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# Structural Analysis: A Tool for Testing 3D Computer Reconstructions of Thule Whalebone Houses

*Abstract:* One criticism of computer modeling in archaeology is that the visual products suggest a higher degree of knowledge of the structure or site than the data warrant, and that they represent only one of several possible outcomes. This paper discusses the benefits of structural analysis as a means of testing 3D computer reconstructions based on limited archaeological data. Thule Inuit whalebone houses will be used as case studies for testing structural behavior. The Thule people are the cultural and biological ancestors of contemporary Inuit societies of the North American arctic. Thule culture developed in the Bering Strait region, and its presence in the Canadian Arctic was established via migration by AD 1300 (Mathiassen 1927; McCullough 1989). The use of whalebone as a construction material by Thule families, in part, represents an adaptation to life in driftwood-poor regions of the Arctic Archipelago (Mathiassen 1927). Structural analysis led us to consider the premise that certain bones, because of their lower strength as structural elements, must have been selected primarily for their ceremonial value in the design of these unique structures.

## *Introduction*

For several decades, computer aided design technology (CAD) originally developed for architects and engineers has been used in archaeology to reconstruct structures and sites with a high level of detail and realism. Though convincing as photo realistic models, these 3D computer models are sometimes criticized because there is no means to test the plausibility of reconstruction scenarios. In cases where an incomplete record of the site or feature exists, computer modelers may take artistic license to create a visually appealing multimedia product (Miller / Richards 1994; Ryan 1996; Roberts / Ryan 1997). With improvements in CAD technology over the last decade, it is possible to overcome many of these criticisms by careful attention to existing data gaps and by alerting the viewers to different levels of certainty in the evidence. Using computer applications designed to simulate and test the behaviour of structures, it is also possible to simulate the impact of various loading conditions on architectural forms of the past. In this work a Thule whalebone house will be used as a case study for testing structural behavior. The approach outlined in this paper will reveal the benefits of 3D modeling as a tool for testing the possible architectural configurations suggested by archaeological data.

In the analysis of Thule whalebone architecture, the application of structural analysis can consider the minimum number of elements needed to span the space under various loading conditions. In this virtual laboratory, it is possible to consider changes in material properties and different construction techniques. Using this approach it is possible to consider any deviation from the ideal form.

## *Design Challenges: Creating and Designing a Methodology*

For this research the test case is a semi-subterranean whalebone house. A distinctive feature of Thule Inuit culture in the Canadian Arctic from 1300 to 1600 AD, these structures were made from whalebone because driftwood was either unavailable or in short supply. Analyzing these unique structures presents a unique challenge because of the houses' distinctive organic form and unusual material properties.

Accurate drawings in plan view of these house ruins provided the critical information on the numbers and approximate sizes of the bones used at each site (Dawson 2001). This data also provides the approximate location of the structural elements that surrounded the subterranean pit which delineated the exterior edge of these houses. In particular, House 4, situated at the Deblicquy site (QiLe-1), Bathurst Island, Nunavut, formed the basis of the initial reconstruction completed by the authors *(Fig. 1)* (Dawson / Levy 2005; Dawson / Levy 2006). Using

Fig. 1. Reconstruction of House 4.

this first reconstruction as the starting point for an initial test, an optimized version of a Thule whalebone house was created. This was done to find the best possible structural configuration of the house, using Multiframe (http://www.formsys.com/multiframe), a program that uses finite element analysis to determine the stresses and deflections in framed structures. Multiframe offers the user an application that can analyze structural behaviour under various loading conditions including wind and snow loadings. Comparisons between this idealized structure and one represented in the architecture of House 4 will reveal any deviation from a more optimal solution. Also examined by this approach is the importance of ribs as a means of reducing racking and hoop stress in the structure. Finally, it is possible to study how substituting crania and maxillas for selected mandibles impacts the strength of these structures. In this case we determined that houses using crania or maxilla elements were only capable of sustaining modest loadings without affecting the structure's integrity. Taking this into account, we considered the possibility that certain elements, because of their lower strength as structural elements, were selected primarily for their ceremonial value in the design of these unique structures.

## *Assumptions*

All structural analysis applications require specific assumptions about the material properties behaviour of structural elements including values for Young's modulus of elasticity (E), ultimate yield (Y), the shear modulus (G), and Poisson's ratio. Materials such as wood, steel and concrete have been carefully studied by engineers. Experimental testing under controlled conditions provides designers with published values for E, Y, G and Poisson's Ratio. Values in these tables incorporated into structural analysis applications provide designers with an assurance of the accuracy of their predictions. However knowledge of the behavior of whalebone is very limited. Houses constructed out of whalebone were built using scavenged bones. Experimental research provides some approximate values for the modulus of elasticity (E) and the Shear modulus (G) for fin whale and cow bone (CURRY 2002; ERICKSON / CATANESE / KEAVENY 2002; RAYFIELD ET AL. 2001; SNIVELY / RUSSELL 2002). Without testing actual bone samples from selected sites, it is only possible to assign approximate values for G (6.423 MPa), E (18), ultimate stress (29 MPa), yield stress (143 MPa) and Poisson's ratio (0.4). For this research, it was assumed that material would not be fresh but considerably aged. Whether Thule peoples acquired bone through active whaling, or scavenged bone along shorelines where beached whales died hundreds or even thousands of years earlier, is a contentious issue in arctic archaeology (SAVELLE / MCCARTNEY 1994; MCCARTNEY 1980; FREEMAN 1979). For the purposes of this paper, we take the position that elements of choice would have been acquired primarily from beached whales and abandoned dwellings at Thule sites, because recently harvested bone would have been difficult to work with and highly malodorous. Furthermore, bone becomes less elastic and more brittle with age. Using the constants for aged bone should also provide a more conservative calculation of the strength of these unusual structural elements.

### Homogeneity

The homogeneity of the material also presents issues for the analysis of structural elements. Considerable

Fig. 2. Cross-section of a typical mandible.

| | Stress | | Deflection | | | Rotation in degrees | | |
|---|---|---|---|---|---|---|---|---|
| | SBzTtop Mpa | SBz Bottom Mpa | dx in | dy in | dz in | X | Y | Z |
| Case I: Idealized Form with 8 Mandibles | | | | | | | | |
| MAX | 0.059 | 0.128 | 1.860 | 0.093 | 1.895 | 4.038 | -0.085 | 4.299 |
| MIN | -0.130 | -0.058 | -1.341 | -0.836 | -2.130 | -4.151 | -4.113 | -4.085 |
| Case I: Idealized Form with 8 Mandibles Applied Wind-loadings | | | | | | | | |
| MAX | 0.443 | 0.414 | 1.113 | 2.761 | 9.501 | 13.154 | 1.874 | 12.471 |
| MIN | -0.414 | -0.437 | -5.980 | -4.203 | -0.058 | -7.862 | -7.954 | -6.462 |
| Case II: Reconstruction with 15 Mandibles | | | | | | | | |
| MAX | 0.048 | 0.088 | 0.757 | 0.015 | 0.644 | 1.700 | 0.781 | 1.722 |
| MIN | -0.090 | -0.048 | -0.511 | -0.443 | -0.845 | -1.813 | -1.657 | -1.697 |
| Case II: Reconstruction with 15 Mandibles and connecting ribs | | | | | | | | |
| MAX | 0.048 | 0.088 | 0.475 | 0.036 | 0.408 | 1.004 | 0.085 | 1.350 |
| MIN | -0.089 | -0.048 | -0.403 | -0.437 | -0.557 | -1.226 | -1.225 | -1.121 |
| Case III: Reconstruction with 15 Mandibles and Connecting Ribs with Applied Wind-loadings | | | | | | | | |
| MAX | 0.375 | 0.383 | 2.101 | 1.659 | 0.000 | 4.109 | 2.014 | 3.871 |
| MIN | -0.383 | -0.375 | -0.038 | -2.696 | -5.288 | -8.997 | -4.441 | -3.667 |
| Case IV: Reconstruction with 13 Mandibles, 2 Maxillas/Crania and Connecting Ribs | | | | | | | | |
| MAX | 0.474 | 0.708 | 0.688 | 0.098 | 5.059 | 18.792 | 10.893 | 13.446 |
| MIN | -0.708 | -0.474 | -3.480 | -2.610 | -1.190 | -23.660 | -37.681 | -15.064 |
| Case IV: Reconstruction, 13 Mandibles, 2 Maxillas/Crania and Connecting Ribs, Wind-loadings | | | | | | | | |
| MAX | 0.540 | 0.706 | 2.123 | 1.150 | 3.043 | 13.788 | 11.791 | 10.853 |
| MIN | -0.706 | -0.540 | -2.151 | -2.534 | -3.743 | -23.340 | -32.324 | -15.940 |

Fig 3. Summary of stress levels and deflections, Cases I-IV.

variation exists from the centre to the outer surface of the mandibles, the primary elements used in construction of Thule whalebone houses *(Fig. 2)*. At the centre the bone is largely made up of a spongy material (cancellous), while the surface material is harder and more compact. To compensate for this difference in bone density, the mandibles have a donut like cross-section. Given that the moment of inertia (I) varies with the 4th power of the diameter of a tube, assuming that the bone is hollow for the first third of the radius should not significantly impact overall calculations.

## Loading

Two loading conditions were considered in this research. The first considers the impact of dead loads on the weight of the structure: the weight of skin, sod, and snow. For these trials, 118 lb/ft$^3$ was used for the weight of the bone. It was assumed that the materials were homogeneous, as required for calculations. The weight of sod, snow and skin are based on the approximate numbers available from published sources. For wet sod and skin the value used was 20 lb/ft$^2$. For the weight of the snow load, a value of 20 lb/ft$^2$ was used. For all three dead loads, adjustments were made for the changes in loading due to the curvature of the member. In the case where wind (a live-load) was applied to the structure, a value of 16 lb/ft$^2$ of exposed surface was used to approximate the pressure of a 70 mph wind.

## Reconstruction I: The Idealized Form

In reconstructing the idealized form of the house, only eight mandibles were used, placed as a dome around the edge of a circle with a radius of 10 ft. This form approximates that of House 4 but with 50%

fewer mandibles than found in the actual structure (Case I). In this configuration, there is a spacing of approximately three feet between the points where each of the mandibles touch the ground. The results of this analysis can be seen in *Fig. 3*. In this trial the stresses are all within acceptable ranges. Under dead loads of snow and sod, the stresses would reach less than 1% of the ultimate strength of the material, giving a high factor of safety to occupants. Deflections under this scenario would reach no greater than 2 inches, even without the addition of ribs to provide additional stability and resistance against hoop stress. In the case of wind loads, stress levels are still in an acceptable range, but with a slightly lower safety factor. However with deflections higher than 9 inches in one of the members the structure would have been unstable in high winds *(Fig. 3)*.

### Reconstruction II: House 4

Fifteen mandibles arranged as a simple dome around the periphery of the pit are used to reconstruct the form of House 4, Case II (Dawson 2001). With almost twice the number of mandibles than Case I, all of the stresses are within acceptable ranges. Like the previous form a considerable safety factor would be achieved even with snow loadings of 20 lb/ft$^2$. Bending stresses of less than 1% of the ultimate strength of the material would provide a high factor of safety. Deflections under this scenario are less than one inch. In the case of wind loads, stress levels are in the acceptable range though deflections increase significantly compared to Case I, to slightly over 5 inches in one member, indicating that wind-loadings would have been the critical test for these structures.

### Reconstruction III: House 4, with the Addition of Ribs

In this test case, ribs are added to House 4. Adding these ribs may have served two purposes. First, the use of ribs during the construction process would have aided in the erection of mandibles to form the dome-like structure. Securing the mandibles with lateral bracing would help achieve a stable form. Unlike tent poles, mandibles with a bow-like curve along their major axis would tend to rotate inward, though it may have been possible to lash three of the mandibles together to form a tripod. Securing a set of ribs lashed across the mandibles would have acted as a gusset plate, offsetting the rotation once the mandibles were raised to the vertical position of House 4. Though House 4 was only partially excavated, it appears that at least fifteen ribs could have been used in this manner. Excavation in the future may reveal that additional ribs were used in building these houses. The structural analysis of this form shows that the additional fifteen ribs would have added only marginally to the strength of the structure. Deflections and bending stresses are close to those found in the case without ribs. In the case of wind loads, stress levels are also almost identical to the previous case (Case II). Rather than contributing to the strength of the structure these ribs may have been more important in maintaining the stability of the structure by eliminating rotation of the mandibles once they were erected into position.

### Reconstruction IV: House 4 Substituting Crania/Maxilla Assemblies for Selected Mandibles

In addition to the mandibles, crania and maxillas were incorporated into the architecture of other houses located near House 4 (Case IV). If these elements are left fused, they form a tripod-like structure composed of a substantial base (crania) supporting a plate like form (maxillas). Substituting two of the mandibles found in House 4 with crania/maxillas can offer some insight into how the strength and stability of these houses might be affected by their use as structural supports. Analysis reveals that under the dead loads of snow and sod considerable deflections would have been introduced in the structure. When compared with Case II, deflections increase from less than 1 inch to a maximum of 5 inches. Not surprisingly, maximum angular rotation of maxilla elements reveals increased instability compared to Cases II and III. In this case, racking of the frame shows a large defection in these crania/maxillas, which would contribute to a partial collapse of the structure (max. angular rotation over 30 degrees). This suggests that when these elements are introduced with less strength, they become critical weak links in the structure. This also implies that when crania/maxillas were introduced into the structure, additional strengthening would have been required by placing mandibles adjacent to these members. This raises an interesting question: Why are there Thule whalebone dwellings that display conspicuous uses of maxillae/crania combinations in roof frame construction if they constitute a weakest link? A dwelling adjacent to House 4 at the Deblicquy site, for example, incorporates three maxillae/cra-

Fig. 4. Reconstruction of House 8.

nia combinations in its roof frame – one of which is placed directly over the entrance passage. The answer seems to be that symbolic uses of whalebone in Thule architecture occasionally trumped purely structural concerns.

## *Discussion and Conclusions*

Structural analysis techniques were employed to evaluate the reconstruction of a Thule whalebone house. Although computer applications designed for analysis of structural frames built of wood, concrete or steel are not specifically designed to deal with the peculiarities of Thule whalebone houses, this approach can be used to assist archaeologists in the reconstruction and interpretation of these house forms. In this research, a series of houses were tested. Each was subjected to both the dead loads of snow, sod and hide and live loading from wind.

Structural analysis techniques were used to refine the computer reconstruction of a Thule whalebone house. Beginning with the analysis of an idealized form it was possible to look at issues of stability, strength and assembly. Comparing House 4 with an idealized version suggests that a high factor of safety was incorporated into these structures. Adding ribs to the form of House 4 revealed that although their addition did little to increase the strength of the structure, their importance in construction and stability may have been critical. Ribs added to the erected structure may have helped maintain the dome like form by limiting the rotation of mandibles. The addition of crania/maxillas revealed a potential weakness. Offering less strength than a mandible, these early architects may have had to compensate by adding redundancy into the structure. This would have been accomplished by doubling members. An additional mandible to shore up the weakness of these crania/maxillas could have been a solution. The use of these structural members supports the premise that employing crania/maxillas in the construction of Thule whalebone houses may have served a symbolic function, suggesting that these dwellings may have functioned as metaphors for actual living whales. This seems to be the case with one dwelling at the Deblicuqy site, where crania/maxilla combinations were used to frame the entrance passage to dramatic effect *(Fig. 4)* (Dawson / Levy 2006; Lee / Reinhardt 2003, 114). The whale and the whale hunt was a central part of Thule culture. The creation of a striking entrance, though less efficient in form, would have served as an important symbolic reminder of the economic and ideological significance of whales in Thule society.

Structural analysis applications like Multiframe offer some promise as a technique for testing computer reconstructions. In the case of reconstructing a Thule whalebone house, some consideration had to be given to the uniqueness of the material. Values used for E, G and Poisson's ratio were at best approximate values. Using conservative values, though, offers some lower bound for the strength of these structures. Further testing will be needed to achieve a more exact understanding of these unique structures. In addition, a more exact description of the cross-sections of mandibles and crania should allow more accurate predictions of shear and bending stress under various loadings. Finally, knowledge of the impact of various lashing systems could provide the basis for understanding their role during the construction process.

The use of structural analysis applications may be able to offer a testing environment which, though not always able to reveal exactly how these structures were built, can answer questions about which configurations would have been unstable and less likely to have withstood the elements. Ultimately, structures must be built and tested in the real world. Having a virtual testing environment gives researchers a clue into the shape of these unique structures built to withstand the environmental demands of the North.

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