13th International Conference on
Structural Health Monitoring of Intelligent Infrastructure
DOI: 10.3217/978-3-99161-057-1-150

Icelandic turf houses: A one-year monitoring overview

Kathryn Ann Teeter[1, ORCID (0000-0001-8760-375X)], Björn Marteinsson[2, ORCID (0000-0003-3368-0674)], Ágústa Kristófersdóttir,[1] Alma Sigurðardóttir,[1] Dorotea H Sigurdardottir,[1, ORCID (0009-0006-8496-4625)]

[1]Department of Civil and Environmental Engineering, University of Iceland, Hjarðarhagi 2-4, 107 Reykjavik, Iceland
[2]Architect and Engineer, Reykjavik, Iceland
[3]National Museum of Iceland, Suðurgata 41, 102 Reykjavik, Iceland
email: kat12@hi.is , bjomar@hi.is , agusta.kristofersdottir@thjodminjasafn.is , alma.sigurdardottir@thjodminjasafn.is, dorotea@hi.is

ABSTRACT: Structural Health Monitoring (SHM) is employed to provide insights and conservation guidelines for Icelandic turf houses through periodic and continuous monitoring of hygrothermal and geometrical parameters. The turf houses are unique vernacular structures that were the primary dwelling form in Iceland from settlement (~ 874 A.D.) through the 20th century. These structures, now maintained predominantly by the National Museum of Iceland, represent a cultural legacy but suffer from limited research on their materials, structural behavior, and long-term maintenance requirements.
Key conservation challenges include water leakage, differential settlement, and geometrical distortion, highlighting the need to understand the hygrothermal performance of the turf roofs and the structural behavior of the timber frames carrying the roofs. To address these issues, a remote and unobtrusive SHM system was designed, tailored to the constraints of heritage buildings.
This paper provides a one-year overview of monitoring at two sites: Keldur farm in southern Iceland and Laufás in the north. The study details the monitoring strategy, system design, installation, and operation, presenting results such as 3D point scans, hygrothermal data, and comparative analyses between the two sites. Findings from the study contribute to understanding the behavior of Icelandic turf houses, offering insights for their long-term conservation and ongoing management.

KEY WORDS: Hygrothermal and geometrical monitoring, museum artifact, monitoring in remote locations, vernacular structures

1 INTRODUCTION AND MOTIVATION

Turf houses represent the vernacular architecture of Iceland. The tradition spans from the 9th-20th centuries, surviving far longer than turf architecture traditions in most other countries. Turf was historically an ideal building material in Iceland due to its ready availability, its excellent insulation properties, its ability to protect against wind and precipitation, and the lack of available timber in Iceland (Zöega et al 2023). It was used to build different types of houses, churches, stables, sheds, raised roads, and boundary walls by members of all social classes (Hafsteinsson and Jóhannesdóttir, 2024; Zoega et al 2023, Ágústsson, 2000).

The turf house developed alongside the inhabitants, serving as the main form of residence for most of the country's history. This declined rapidly into the 20th century as they were largely replaced by timber and concrete houses. By the 1950s, only 716 turf houses were registered, representing 3.6% of all residences in the country (Hagstofa Íslands, 1997). Most turf houses were either abandoned to decay or deliberately destroyed (Hafsteinsson and Jóhannesdóttir, 2024). The few remaining turf houses generally represent wealthy or influential farms that have been taken under the protection of the National Museum of Iceland through their Historic Buildings Collection, including Laufás and Keldur, monitored and presented in this paper (see Figure 1). There are also a handful of smaller houses under private ownership or owned by other institutions.

These surviving turf houses no longer function as homes, instead operating as museums intended to conserve this unique aspect of Iceland's cultural heritage. As no one lives in them, the buildings must be monitored and repaired to ensure their continued survival and operation. This can pose difficulties as the museums are not open year-round and funding is limited. Damage is therefore not always immediately noticed and necessary repairs must be identified and prioritized. There are also few experts remaining who are experienced enough to undertake these repairs. While research has been done on traditional building methods and the cultural and historical importance of the turf tradition, little to no research has been done on the structural behavior of the buildings themselves, the properties of turf as a building material, or on the additional materials often used in turf roofs, leaving a large gap in the field of study.

This project seeks to fill this gap in research by studying the structural behavior and monitoring the structural health of several turf houses in the Historic Buildings Collection of the National Museum, including Laufás and Keldur. This research seeks to create a remote monitoring system that the museum can use to more effectively identify and prioritize repairs and keep track of the condition of the turf houses in their collection, many of which are very remote and far from the museum's headquarters in the capital region. This will be done through an interdisciplinary approach combining structural engineering, museology, and conservation studies. This comprises creating a monitoring strategy, 3D scan analysis, monitoring fluctuations in temperature and moisture in the turf roofs, modelling the hygrothermal behavior of turf, literary research, and interviews with experts actively working in the field. This paper provides a one-year overview of the monitoring process.

2 TURF HOUSES: LAUFÁS AND KELDUR

2.1 *Development of turf houses*

The Icelandic turf tradition began with the settlement in the 9th century and can be divided into three main developmental

DOI: 10.3217/978-3-99161-057-1-150

stages (National Museum of Iceland, 2011). The so-called Viking-Age longhouse represents the first stage of the turf tradition, featuring a long building made of turf, timber, and stone (Stefánsson, 2013 Abrecht, 2018). This first stage existed with relatively few changes until the 13th and 14th centuries, with the gradual emergence of the passageway farmhouse.

The passageway farmhouse represents the second stage of development. This did not replace the longhouse, and both forms as well as combinations of the two existed. The passageway farmhouse layout featured a long hall or passageway with individual rooms added to the sides and rear of the building (National Museum of Iceland, 2011).

The third and final stage of the turf tradition, the gabled farmhouse, emerged in the late 18th and early 19th centuries. The gabled farmhouse features individual but interconnected rooms, typically facing the front yard, with wooden gables and individual turf roofs (Abrecht, 2018). This is the version of the turf house that people are most familiar with today and serves as a physical representation of this aspect of Icelandic cultural heritage (Stefánsson, 2013).

Spanning over 10 centuries, the turf tradition represents the primary dwelling for Icelanders throughout its history. By the mid-20th century, the tradition had largely been abandoned, and a shift from residential buildings to museum buildings began to take place, largely under the supervision of the National Museum. Once representing a long-standing housing tradition, turf houses today serve a different function as museums to educate and conserve both the architectural tradition, but also cultural and social aspects of the nation's history.

Figure 1: Location of the monitored houses presented in this paper.

2.2 *Turf roofs*

The roofs of turf houses are mainly composed of turf blocks that rest on the top of an interior timber frame, as the turf walls themselves are typically not load-bearing (National Museum of Iceland, 2011, Zoega et al., 2023). There are two main roof types depending on the interior lining, either slate or thatch (Icelandic: helluþök eða tróðþök) (Ágústsson, 2000). Different types of turf can be used, and there are multiple ways of laying a turf roof (Sigurðardóttir, 2008). Additional materials and methods have also been introduced, particularly from the late 19th century onwards. The materials and methods were used based on material availability, the layout of the house itself, and decisions made by the craftsmen. This leaves much room for variation, and different layering can be found between locations and within the same house, depending on the intended use of the specific room or building.

Figure 2: Example of dried birch twigs carried by purlins and rafters (thatched roof).

Turf roofs typically need to be steep to support moisture runoff and thick for insulation purposes and to allow absorption. If the top layer of turf in a roof is compromised, leaks are likely to occur (Zoega et al 2023, Sigurðardóttir, 2021). The problem of leaking with turf houses is not new, and people in the past dealt with this issue in a number of resourceful and creative ways. Layers of stone, brush, and straw were added in some places to support the turf, which can be seen in Figure 5. When corrugated iron and tar paper arrived in Iceland in the latter half of the 19th century, people almost instantly began adding these materials to their houses as a waterproofing layer in the roofs, examples of which can be seen in Figure 3 (Stefánsson, 2020, Hafsteinsson, 2024).

Figure 3: Examples of corrugated steel in turf roofs. A fishing net has also been added likely because the turf slides on the corrugated steel.

As turf houses began to transform from dwellings to buildings in a museum collection, their maintenance and upkeep changed as well. As the buildings were no longer lived in, the constant cycle of coexistence and repairs shifted. One of the biggest changes has been the roof itself; historically, the roof could be up to 1 meter thick, which promoted absorption and the correct conditions for the grass on the outermost layer to survive and hold itself up (Sigurðsson, 2025).

In the latter part of the 20th century, the roofs of many turf houses were significantly thinned, and a waterproofing layer of PVC or plastic was added as an attempt to prevent leaks and improve the aesthetics of the buildings, see examples in Figure 4 (Stefánsson, 2013). All turf houses in the Historic Buildings Collection of the National Museum have thinned roofs with PVC or plastic membrane, and many also have corrugated iron.

DOI: 10.3217/978-3-99161-057-1-150

When constructing a turf roof today, the ideal thickness ranges from 40-70 cm (Sigurðsson, 2025). We have not yet seen a roof with this thickness in any of the buildings we are monitoring. Additionally, many of the roofs have holes or chunks of turf missing.

Figure 4: Examples of plastic membranes in turf roofs. Left: membrane visible from the inside. Right: membrane visible from the outside.

When the turf becomes too thin, it is unable to support itself and becomes more prone to damage from the elements. All additional roofing materials used in the past and in the present have been a response to problems, but these new materials have often had unexpected or unintended consequences, which is part of the focus of this study (Stefánsson, 2013).

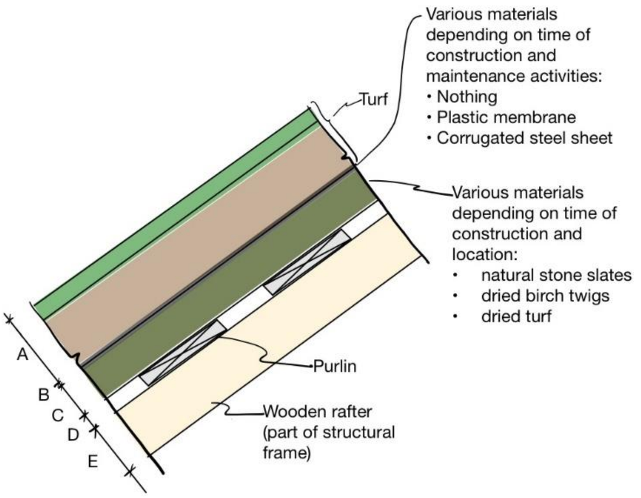

Figure 5: Typical cross-section of a turf roof.

Figure 5 shows a typical cross-section of a turf roof. As mentioned, the thickness of the different material layers can vary greatly from house to house and even within one house.

A: The turf layer itself can be divided into three sections: 1) the outermost layer is living grass serving as the first water barrier and provides possibilities for runoff from the roof, 2) root mesh serving as stabilizing layer that prevents the turf from sliding (this layer also has moisture absorption and insulation capabilities), and 3) the innermost layer is soil without roots, used to even out the surface for turf laying. B: The next layer, as discussed previously, was added when new materials arrived, such as corrugated steel and plastic membranes. These materials make it more challenging to keep the turf in place since they are slippery. C: Various materials have been used under the membrane and turf depending on the time of construction and the local availability of materials. Natural stone slates, dried birch twigs and dried turf (Icelandic: nærtorf), are common materials. Some of them, like birch and turf, have some insulation properties, whereas stone is a poor insulator. D: These materials rest on purlins. E: The purlins are carried by a wooden rafter which is part of the structural frame carrying the whole roof.

2.3 Timber frame

The structural system of the turf houses is a timber frame which carries the roof, see for example Figure 6. The foundations for the frame are stone blocks resting on the ground. Each column in the frame is resting on individual blocks which are not connected to each other. Two columns are connected to each other by joists perpendicular to the walls. Parallel to the wall, columns are connected by beams. Sometimes the rafters only rest on the columns and sometimes the rafters are connected to beams between the columns. The walls, built by turf or stone, only carry their self-weight and do not support the roof.

All elements of the structural system are made from natural materials, that is timber and stone, making them susceptible to temperature and moisture fluctuations. Furthermore, the foundations, stones placed on the earthen floors, can suffer from differential settlements. However, the characteristics of the movements of the timber frames have not been studied in a structural context and are therefore not fully understood.

Figure 6: Structural system in the kitchen in Keldur.

2.4 Laufás

Laufás was a prosperous manor farm that also served as a priest's residence, see Figure 7. It is in Eyjafjörður in the North of Iceland. Its history dates back to at least the early 11th century, though the present buildings reflect 19th century building traditions (National Museum of Iceland, *Húsasafn*, Stefánsson, 2013). The farm entered the National Museum's collection in 1948 and has since undergone extensive renovations and repairs.

The farm consists of 12 interconnected houses and is approximately 29 meters long and 28 meters wide (Hafsteinsson, 2008). It is representative of the gabled farmhouse with older elements of a passageway farmhouse, and the roof falls under the thatched category as the inner lining is

DOI: 10.3217/978-3-99161-057-1-150

turf. The room being monitored is called dúnhús, or down house, referencing the valuable down from eider ducks that was once an important source of income for the farm. The down house is on the western side of the farm facing the yard, with a door and three windows facing the yard.

Figure 7: Laufás in Eyjafjörður.

2.5 Keldur

Keldur was a prominent farm in the South of Iceland with a rich history dating back to the 12th century, see Figure 8. It is the largest turf farm in the south and is mentioned in several of the famous Icelandic sagas. The present buildings were primarily rebuilt in the 19th century, and the farm entered the National Museum's collection in 1946.

Keldur also represents a gabled-farmhouse with earlier elements of the passageway-farmhouse, but the roof is representative of the slate category. The inner layer of the roof is entirely slate, with an interior plastic membrane and turf as the outermost layer. Both the skáli, or longhouse, and the eldhús, or kitchen are monitored in Keldur.

Figure 8: Keldur in Rangárvellir.

2.6 Comparing Keldur and Laufás

The two farms are representative of turf building traditions in their respective regions. Laufás provides a classic example of the turf houses built in the north, with more turf used in the building and roof, and visible turf blocks in the walls. Keldur represents the turf building traditions in the south of Iceland, with more stone used in the building and roof and a grass covering on the top of the houses. These differences can be seen in Figure 7 and Figure 8, and relate to differences in climate in the north and south of the country.

The climate in the north of Iceland is more stable, with longer cold and dry periods providing better conditions for turf houses. This results in the northern turf houses having more turf and needing to be repaired and rebuilt less frequently. Historic records suggest that turf houses in the north lasted significantly longer before needing major rebuilding or repairs than those in the south, with one source reporting turf houses in the north lasted for 50-60 years, while those in the south lasted 10-20 years (Bald, 1897).

The climate in the south of Iceland fluctuates more in regard to both temperature and precipitation. Additionally, parts of the south do not have the same access to large amounts of good quality turf as in the north, and it is much more common to have higher amounts of stone in the buildings and the roofs.

The walls in Laufás are made from turf and rest upon a stone base. Different patterns of turf blocks can be seen from the interior and exterior of the building. The inner-most layer of the roof in the down house of Laufás is dried turf. In Keldur, the walls are layered with both turf and stone. The inner-most layer of the roof in the kitchen of Keldur is made of stone slates. It is not possible to see distinct patterns of turf blocks in the walls, and the exterior of the houses is grass.

3 MONITORING STRATEGIES, SYSTEM DESIGN, AND INSTALLATION

This project began in part as a response to reports from those working in close contact with the museum buildings. Issues with leaking roofs, moving timber frames and turf walls, losing turf from the roofs, and complications with the plastic membranes were reported. In order to research these issues, an unobtrusive monitoring system that could be utilized in a museum environment was employed. As these buildings are all active museums, any visible signs of research or monitoring must be limited, and museum activities and visitor access cannot be hindered.

Two monitoring strategies have been employed in the course of the research, targeting the pre-selected rooms at each location. One is continuous monitoring of the hygrothermal parameters in the turf roofs through sensors that were installed in both the exterior and interior layers of the roofs. The second is a periodic monitoring strategy where 3D scans are taken using LiDAR with an Artec Ray scanner. These scans are planned 3-4 times per year. Comparisons between the point clouds are planned in the open software CloudCompare.

3.1 Differential settlement and geometrical distortion

LiDAR scanning has been used to help monitor the structural health and behavior of buildings, bridges, roads, tunnels, and other forms of civil infrastructure (Kaartinen et al., 2022). LiDAR has also been implemented in the cultural heritage sector for a variety of purposes, including to detect and identify damage and degradation in wooden components of historic buildings (Liu et al., 2024) and documenting and assessing deformation (Yaagoubi and Miky, 2018).

LiDAR scanning was selected as a method in this study as a way to better understand the behavior of the interior timber frames of the turf houses. The reported displacements in the timber frames can impact the roof and the walls, which can lead

DOI: 10.3217/978-3-99161-057-1-150

to accelerated decay and degradation, putting the overall health of the building at greater risk.

Some of these displacements can be seen with the naked eye, including tilt in passageways, halls, and door frames, warped wood, and compacted or deteriorating turf. Although this can cause strain on parts of the building, strain monitoring is not a feasible method, as the structural frames may be undergoing rigid body movement and displacement without deformation. While we know that movement is occurring, it is still unknown exactly why and how this movement happens. LiDAR scans and the subsequent point clouds that are created will be compared in CloudCompare. This will enable a greater understanding of the movement of the timber frames, particularly if the movement is related to the decay of the timber, seasonal fluctuations, or changes in weather.

Figure 9: Artec Ray scanner in operation in the kitchen of Keldur.

3.2 Turf monitoring

The hygrothermal behavior of turf is relatively unknown despite its usage in buildings for centuries and across the world. Turf is known for its insulation properties and its ability to absorb moisture, but the specifics are lacking. The usage of sensors in the indoor and outdoor climate of the turf roofs is a way to better understand the moisture and thermal characteristics of the turf.

Research into the hygrothermal properties and behavior of different earthen building materials has covered many types of materials, including earthen bricks (Cagnon et al., 2014), light-earth construction materials (Colinart et al., 2020), and various soil types (Kehrer and Pallin, 2017). A 2019 literary review provides a detailed overview on the research into hygrothermal properties of earthen construction materials, noting renewed interest in their sustainable building qualities and ability to support comfortable living environments, but turf and the turf tradition is not included (Giada et al., 2019). Therefore, research is needed to address this gap.

As mentioned earlier, the monitoring system needed to be unobtrusive and operable in remote locations. To that end, wireless sensors with Bluetooth connection to gateways that can connect and send the data to the cloud were chosen.

The first monitoring system was installed in Keldur. A monitoring system from SensorPush was chosen. The SensorPush sensors are small, battery-operated devices with no wires, see left picture in Figure 10, making them ideal for this project. They measure air temperature and relative humidity. Eight sensors were installed in pairs, the inner laying on the plastic membrane and the outer very close to the surface of the turf. Two additional sensors were installed to measure the indoor and outdoor climate. In Keldur the thickness of the turf is approximately 10-12 cm. Figure 11 shows the monitored locations on the south side of the roof, one very close to the ridge, one close to the inside of the outer wall, and one in the valley where the gable house meets the longhouse.

In Keldur a service house is located close to the turf house making it possible to run an ethernet cable into the turf house for direct connection with the gateway. However, since the gateway was located inside the house and the sensors were installed inside the turf from the outside, it was challenging to connect to them through the turf. However, the installation was successful. Shortly after installation all the humidity sensors read a constant 100%RH and that did not change. Even though the moisture sensors did not survive the wet and cold Icelandic summer the temperature sensors kept operating until October 2024 when all sensors were unresponsive.

Figure 10: Left: Air temperature and humidity sensor from SensorPush. Middle: Soil moisture and temperature sensor from HOBO. Right: Air temperature sensor from HOBO.

Figure 11: Sensor locations on south side of roof in Keldur.

The next monitoring system was installed in Laufás. This time sensors for soil monitoring were chosen, see the middle picture in Figure 10. The sensors are from the MX series from HOBO. They have a robust casing, and the logger is connected to the sensors with wires, so the logger does not have to be buried into the turf. This makes the sensor more likely to survive harsh weather conditions, but it also makes it more visible.

Two pairs of sensors were installed in Laufás. Like in Keldur, the inner sensors were close to the plastic membrane and the outer sensors were near the surface. In Laufás the thickness of the turf was approximately 25-30 cm. The sensors were installed on the north side of the down house, close to the rear

DOI: 10.3217/978-3-99161-057-1-150

gable wall, one upper location and one lower, which can be seen in Figure 12.

Figure 12: Sensor locations in down house roof in Laufás.

In Laufás an internet connection is established by SimCard WiFi Router which is then connected to the gateway. The gateway communicates with the dataloggers via Bluetooth. In Laufás the dataloggers were installed inside the house and the wires run through a small hole in the gable avoiding the problem with poor Bluetooth connectability through the turf. This was possible since the loggers were connected with wires to the senors which were installed in the turf.

4 OPERATION AND SITE VISITS

4.1 Laufás

In October 2024, a research team undertook the first visit to Laufás to examine the building, photograph conditions, install sensors, and take the first round of 3D scans in the down house. Several issues were noticed with the roof, including holes, missing pieces of turf on the top layer, and degradation of the inner and outer layers of the turf roof, resulting in the plastic membrane showing. The back wall of the down house also had considerably higher moisture. The sensors were installed in the roof of the down house and the 3D scanning was performed.

The second trip to Laufás was taken in February 2025. Some small-scale repairs had been done to parts of the turf walls, but there were still holes in the roof of the down house. The back wall also had visibly more moisture than the other three walls. The sensors were still in place and actively logging data, and the second set of 3D scans were taken.

4.2 Keldur

Sensors were installed in the roof of Keldur in May 2024. The sensors were installed on the north and south side of the long-house. Several of the sensors went offline, so a second trip was taken in October 2024 to attempt to reconnect to the sensors. This was unsuccessful, and six out of ten sensors remained offline, unable to log data. This was thought to be related to the extreme weather conditions, as the sensors were unable to cope with the high amount of rain. Scans were not taken on either trip, as the 3D scanner is shared between departments at the National Museum and had been rented out.

Due to the remote location of Keldur, poor weather and road conditions prevented a return trip in the winter of 2024. The third trip took place in February 2025, where the kitchen was scanned. An additional trip is planned for the spring of 2025 to take the next round of scans and install new sensors that can withstand the outdoor climate.

5 RESULTS FROM STUDY HOUSES

In this section current results from the monitoring strategies are presented.

5.1 Laufás

The down house in Laufás has been 3D scanned twice, once in October 2024 and again in February 2025. Comparative analysis of the scans is ongoing. Renderings of the scans are shown in Figure 13.

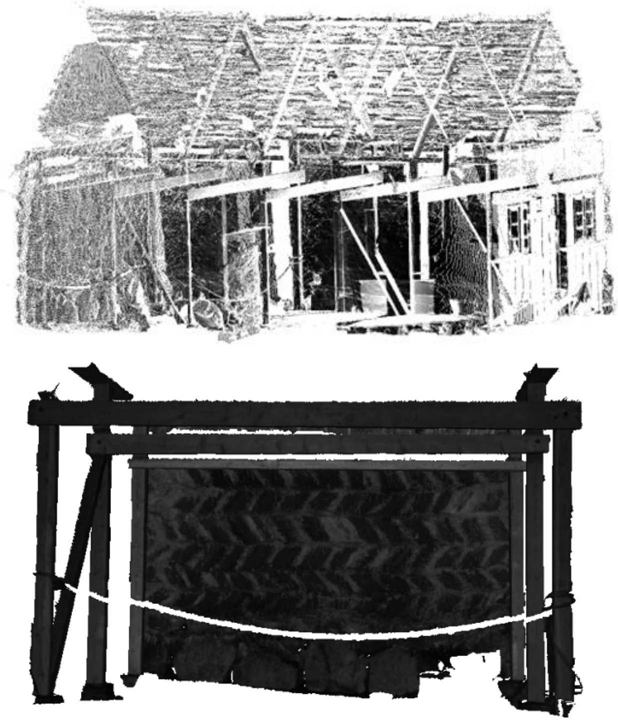

Figure 13: Renderings of 3D scans of the down house in Laufás.

Figure 14 shows the time series for temperature at Laufás. The blue shows the temperature measurements from the nearest weather station, Végeirsstaðir, approximately 12 km from Laufás. The orange shows the air temperature as measured outside by the monitoring system and the green shows the air temperature measurements from inside the house. The turf temperature close to the surface is shown in red and the turf temperature 20-24 cm deeper is shown in purple. The two monitored sections are shown, one upper and one lower, see Figure 12.

The temperature in the turf shows less fluctuations than the air temperature outside and inside the house. The difference between the outer and inner sensor is remarkably low, only 1-3°C, as shown in the lowest plot in Figure 14.

Figure 15 shows the turf moisture measurements in Laufás. In this first analysis the manifacturer calibration of the moisture sensor was used. That can have an effect on the absolute values but does not affect the trends. The moisture is plotted together with rainfall measurements from the weather station in Akureyri, 20 km from Laufás. Heavier rain can be correlated with higher moisture content.

DOI: 10.3217/978-3-99161-057-1-150

Generally higher moisture content is measured in the lower location than in the upp location. This observation is consistent with that rainfall and moisture within the turf seeps downwards.

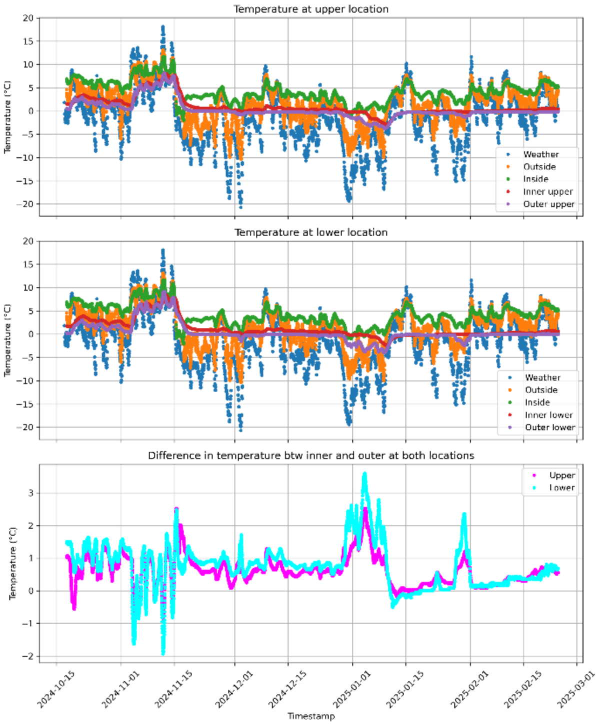

Figure 14: Temperature measurements in Laufás. Note: Weather refers to temperature from nearest weather station, Végeirsstaðir.

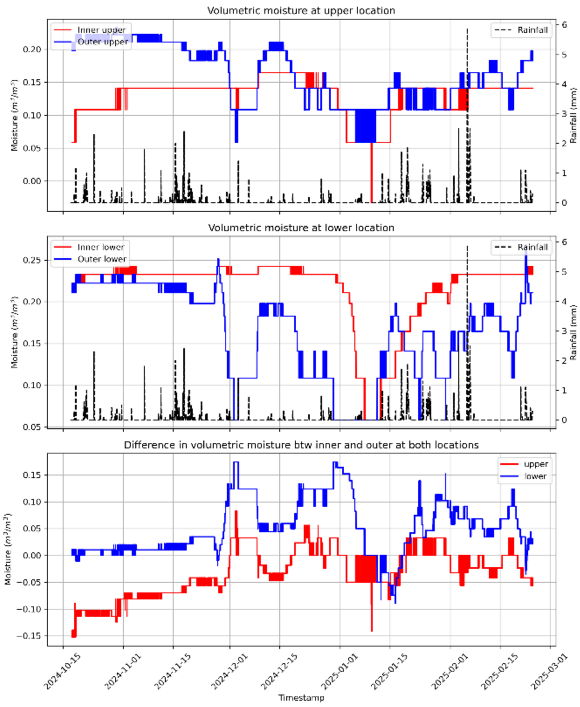

Figure 15: Turf moisture measurements in Laufás. Note: Rainfall measurements from weather station in Akureyri.

Moreover, the inner sensor at the upper location is drier than the outer sensor, also consistent with expected behavior. However, at the lower location the outer sensor is drier than the inner. More investigation is necessary to fully explain this observation.

5.2 Keldur

Figure 16 shows the time series for temperature at Keldur. The blue shows the temperature measurements from the nearest weather station, Sámstaðir, approximately 5 km from Keldur. The orange shows the air temperature as measured outside by the monitoring system and the green shows the air temperature measurements from inside the house. The turf temperature close to the surface is shown in red and the turf temperature 10-12 cm deeper is shown in purple. Two cross sections are represented, one close to the ridge and the other in the valley.

In general, the temperature close to the surface (red) fluctuates more than the temperature deeper in the turf close to the plastic (purple). The temperature inside is more stable than outside. Close to the ridge the temperature increases significantly, even higher than the air temperature. This is most likely because this part of the roof is facing south and highly affected by the sun radiation.

In the valley, which has more shadow, the outer sensor measures higher temperatures than the inner. The lowest plot in the figure shows the temperature difference between the outer and inner sensor at both locations. The temperature difference is higher at the ridge than at the valley, showing that the surface of the turf is very prone to temperature fluctuations. It even indicates that the turf, albeit thin, exhibits good insulation properties and/or high thermal inertia.

Note that for less extreme temperatures, between 5°C and 10°C, the difference between the outer and inner measurements is not as pronounced.

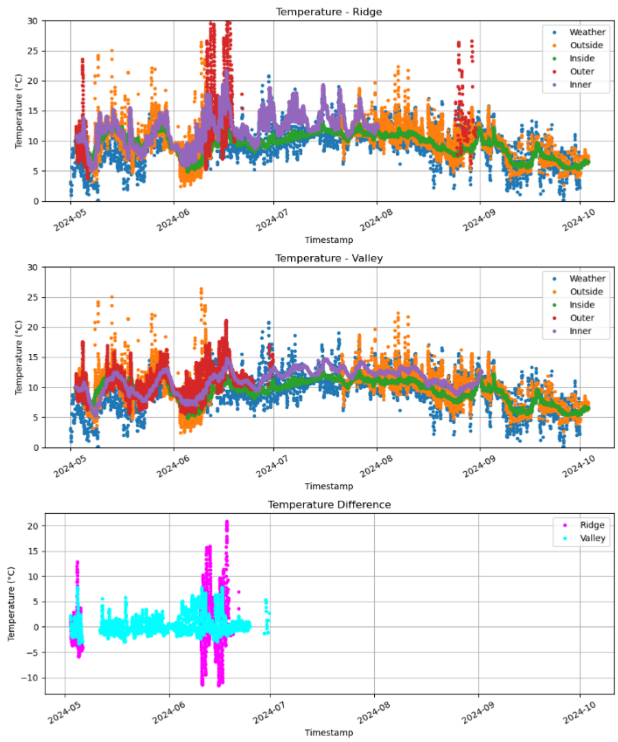

Figure 16: Temperature measurements in Keldur. Note: Weather refers to temperature from nearest weather station, Sámstaðir.

DOI: 10.3217/978-3-99161-057-1-150

6 CONCLUSION

The implementation of this structural health monitoring system combines different methods and approaches to better understand the Icelandic turf buildings whose structural behavior has not been studied. One year into the monitoring reveals several details about working with these technologies in museum buildings and in the Icelandic weather conditions. Early results provide information on the buildings, but additional scans and continued monitoring with the sensors is necessary to provide a more complete picture.

The Artec Ray scanner had some difficulties operating in cold temperatures. While the interior temperature of the turf houses was just above the minimum operating temperature, some scans were incomplete and needed to be repeated.

Additional sets of 3D scans are necessary to perform a comparative analysis of potential displacement in the timber frames.

The first installation of sensors at Keldur revealed that the SensorPush sensors struggled to operate in wet conditions, resulting in a 100% RH reading before all sensors stopped logging data. Additionally, there were difficulties in getting the Bluetooth connection to work through the turf roofs.

These obstacles in the first round of sensors led to the selection of the HOBO sensors that were installed in Laufás. These sensors are better able to withstand harsh weather conditions and can connect to the gateway. Laufás has cellular reception, making it possible to send the data to the cloud. Multiple sensors can operate on the cellular internet with good reliability.

New sensors will be installed at Keldur this spring. Since Keldur has ethernet connection, good uploading capabilities are available. However, it is important that sensors in remote locations have internal memory in case the system goes offline.

The data from the sensors at Keldur shows that the turf roofs can get quite warm in the summer, well above the outdoor temperature. Smoother temperature readings by the inner sensors at Keldur also show the insulation capabilities of the turf. This difference is not as visible in Laufás, possibly because the sensors in Laufás are located on the north side and have only been monitoring during the wintertime.

Moisture content of the turf roof is correlated with the rainfall. The cross-section closer to the ridge is drier than the cross-section further down. At the upper location the outer sensor measures higher moisture content than the inner sensor. This is not the case at the lower location.

Monitoring of these two houses and more are planned for the next few years providing insights into long-term continuous monitoring strategies at remote locations.

ACKNOWLEDGMENTS

Funding from the Icelandic Research Fund grant no. 2410205-051 is gratefully acknowledged.

REFERENCES

[1] G. Zöega et al., "Turf Building in Iceland – Past, Present, and Future," *Open Archaeology*, 9(1), 2023.
[2] S.B. Hafsteinsson and M.G. Jóhannesdóttir, "Dirt Hovels' and Cultural Heritage: The Eradication and Inheritance of the Icelandic Turf House," *Vernacular Architecture* 54(1), 2024.
[3] H. Ágústsson, *Íslensk byggingararfleifð I (Ágrip af húsagerðarsögu 1750-1940)*, Reykjavik: Húsafriðunarnefnd Ríkisins, 2000.
[4] G. Jónsson and M.S. Magnússon, Eds., *Hagskinna: Sögulegar hagtölur um Ísland*, Reykjavík: Hagstofa, 1997.
[5] National Museum of Iceland, "The Turf House Tradition," UNESCO World Heritage Convention, Tentative Lists, 2011, https://whc.unesco.org/en/tentativelists/5589/.
[6] H. Stefánsson, *Af jörðu - íslensk torfhús*, Reykjavík, Crymogea, 2013.
[7] B. Abrecht, *Arkitektúr á Íslandi – Discover Icelandic Architecture – Entdecke Islands Architektur*, Reykjavík: Mál og Menning, 2018.
[8] S. Sigurðardóttir, Building with Turf, Sauðárkrókur: Byggðasafn Skagfirðinga, 2008.
[9] Sigríður Sigurðardóttir, "Byggingarefnið torf: Meira en þúsund ára umgjörð íslenskrar mannvistar (Master's Thesis), Reykjavík, University of Iceland, 2021, https://skemman.is/handle/1946/37431.
[10] H. Stefánsson, *Hvılıkt torf—tom steypa: Ur torfhusum ı steypuhus*. Reykjavık: Haskolautgafan, 2020.
[11] K. Teeter, "Interview with Helgi Sigurðsson," Helgi Sigurðsson, February 20, 2025.
[12] National Museum of Iceland, "Laufás í Eyjafirði," Laufás í Eyjafirði, Húsasafn, Þjóðminjasafnsins, www.thjodminjasafn.is/soguleg-husasofn/laufas-i-eyjafirdi.
[13] National Museum of Iceland, "Keldur á Rangárvöllum," Keldur á Rangárvöllum, Húsasafn, Þjóðminjasafnsins, www.thjodminjasafn.is/soguleg-husasofn/keldur.
[14] G.L. Hafsteinsson, "Byggingarlýsing 2008," Reykjavík, National Museum of Iceland, 2008.
[15] F.A. Bald, "Um húsabætur á landskjálftasvæðinu og víðar," *Ísafold*, 24(10), 1897, https://timarit.is/page/3945073#page/n0/mode/2up.
[16] E. Kaartinen et al., "LiDAR-Based Structural Health Monitoring: Applications in Civil Infrastructure Systems," *Sensors* 22(12), 2022.
[17] H. Liu et al., "Precision detection and identification method for apparent damage in timber components of historic buildings based on portable LiDAR equipment," *Journal of Building Engineering*, 98(1), 2024.
[18] R. Yaagoubi and Y. Miky, "Developing a combined Light Detecting And Ranging (LiDAR) and Building Information Modeling (BIM) approach for documentation and deformation assessment of Historical Buildings," MATEC Web Conf., 149, 2018.
[19] H. Cagnon et al., "Hygrothermal properties of earth bricks," *Energy and Buildings*, 80, 2014.
[20] T. Colinart et al., "Hygrothermal properties of light-earth building materials," *Journal of Building Engineering*, 29, 2020.
[21] M. Kehrer and S.B. Pallin, "Hygrothermal Material Properties for Soils in Building Science," US Department of Energy, Technical Report: Hygrothermal Material Properties for Soils in Building Science, 2017.
[22] G. Giada et al., "Hygrothermal Properties of Raw Earth Materials: A Literature Review," *Sustainability*, 11(19), 2019.