_c / A_o)*100 = \Omega\ (\%)$$

The relationship between crack grade and crack area ratio can be described using a logarithmic function (see Figure 7).

Figure 7: Crack grade as a function of crack area ratio.



In general, the theoretical value read from the curve is in good agreement with the experimental mean values. Slightly larger deviation is observed only in the case of a value for crack grade 3. Table 5 summarizes the discrete point results together with their percent difference.

TABLE 5. Average crack area ratio per crack grade.

Crack Grade	**0**	**1**	**2**	**3**	**4**
Experimental crack area ratio (%)	0.08	0.12	0.22	0.42	0.58
Theoretical crack area ratio (%)	0.07	0.12	0.23	0.37	0.60
Percent difference (%)	13	/	5	12	3

2.2.2.2 Relationship between crack grade, crack area ratio and air tightness quality

The logarithmic relationship between crack grade and crack area ratio provides a new method for determining airtightness quality of plastered straw bale surfaces (or, in practice, the building envelope of a straw bale building). Table 6 presents the proposed system. For each crack grade, an air tightness quality level is prescribed. The quality level is calibrated with the assumption that crack grade 0 is valid for superior air tight buildings; that is, when there are less than 3 Air Changes per Hour at 50Pa in a typical building with a floor area of approx. 120 m^2 (ACH_{50}) in accordance with MORS (2010). Similarly, crack grade 1 reflects buildings with normal airtightness (ACH_{50} = $3h^{-1}$) When ACH_{50}=3h-1 the building does not need a mechanical ventilation system. When ACH50<3h-1, a technical system for ventilation is needed which provides appropriate air quality for the building users. For crack grade 4, the large crack area on the surface provides extremely poor air flow retardation, and worse, may let in enough moisture to compromise the physical integrity of the straw bale.

TABLE 6. Evaluation of air tightness quality level:

Crack grade	Crack area ratio, Ω (%)	Air tightness quality level*
0	$\Omega \leq 0.07$	good (ACH50<3h-1)
1	$0.07 < \Omega \leq 0.13$	normal (ACH50=3 h-1)
2	$0.13 < \Omega \leq 0.23$	poor (needs improvement) (ACH50>3 h-1)
3	$0.23 < \Omega \leq 0.37$	very poor (significant improvement needed)
4	$0.37 < \Omega \leq 0.60$	extremely poor (straw bale wall system may fail)
5	$\Omega > 0.60$	unsuitable airtightness

* ACH_{50} = Air changes per hour at 50Pa in a typical building with a floor area of approx. 120 m^2.

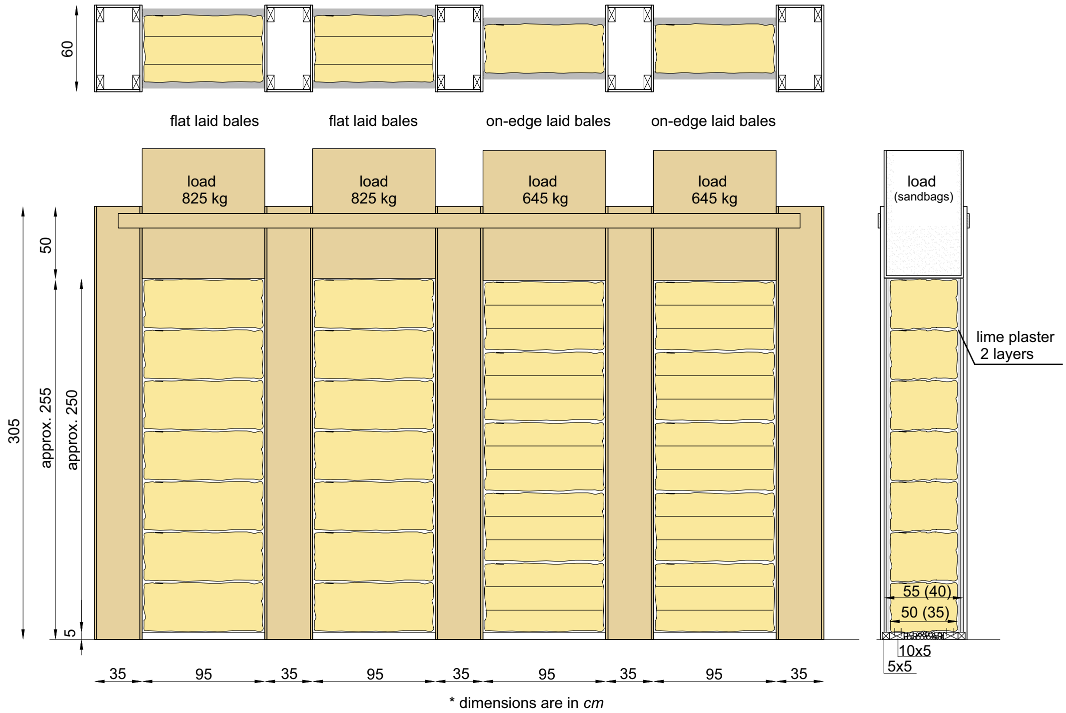
2.3 AIR TIGHTNESS OF STRAW BALE WALLS

2.3.1 Wall test setup

Four test walls were constructed in conjunction with a separate experiment to evaluate creep and deflection under loads, as shown in Figure 8. All four walls were coated with lime plaster using plaster mixture as described in section 2.2.1. Two walls were assembled with flat bale orientation and two walls with on-edge bales. All four walls were loaded with sand; walls with flat bales carried 825 kg and walls with on-edge bales carried 645 kg. Load was first applied to the straw bales alone (without plaster) which is commonly done to pre-compact loadbearing walls. One wall of each orientation type was plastered one week after loading and the remaining two were plastered four weeks after loading.

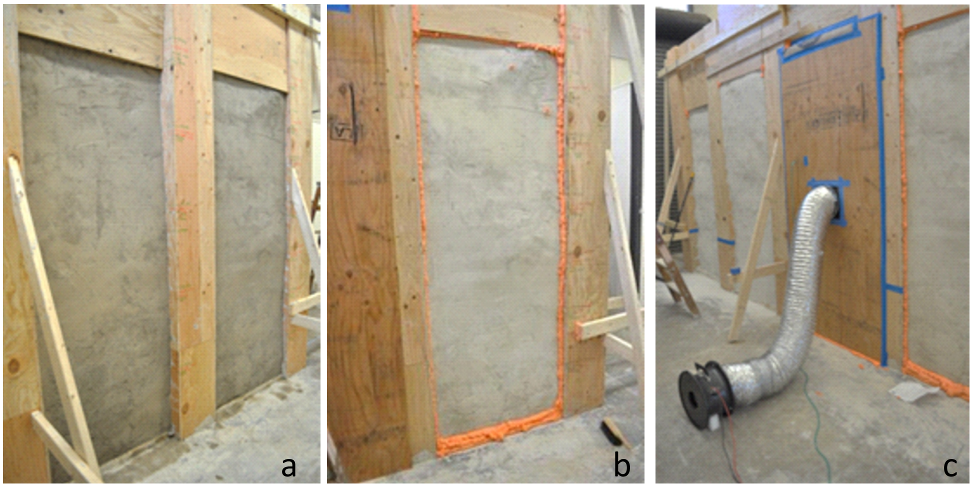
More cracks were expected on walls that were plastered only one week after load was applied, but in the end, it appeared there was little difference between walls. Cracks were observed at joints between straw bale, plaster and construction elements (columns, top box and foundation – toe ups) on the perimeter of all four walls. Cracks were expected since plaster contracts during the drying period.

Figure 8: Schematic of experimental wall setup.



In the first round of air-tightness testing, measurements were taken without sealing the perimeter of the wall (Figure 9a). In a second step, measurements were taken after a complete sealing of the perimeter of the wall with one-part expandable urethane foam (Figure 9b). The testing apparatus consisted of a plywood sheet treated with polyurethane coating to insure airtightness with a 0.25 m diameter hole for connection to the Duct Blaster fan and a hole to accept insertion of a pressure tap. This was attached to the wall frame and the perimeter of the plywood was sealed with airtight tape and urethane foam. All connections were tested with depressurization and smoke to assure no air leaks were possible except through the wall specimen (Figure 9c).

Figure 9: a) no sealing, b) sealed perimeter, c) during air flow measurement.



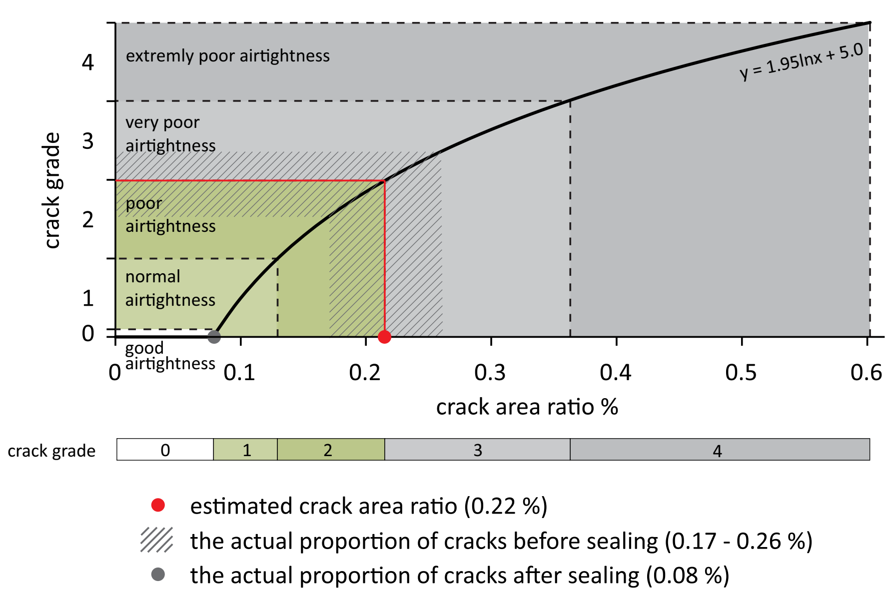
2.3.2 Wall crack grade results

All four walls were evaluated and categorized into one of the five crack grade groups before the measurements of air tightness were taken. There were no surface cracks noticed on any of the walls. But around the entire perimeter of all four walls (i.e. between straw, plaster and the wood framing) loose contacts were observed. The walls were first visually inspected and qualitatively evaluated as a crack grade 2. Subsequently, length and width of cracks were measured and an average crack area ratio was calculated. The crack area ratio was 0.22 % for all walls which corresponds to a crack grade of 2, validating the visual evaluation.

2.3.3 Wall air tightness results

On all four walls, two series of measurements were taken: 1) without sealing, and 2) with sealing. Each time, eight readings of airflow at different pressure were taken and analyzed. The ratio between Ac and wall surface on walls with no sealing was between 0.17 % and 0.26 %. After sealing the perimeter of walls, the average crack ratio between Ac and wall surface was 0.08 % (Figure 10). This demonstrates the competence of the crack grade method to estimate air tightness as the estimated crack ratio fell within the range of the instrumentally tested crack area ratios. After sealing the perimeter of the wall, the air flow q decreased by 48 %, on average. This reinforces the importance of proper workmanship and detailing of construction joints in the building process.

Figure 10: Crack grade determination based on estimated crack ratio.



3. CASE STUDY – AIR TIGHTNESS OF A STRAW BALE HOUSE

The crack grade system was implemented on a straw bale house in Radomlje, Slovenia (Figure 11). The straw bale house is a timber frame structure where the straw bales are nonstructural and used only as infill. They are plastered with solely clay on the inside and on the outside, clay for the first layer and lime for the second layer. The clay was obtained from the house's construction site. The house has a simple two-story floor plan with a floor area of approximately 121m^2.

Figure 11: Case Study Straw Bale House in Slovenia.

As in the case of the wall experiment, a visual inspection of the building envelope was first performed to qualitatively establish crack grades. Based on numerous wall cracks and gaps on construction joints, the house was categorized as crack grade 4, which means that the crack area ratio is between 0.37 and 0.60. Therefore the airtightness of the building was expected to be inadequate.

The crack area over the entire wall surface of the house was physically measured to be approximately 1.1 m^2. Around 90 % of the cracks were observed at the construction joints (e.g. wall/floor, wall/ceiling). The area of the building envelope of the case study house was 266 m^2 giving a crack area ratio, Ω, that is 0.41 % of the building envelope. Based on the crack grade system, the air-tightness of the house was expected to be extremely poor.

3.4.1. Blower door results – first test

A blower door test was performed on the house following the standard SIST EN 13829 (2001). At a pressure difference of 50 Pa, air flow (q) was 2998 m^3/h. Analysis of the results shows the air exchange of the house with a volume of 300 m^3 was $ACH_{50} = 9.99\ h^{-1}$. The most critical air loss locations were:

1. between the external wall and the raised ground floor
2. between the floor and the fireplace – brick stove
3. through air channels
4. through cracks in columns
5. between the roof and wall joint
6. through electrical outlets in external walls

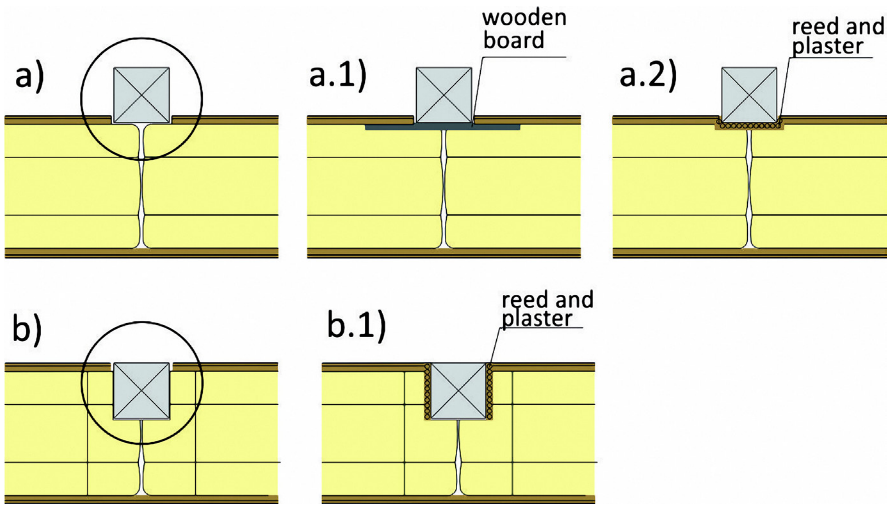
3.4.2. Blower door results – second test

Based on the results of the first blower door test, the cracks and poorly designed construction joints were improved. Before the second blower door test, again the crack ratio was calculated, R 0.23 % (crack area size approximately 0.61 m^2). The crack area ratio was classified to be in class 2 (i.e. poor and needs improvement). This means the number of air exchanges will be lower but still more than desirable for energy efficiency and durability. The air flow (q) of the second blower door test was 2255 m^3/h ($ACH_{50} = 7.52\ h^{-1}$). The number of air exchanges decreased by approximately 25%. Experience suggests that when construction joints in the house are more thoroughly sealed, the blower door test result can meet the criteria of the standard (ACH_{50} = 3 h^{-1}) (MORS 2010). Data from Racusin et. al. (2011) indicates that the average straw bale house air changes per hour at 50 Pa test pressure is 5.12 (max = 11.81, min = 2.5). Thus, the air leakage of the case study house (7.52 ACH_{50}) is slightly above average but well within the range found elsewhere.

3.4.3. Potential solutions

Even well designed details can be poorly executed in practice. In the case study house, an air barrier was specified in the building documentation but it was not correctly installed during the building procedure. Also, details of timber frame and straw bale wall joints were designed (using a reed mesh attached to timber) but the contractor did not follow the plans. As with all building methods and materials, good communication and rigorous quality control and testing are necessary to construct a high performance air barrier. However, in straw bale construction carefully designed details and inspection are particularly critical due to the moisture sensitivity of the wall material and the varying levels of skill among builders. With simple interventions, such as inspection using the crack grading system, one can improve the airtightness of straw bale houses. But to ensure air tightness to a higher standard, for example "passive house", more specific details need to be developed, which should be the focus of future studies of straw bale building. For example, Figure 12 illustrates simple, economical solutions which should be further investigated.

Figure 12: Possible solutions in providing better airtightness.



4. RESEARCH FINDINGS AND CONCLUSIONS

This research presents basic information about the air tightness behavior of straw bale as a stand-alone material and as part of a composite structure. The orientation and density of the bales alone have no significant effect on air flow through a wall assembly. The results indicate clearly that the material is a poor air flow retarder, and that construction detailing is extremely important to insure appropriate air barrier performance. Results of a second series of experiments, in which plastered surfaces of straw bales were tested, indicated that visibly detected cracks can be correlated with actual measured data. A crack grade system was devised as a practical tool for quality control in the field. A third, full-scale wall experiment was also conducted to verify the crack grade system which brought to attention the importance of appropriate sealing between building joints. The crack grade system was then implemented on an actual straw bale house. Blower door results confirmed the accuracy of the crack grade system and pin-pointed the most critical air-loss locations. The results of the study on the whole indicate the need of future research on the means of assuring air barrier continuity between different elements of straw bale construction. With solid details at joints, better air tightness performance of straw bale buildings can certainly be achieved.

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