THE DESIGN AND CONSTRUCTION OF THE 4C'S BUILDING

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INTRODUCTION

The Haliburton 4C's Food Bank and Thrift Store building, shown in Figure 1, was designed and built in June through August 2005. The structure combines an impressive variety of sustainable design options, while meeting specific functional and financial goals. The vision for the building was for it to serve as a working food bank and thrift store, while being a demonstration of the applicability of various alternative building materials and design options for a public building located in a very "traditional" neighbourhood.

The Haliburton 4C's (Christian Concern Community Centre) is a non-profit, charitable collaboration of four Haliburton Churches that work to provide food and second-hand clothing for members of the community who require moderate support. The food bank and the Lily Ann second-hand clothing store are the two main components of the operation, with the clothing store providing funding for the food bank. A partnership was created between the 4C's and the Sustainable Building Design & Construction Program of Sir Sandford Fleming College. The goal was to create a cost-effective and sustainable home for the Haliburton 4C's group.

The use of alternative building materials and design techniques has traditionally been limited to private residences, with public use restricted to a small number of projects utilizing only a few of the many sustainable building options available. The reason for this is a general lack of knowledge in the area of sustainable design and construction, and a false belief that sustainable construction leads to a structure that is not aesthetically pleasing, and has limited functionality. One goal of the 4C's project was to showcase sustainable building in a public structure, and thus to dispel the negative perceptions that may exist regarding alternative building. This goal was achieved, in conjunction with the needs of the Haliburton 4C's group, and the requirements of the Sir Sandford Fleming Sustainable Building Design and Construction Program.

In this paper, the conceptual design for the building is outlined, with an emphasis on describing the sustainable and unique wall design, which included the use of hemp bale construction, earthen plasters, and an earthbag stacked footing. In order to obtain building code approval, testing of the proposed wall system was required. This was carried out at Queen's University in Kingston, Ontario. Further testing was carried out to better understand the structural performance of some of the materials used in the building design.

FIGURE 1. Haliburton 4C's thrift store and food bank.

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DESIGN PROCESS

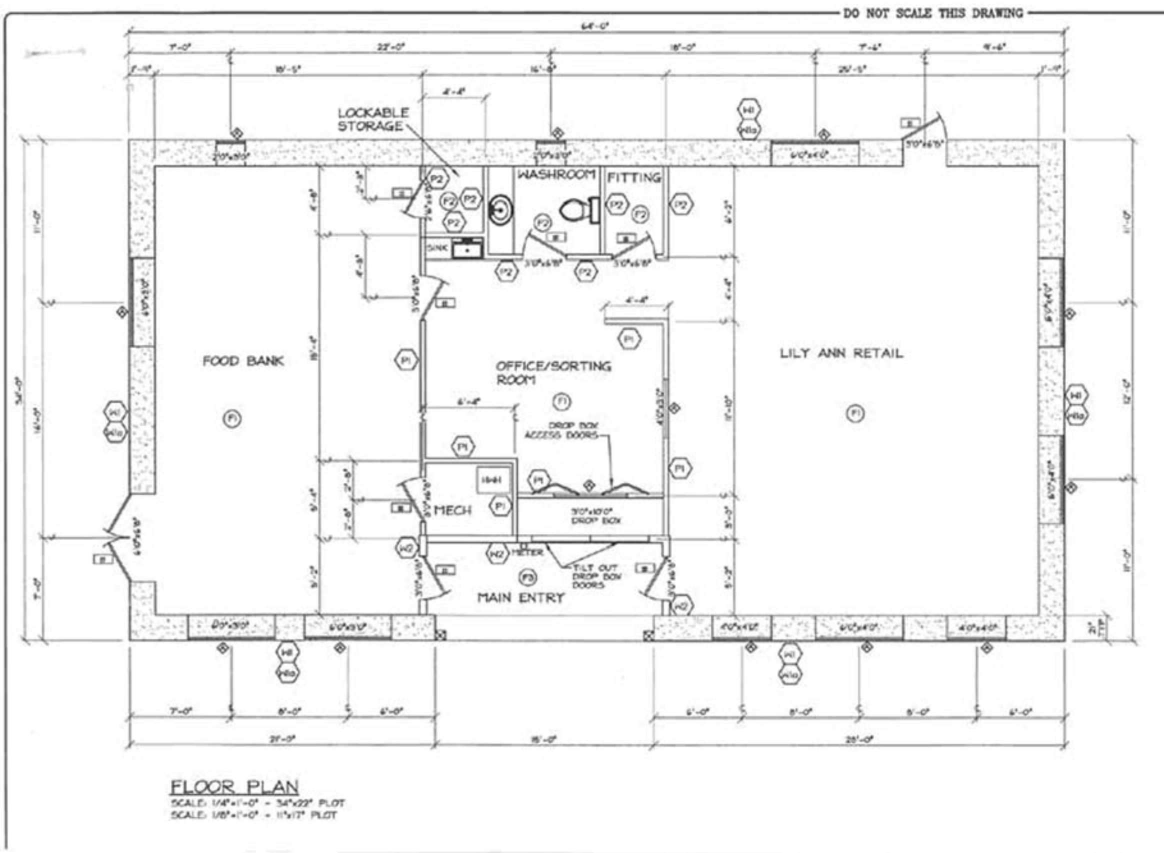
Conceptual Design

The Municipality of Dysart, et al, contributed the corner of an existing parking lot in the centre of Haliburton for the 4C's building. Fortunately, the lot had a southern exposure for creating a sound passive solar design. Three distinct areas within the building were required: a food bank, an office and sorting room, and a retail area for a thrift store. Lot size and budget limited the building to a size of approximately 170 square meters on the interior. Figure 2 shows the floor plan of the 4C's building. By the client's request, a very simple rectangular design with a minimum of interior partitions was used.

Exterior Walls

Load bearing plastered straw bale construction was selected for the exterior walls of the building. Straw bale construction is increasing in popularity in Ontario, with over one hundred approved buildings in the province. The design and construction of straw bale walls has evolved dramatically over the last decade, and is now at a point where the available anecdotal knowledge provides substantial support for the method. Straw bale construction also met the owners' desire for a wall system that is environmentally sustainable. Straw is an annually renewable resource that is locally available, minimizing the environmental impact of the structure. Furthermore, straw bale walls can be built fairly readily by un-skilled labourers, with minimal need for supervision. This feature can reduce the cost of construction, while the excellent insulation properties of straw are expected to reduce the longer term costs of heating and cooling the building. Hemp bales were chosen for the project as they were known to be locally available, and their strength and stiffness

FIGURE 2. Floor plan of 4C's building.



typically surpasses that of other locally available straw bales. It was also decided that reinforcing mesh would only be used in the walls in areas of potential plaster cracking, such as around windows and doorways.

The final wall design is given in Figure 3, which shows a typical exterior load-bearing wall, the wall connection to the roof trusses, the earthbag stacked footing that supports the wall, and the details of the floor.

In order to make the walls even more environmentally friendly, it was decided to use earthen plaster as the render for the walls, as opposed to lime-cement plaster. The earthen plaster was created from a clay/silt soil that came from a nearby construction site. The interior and exterior faces of each bale were dipped into a tub of clay slip before stacking to form the wall. The slip contained clay, soil, and water, and was mixed to the consistency of thick cream. This provided a deep

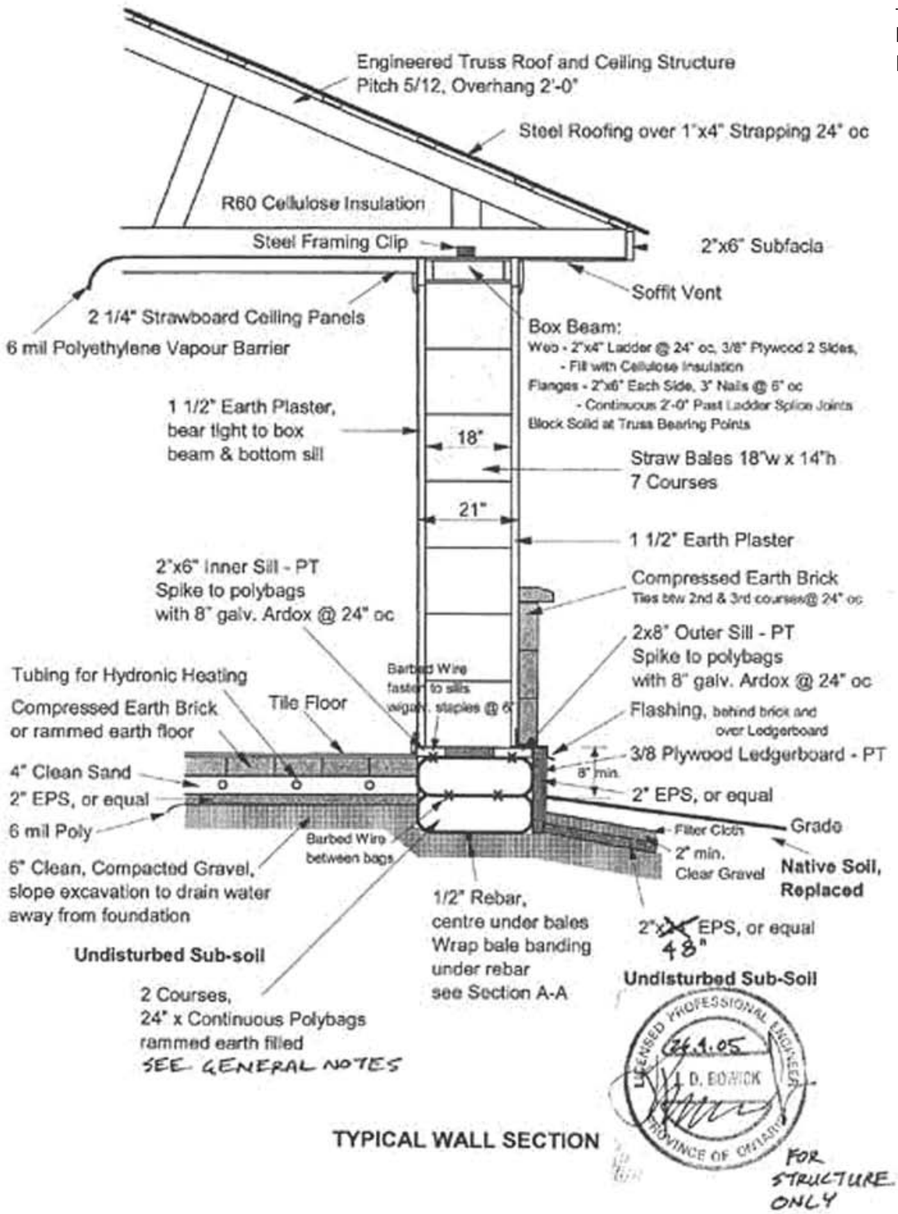


FIGURE 3. Typical exterior load-bearing wall detail.

penetration (25–50 mm) of clay into the straw and ensured a good bond between the earthen plaster and the straw.

After some experiments for the wall render, a mix of two parts sand to one part of the clay/silt soil was used. Some mixes also included between eight and twelve cattail heads and four large handfuls of chopped wheat straw, in lengths from 6 mm to 50 mm. The cattail heads and chopped straw were used to improve the tensile strength of the plaster, similar to the use of glass or steel fibres in concrete.

The plaster was hand-applied to the wall surface inside and out, to an average thickness of 38 mm. In many places, however, it was much thicker to make up for inconsistencies in the wall. A specific attempt was made to make the walls as straight as possible. In most cases, the entire 38 mm thickness was applied at once. This was followed by a second coat, which was used to make the surface as flush as possible. The second coat was mixed in the same way as the first, but with slightly more sand (2.5 parts sand to 1 part clay/silt soil). Finally, a finish coat was applied by trowel to a thickness of 2–5 mm. This coat used 3 parts sand to 1 part of the clay/silt soil. Cattail fluff was again used but chopped straw was not. This was because the chopped straw would interfere with the intended thin, fine finish. As this coat dried, it was rubbed with a damp sponge to eliminate trowel marks.

For one large section of the interior, a commercial plaster pump was used to apply the earthen plaster. This machine was very sensitive to the gravel that was in the clay/silt soil, but once the soil was screened it proved just as easy to pump as the lime/cement plasters the machine is typically used to apply. With such a machine, applying the earthen plaster could be done commercially at costs and times very similar to concrete-based materials.

Both the inside and outside plaster layers were then painted with silicate dispersion paints, made by Eco-House of New Brunswick, Canada. This potassium silicate paint does not create a waterproof film on the walls, but rather deposits a mineralized surface with very small pores. This eliminates the infiltration of most liquid water (rain and snow) but allows for moisture to transpire through the walls in order to maintain a balanced humidity between the interior and exterior atmosphere. This is important, as the wall system does not use vapour barriers, and relies on the penetrability of the wall for humidity to diffuse from inside to outside the building.

Unfortunately, there is little data in the currently available literature regarding the structural performance of earth plastered straw bale walls. Thus, the project engineer, Anthony Spick, of Blackwell Bowick Partnership of Toronto, Ontario, requested that testing data be provided as a basis for load calculations. The Department of Civil Engineering at Queen's University, Kingston, Ontario undertook the testing of an earth-plastered wall as will be discussed below.

Interior Walls

The interior walls were a combination of compressed straw panels and timber stud walls with a variety of infill materials. The compressed straw panels consist of straw which has been compressed at high heat to create a solid panel segment. The infill walls were constructed by placing the infill in the wall and plastering over with an earthen plaster. Plastic bottles, as shown in Figure 4, and hempcrete, which consists of lime, chopped hemp fibres, and water, were used as infill materials.

Foundation

Figure 3 shows the rubble trench foundation with rammed earthbag stacked footing. The rubble trench foundation was constructed by excavating the soil over the entire footprint of the site and filling the trench with compacted gravel. The rubble trench provided adequate structural stability, and drainage for the structure. Figure 5 shows the earthbags that were placed over the gravel around the perimeter of

FIGURE 4. Pop bottle infill wall.

FIGURE 5. Placement and tamping of foundation.

FIGURE 6. Laying and tamping earthen floor.

the footprint to provide support for the load-bearing exterior walls. The earthbags were constructed by filling 60 mm diameter continuous polypropylene bags with a mixture of granular "B" gravel, water, and Portland cement for most of the perimeter. Rammed earth was used in the earthbags for the framed alcove area on the south side of the building. Once the first course was laid, the bag was tamped to ensure adequate consolidation of the mixture. The second course was also tamped for consolidation and levelling. An issue that arose with the earthbag design was a lack of confidence from the engineer in the ability of the earthbag to withstand the appropriate loads with minimal deformation. Thus, it was required that experimentation be conducted at Queen's University to quantify the amount of deformation that may be expected under the anticipated loading. This experiment is discussed in greater detail below.

Floor, Ceiling, and Roof

The ceiling was constructed of locally milled tongue and groove pine, while the roof was constructed using an engineered truss roof with galvanized steel sheathing, and was insulated using cellulose insulation made from a minimum of 85% recycled paper. The floor was a finished earthen floor.

The earthen floor was constructed by first laying and tamping local soil as shown in Figure 6. The soil was then overlaid with a variety of finishes. Much of the floor was finished with earthen clay, similar to that used on the exterior walls. A mixture of earth, sand, and chopped straw was used. In some areas 5% Portland cement was added to the mixture to speed the curing time. The earthen floor was given a mosaic pattern to control where drying cracks occurred. Once the floor had cured the cracks were filled with grout. The earthen floor was tinted terracotta and coated with linseed oil and wax as a finish. Other floor finishes included tile and limestone.

It was later noted that the addition of Portland cement to the floor mix resulted in a finished product that was much more brittle and likely to begin "dusting" under regular use. Mixes using only clay and sand were much stronger and wear resistant, and combined more successfully with the oil finishes. Due to problems with the floor dusting, a concrete sealant was later added on the floor to provide additional protection.

FIGURE 7. Installation of photovoltaic modules.

Heat and Electricity

The building is heated via hydronic radiant floor tubing with solar pre-heating and a temperature-sensitive, on-demand propane boiler. This system pumps hot water through tubing located in the floor of the structure, as indicated in Figure 3. The water is heated using roof-mounted thermal panels, and if necessary a propane boiler can provide additional heating. This method is also used for the domestic hot water heating.

The electrical system is based around a 1kW grid-intertied photovoltaic (PV) array shown in Figure 7. The system consists of ten 100-watt modules, which are connected to the Province of Ontario's Hydro One power grid, eliminating the need for batteries. Any excess energy produced by the array is fed into the power grid. The energy is then "returned" to the building at times when the PV array does not produce enough energy, such as on cloudy days. The 4C's are then only billed for the net energy being consumed off of Hydro One's grid.

Fixtures and Finishes

Much of the lighting for the structure is provided by sunlight through a number of fibreglass windows located in the exterior walls, and "sun tubes" installed in the roof structure to allow sunlight into the interior spaces of the building. All the lighting and electrical needs were chosen to minimize consumption. Ceiling-mounted, round compact fluorescent units were chosen for the lighting. The large retail space contains four 72-watt units, the food bank has three 72-watt units, and each of the smaller rooms received a single unit of either 48 or 72 watts. Attempts to find affordable controls that would automatically turn the lights on and off, depending on the amount of daylight being received through windows and the solar light tubes, were not successful, and, thus, the lights are manually controlled.

The selection of finishes was intended to minimize the toxicity of the surfaces in the building, both during application and over the life of the building. Silicate paints were used on all the exterior walls. Silicate paints are water-based, and contain no solvents or off-gassing chemicals. They are essentially odourless when being applied, and are dry within a couple of hours, at which point they are still completely odourless and do not emit any volatile organic compounds (VOCs). The interior walls were painted with latex paints that represented the least toxic offerings from the major paint companies. However, those applying these paints still complained of headaches, and the odours remained in the building for a long time. The floors and ceilings were both finished with boiled linseed oil. As discussed above, an environmentally-friendly concrete sealant was later applied to the floor to control dusting.

Cost Summary

The 4C's is a non-profit organization, and thus the project was run on an extremely tight budget. The project was budgeted at $121,000 (excluding a contingency allowance) and the final expenses reached approximately $116,000 CAD before taxes for a cost of just under $700/square metre. A summary of the projected and final expenses is given in Table 1.

The greatest expenses were the mechanical systems at $40,000. These included the ventilation, plumbing, electrical systems, water heating systems, radiant heating, and, most significantly, the PV system, which cost over $11,000 alone. Other significant expenses included the roof structure at nearly $18,000 and the fixtures and finishes, which came in over budget at close to $9,000.

STRUCTURAL TESTING FOR BUILDING CODE APPROVAL

As mentioned above, two particular design features of the building posed a challenge to the structural engineer responsible for sealing the drawings. The use of earthen plaster for load-bearing straw bale construction, and the

TABLE 1. Budget summary.

Item	Proposed budget ($)	Net expenses ($)	Net to date as % of proposed budget
Permit	0	0.00	0.0%
Water quality equipment and testing	3,000	0.00	0.0%
Engineering fees	2,800	2,737.98	2.1%
Site preparation	4,600	4,832.86	3.7%
Foundation	3,100	4,398.31	3.3%
Floor	11,525	7,154.38	5.4%
Exterior walls	6,770	7,107.00	5.4%
Exterior doors and windows	13,235	11,294.18	8.6%
Interior partitions and doors	11,480	9,281.00	7.1%
Roof structure and sheathing	15,363	15,422.88	11.7%
Mechanical systems	40,293	38,876.63	29.6%
Fixtures and finishes	2,190	7,626.60	5.8%
Landscaping	3,110	6,095.48	4.6%
Miscellaneous expenses	4,050	1,322.92	1.0%
Contingency allowance	10,000	0.00	0.0%
TOTAL	131,515.66	116,150.21	88.3%

earthbag footing were both areas of concern and needed to be addressed through additional laboratory experimentation. As a result, it was decided to complete a full-scale test on an earthen-rendered straw bale wall and a deflection test on a segment of an earthbag footing. Furthermore, experiments were conducted on the compressive properties of the earthen plaster itself, and on individual earthen rendered straw bales to better support the findings for the full-scale wall experiment.

A factored design compression load was obtained for the wall section using the National Building Code of Canada (NBCC 1995). Limit states design is used in Canada. Load factors of 1.25 for dead load and 1.5 for snow load are specified. The specified design loads were determined to be 0.8 kPa dead load and 2.0 kPa snow load. A resistance factor of 1.0 was used for the wall. This value was chosen based on the consideration that variability in dimensions and material properties, workmanship, type of failure, and uncertainty in the prediction of resistance were already taken into account, since the proposed wall strength test at Queen's would involve the same construction crew and materials that would be used to build the final wall. Given these considerations, it was determined that the experimental full-scale straw bale wall would be required to resist a compressive load of 23.5 kN/m.

The lateral resistance was considered from information already available in the literature. For the in-plane lateral resistance, the design was for factored wind loads and earthquake loads. The wall shear resistance was based on test results presented by Ash and Aschheim (2003). The wall bending resistance (out-of-plane lateral resistance) was based on the design approach outlined by Dick and Magwood (2002).

Full-Scale Wall Testing

A full-scale wall section, representative of the proposed exterior wall of the 4C's food bank, was constructed in the structural engineering laboratory at Queen's University. The wall was 2.44 m in height and 2.44 m wide. The wall, including timber box beam and sill, was constructed to the specifications given in Figure 3. The plaster was applied to an approximate thickness of 25 mm. The plaster was a mixture of earth and water which was mixed by hand in the Queen's laboratory. The wall was constructed by first stacking the bales, then placing the top plate and compressing the wall to the desired height using two wire cables running over the top plate and under the sill. The wall was then plumbed by pinning two 1-inch × 2-inch slats to either side of the wall and tying them through the wall with twine. The plaster was applied by hand in two coats, with essentially no curing time allowed between coats. The wall was then left to cure. Any shrinkage cracks found to appear as curing took place were filled with a clay mixture composed of store-bought bagged

FIGURE 8. Experimental setup.

clay, masonry sand, and water. The final wall is shown in Figure 8.

A loading apparatus was designed specifically for testing of the full-scale wall. The apparatus consisted of two 1000 kN hydraulic rams, which were fixed to a loading frame and located directly over the wall specimen. The rams were controlled by two hydraulic hand pumps. The load was applied from the rams onto a steel channel section, which was located on top of the wall box beam, as shown in Figure 9. This section acted to distribute the load evenly across the top of the wall. Timber bracing was constructed for the top of the wall to ensure the deformation of the wall was purely vertical at the top surface of the wall. This was done to mimic the bracing a roof structure would provide for a typical wall section. The bracing can be seen in Figure 8, and the vertical deflection of the wall can be seen quite clearly in Figure 9.

Instrumentation for the full-scale wall experiments consisted of two load cells and seven displacement transducers. One load cell was fixed to each of the two hydraulic rams as shown in Figure 9. There were four displacement transducers located at each of the four corners of the top of the wall to measure vertical deformations. These displacement transducers are also shown in Figure 9. The last three displacement transducers were located at mid-height of the wall and were oriented in such a way as to measure the out-of-plane lateral displacement of the wall. These three displacement transducers are shown in Figure 10. The displacement transducers and load cells were connected to a data acquisition system that recorded the load and displacement readings at a rate of 10 readings per second.

FIGURE 9. Steel channel section on top plate.

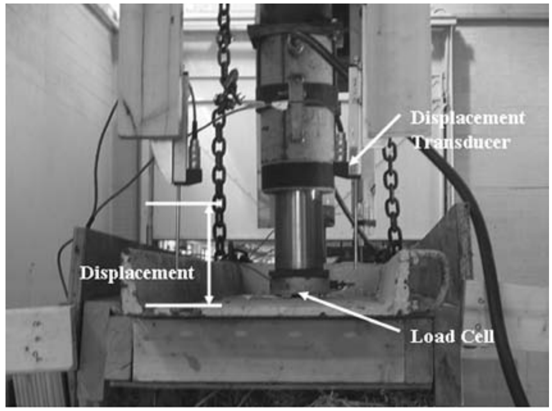
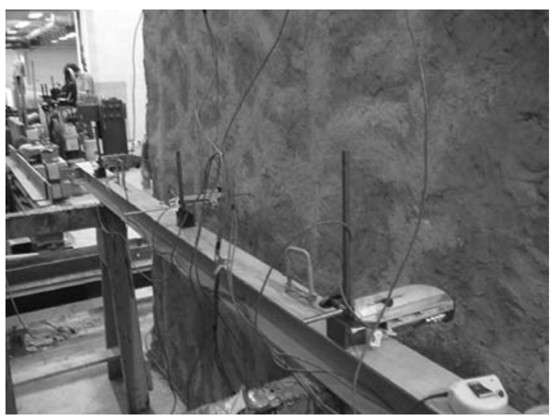


FIGURE 10. Location and orientation of lateral displacement transducers.



Once the wall was constructed, the instrumentation installed, and the plaster had been allowed to cure for approximately one month, the wall was ready for testing. The loading was applied at an approximately constant rate of 2 mm/minute by jacking of the hand pumps. The experiment continued until both of the hydraulic rams had reached their maximum stroke of 150 mm. The load was applied in such a way that the contribution from each of the rams was kept approximately equal throughout the experiment in order to ensure even load distribution across the top of the wall throughout the duration of the experiment.

The wall was loaded to failure and was observed to undergo a significant amount of cracking as it failed. Figure 11 shows the cracking that occurred in the wall as it failed during the experiment. Note that the lighter sections on the wall represent locations where shrinkage cracks had been repaired. It can be seen that much of the cracking initiated at these locations. Despite the observed cracking, there was little debonding of the hemp fibre from the earthen plaster.

An overall view of the failed wall is given in Figure 12, which also shows how the 1-inch × 2-inch wood slats buckled within the wall, causing significant cracking around their location.

The load-vertical deflection response was the most critical result from the experimentation. Specifically, the maximum load was required to be in excess of 23.5 kN/m. Figure 13 gives the load-deflection diagram for the wall. The total load applied was divided by the wall length of 2060 mm, which was the width of the wall that was observed to have adequate straw and plaster.

FIGURE 11. Failure cracking of wall.

FIGURE 12. Overall failed wall.

Figure 13 indicates that the maximum load obtained was approximately 32 kN/m, which far exceeds the required 23.5 kN/m. The wall had exhibited significant cracking at this point, but continued to resist load. The first visible cracking was observed to occur at a load of 12 kN/m, which can be seen as a change in the slope of the curve shown in Figure 13.

The load-lateral displacement response is given in Figure 14. It can be seen that the lateral displacements are very minimal for the majority of the experiment. For loads less than about 30 kN/m, the displacements remain less than about 5 mm. Once 30 kN/m has been reached and plaster cracking becomes significant, the displacements increase to a maximum of nearly 25 mm at the conclusion of the experiment.

Individual Bale Testing

In order to gain additional insight into the performance of earthen-plastered straw bale construction,

FIGURE 13. Load displacement response for plastered straw bale wall.

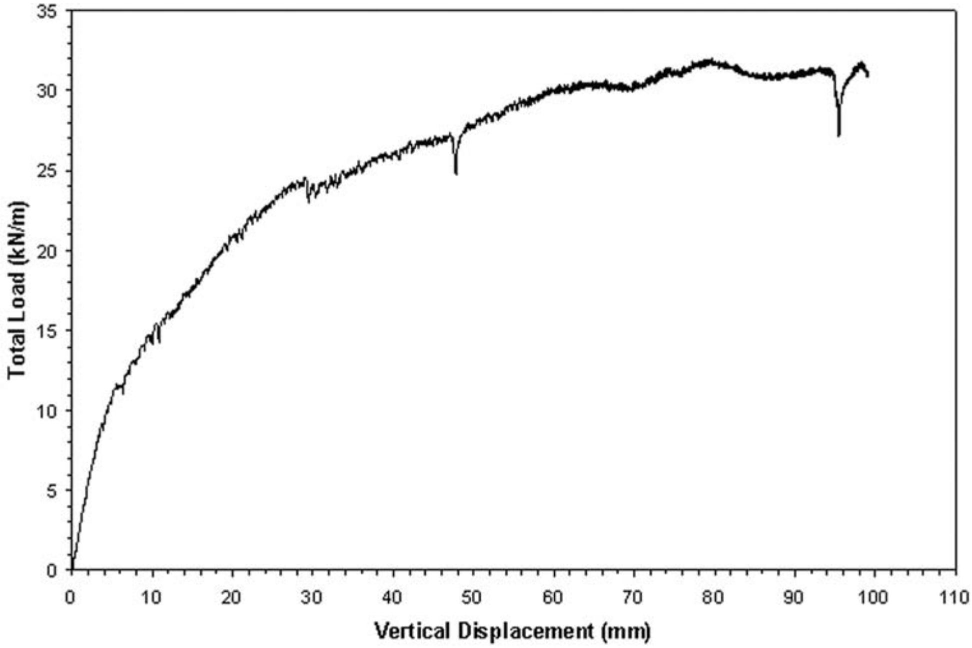


FIGURE 14. Lateral load-displacement response for plastered straw bale wall.

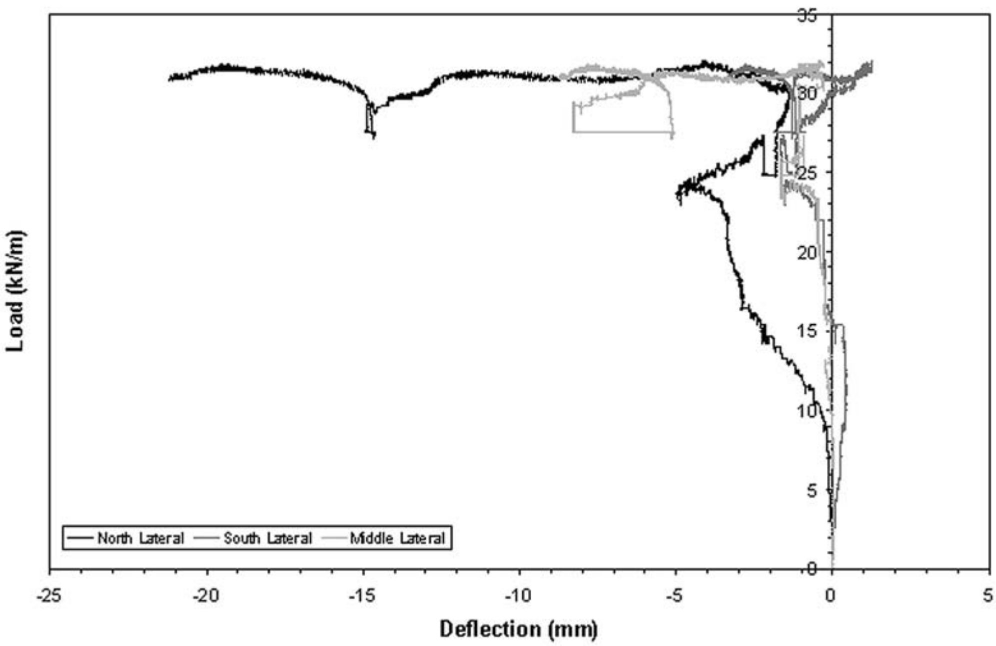


FIGURE 15. Earthen-plastered bale ready for testing.

single-plastered bales were prepared and tested in compression. An example of one of these bales, prior to testing, is shown in Figure 15.

The bales were plastered with 25 mm of earthen plaster using the methods described by Vardy and MacDougall (2006). The plaster itself was prepared and applied in a similar manner to the plaster for the full-scale wall, and was determined to have a cube strength of approximately 1.2 MPa. The straw bales used in the experiments were two-string wheat bales, similar to the bales described by Vardy and MacDougall (2006). Shrinkage cracks developed in the plaster, and were subsequently hand-patched in a similar manner to the patching carried out for the full-scale wall described above. The bales were tested using the apparatus described by Vardy and MacDougall (2006). The bales were loaded at a rate of 1 mm/min, and the load and deformation were recorded throughout the experiment.

Figure 16 shows the load-deflection behaviour for a typical earth-plastered straw bale. The behaviour is linear up to the point of failure except a small portion up to 2 kN load. This represents the initial compression of some of the straw that had bulged above the height of the plaster skins. Once failure was initiated at about 18 kN, severe cracking was noted in the bale as the load dropped significantly to approximately 10 kN. Following this, the bale continued to carry increasing load, but also underwent significant cracking and damage to the plaster skins. This portion of the curve represents the transfer of load from the failing plaster skins to the straw. Under enough deformation, the plaster skins would cease to carry load, and all, or very nearly all, of the load would be taken by the straw.

All three plastered bales tested were observed to reach an ultimate load of approximately 30 kN/m. This value is smaller than was obtained for the full-scale wall, which is likely a result of a slightly thicker

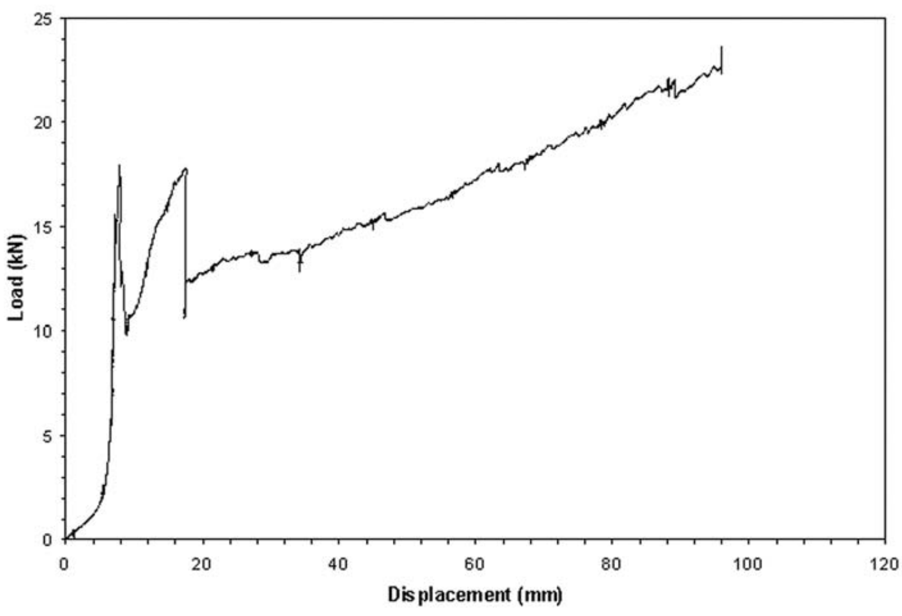


FIGURE 16. Load-displacement response of earthen-plastered straw bale.

than expected plaster thickness on the wall. This suggests that single bale tests may be used to conservatively estimate the strength of full-scale walls in compression, although additional research on this point is needed.

The load of 30 kN/m is less than the ultimate load of around 60 kN/m found for lime-cement plastered bales by Vardy and MacDougall (2006) with a plaster of strength 1.2 MPa and thickness of 25 mm. This is likely a result of the shrinkage cracks that develop in the earthen plaster prior to testing. The shrinkage cracks provided an initiation point for failure, especially where horizontal cracks existed, which could lead to premature buckling of the plaster skins.

Earthbag Testing

An experiment was also conducted on a sample of the proposed earthbag footing. The experiment was conducted in order to ensure that the settlement of the foundation under the weight of the structure would not be significant. The bag was filled with cement, gravel, and water and was left to cure for 28 days. After 28 days the earthbag was loaded in compression, and the deformation and load were recorded.

A deflection limit for the earthbag stacked footing was determined using an interpretation of NBCC (1995). The code specifies a serviceability limit for a maximum relative rotation of 1/500 for short term movements. It was assumed that the differential settlement is about half of the total settlement and that the settlement of the earthbag is about half of the total foundation settlement. The length of the largest window opening (1.8 m) was used as a reference length for calculating the relative rotation.

A plot of the load-deflection relationship for the earthbag is given in Figure 17. The results indicate that from a load range of 0–15 kN the total deflection of the bag was 3.24 mm. However, approximately half of that deflection occurs between an applied load of 0 and 1 kN. This initial deformation is thought to result from compression of the polypropylene bag. Following this initial deformation, the earthbag significantly stiffens, so that the deflection from 1 kN to 15 kN is only 1.52 mm. This deflection was within the allowable limit determined from the NBCC (1995).

Earthen Plaster Testing

In addition to the experiments which directly related to the Haliburton project, further experimentation was conducted to garner a greater understanding of the structural properties of earthen plasters, and what effect the composition of these plasters has on their behaviour. The effect of moisture content, drying time, dry-

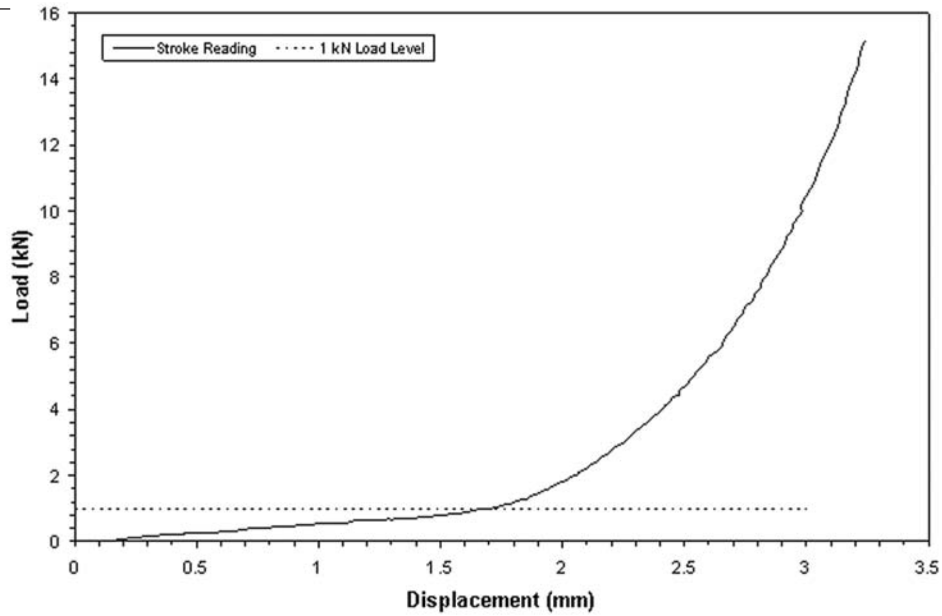


FIGURE 17. Earthbag load-displacement response.

ing conditions, and clay content on the strength and elastic modulus of the earthen plasters was studied.

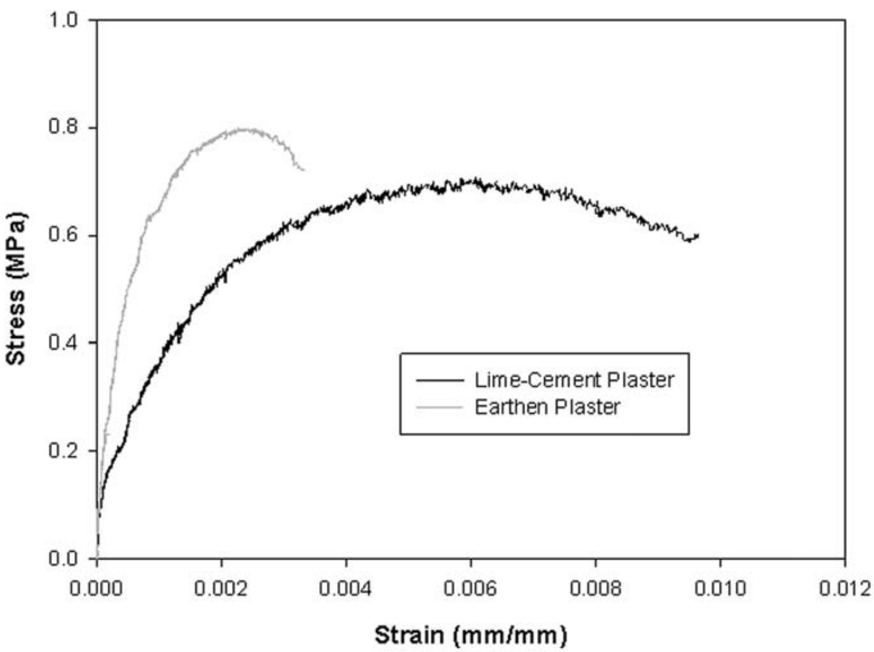
Experiments were conduced on earthen plasters mixed using either commercially available bagged clay, or the clayey-silt soil obtained from the Haliburton construction site. The clay was mixed with masonry sand and water in various proportions to produce a range of plaster mixes. The plasters were then formed into 50 mm cubes for compression testing or 200 mm × 100 mm cylinders for determination of the stress-strain behaviour. Three cubes and three cylinders were tested for each mix.

Figure 18 compares the stress-strain response of a lime-cement and earthen plaster with similar ultimate strength (f'c) values. The response of the earthen plaster is similar to that for the lime-cement plaster and concrete. However, for approximately the same f'c, the ultimate strain of the earthen plaster was much lower.

Contrary to what may be found with concrete and lime-cement plaster, the initial moisture content of the earthen plaster was determined to have negligible effect on the strength and elastic modulus. The drying time was found to have insignificant effect on the compressive strength beyond 10 days, but it was found that the elastic modulus increased significantly as the drying time was increased from 10 to 18 days. On the other hand, the clay content was found to have a significant impact on the compressive strength of the plaster, while the elastic modulus was relatively unaffected by the clay content. It was also found that higher temperature and lower humidity drying conditions lead to a drier, and thus, stronger plaster than more humid drying conditions. Finally, it was found that the earthen plaster had higher strength and elastic modulus than typical lime-cement plasters, and that the clayey-silt plaster had a higher strength and elastic modulus than the plaster mixed with commercial clay.

These results give an initial glimpse into some of the factors that play a role in determining the performance of an earthen plaster under compressive loading. However, it must be noted that in addition to the factors mentioned above, the composition of the clay itself is of major significance in determining the strength of an earthen plaster. For example, it has been noted that the compressive strength of earthen plaster using montmorillonite clay can be more than twice that of earthen plaster using kaolinite clay (Minke 2000).

FIGURE 18. Stress-strain relationships for lime-cement and earthen plasters.



SUMMARY AND CONCLUSIONS

The 4C's building is an excellent example of the use of non-traditional building materials in an environmentally friendly manner. The structure, constructed on a tight financial and time budget, is both highly functional and aesthetically pleasing. The following alternative construction materials and techniques were used with great success:

- earthen-rendered, plastered hemp-straw bale exterior walls
- compressed straw panel interior walls
- infill interior walls, utilizing a variety of infills including pop bottles and hempcrete
- rubble trench foundation with earthbag stacked footing
- cellulose roof insulation made from a minimum of 85% recycled paper
- finished earthen floor
- hydronic radiant floor tubing with solar preheating and solar domestic hot water heating
- electricity provided via 1kW grid-intertied photovoltaic (PV) array
- fibreglass windows located in the exterior walls, and "sun tubes" installed through the roof structure
- lighting and electrical needs chosen to minimize consumption
- finishes chosen for minimal toxicity and optimal functionality

For building code approval it was necessary to perform experimental testing in the Structural Engineering Laboratory at Queen's University. A test wall, 2.4 m × 2.4 m, was constructed and tested to failure. The wall was required to withstand 23.5 kN/m, a load which was reached, and surpassed. In addition, a compression test was conducted on an earthbag footing to ensure it would not undergo significant deformation upon loading. The earthbag was also found to be within the required specifications. In addition, experiments were conducted on earthen-rendered individual straw bales and on the earthen plaster itself. These results further support the use of earthen-rendered plastered straw bale walls for load-bearing construction.

Blackwell Bowick Partnership had been the structural engineering group on record for about 30 bale projects, about 50% of which had used load-bearing bale walls. Despite this experience, this project proved unique in a number of ways, and served to broaden the knowledge of the project engineer. This was the first use of load-bearing, earthen-rendered bale walls for significant loads. Previous projects with earth-plastered bale walls had only involved about half of the gravity load anticipated for the 4C's building. Furthermore, the 4C's project provided the project engineer with his first experience using a foundation system of a frost-protected, stacked earthbag footing. The uniqueness of this project provided an opportunity to broaden the Blackwell Bowick Partnership's knowledge of straw bale construction, and other alternative construction techniques. Specifically, the testing done at Queen's added significantly to their confidence in the strength of earth-plastered, load-bearing walls, and the stiffness of earthbag construction. However, due to the inherent variability in earth plasters, there is still a need for laboratory testing for future projects, but the scale of the testing may be minimized with the knowledge obtained from the 4C's project.

As an example of sustainable building practices put into a budget-driven, time-sensitive, commercial building scenario, the 4C's building is a good model. Its design was shown to be compatible with modern limit-states design codes. Its high energy efficiency makes it a very low-overhead building for a charity group to operate, and its material choices make it a showcase for the kind of decision-making that can dramatically reduce the negative effect that new construction can have on the environment.

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