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Analysis of Mechanical properties of Alternative Timber Beams for a Native American Earth Lodge

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ANALYSIS OF MECHANICAL PROPERTIES OF ALTERNATIVE TIMBER BEAMS FOR A NATIVE AMERICAN EARTH LODGE

BY

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This thesis is approved as a creditable and independent investigation by a candidate for the Master of Science in Civil Engineering degree and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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ABBREVIATIONS AND SYMBOLS

Abbreviations

ASCE	American Society of Civil Engineers
ASD	Allowable Stress Design
AWC	American Wood Council
CEE	Civil and Environmental Engineering
D F-L	Douglas Fir-Larch
E	Modulus Of Elasticity
EMC	Equilibrium Moisture Content
E – API	Energy – American Petroleum Institute
FEA	Finite Element Analysis
FSP	Fiber Saturation Point
IBC	International Building Code
LRFD	Load Resistance Force Design
MC	Moisture Content
MOR	Modulus Of Rupture
mph	miles per hour
MWFRS	Main Wind Force Resisting System
NA	Native American
ND	North Dakota
NDS	National Design Specifications
NPS	National Park Service
NSF	National Science Foundation

psf	pounds per square foot
psi	pounds per square inch
S4S	Four side surfaced member
SDSU	South Dakota State University
WWPA	Western Wood Products Association
2D	Two-dimensional analysis
3D	Three-dimensional analysis

Symbols

A	Area
A_T	Tributary area of roof members
A_y	Vertical reaction force at point A
$b_{nominal}$	Nominal width
B_y	Vertical reaction force at point B
C	Wind exposure category
C_b	Timber bearing area factor
C_c	Timber curvature factor
C_D	Timber load duration factor
C_e	Snow exposure factor
C_F	Timber size duration factor
C_f	Timber form factor
C_{fu}	Timber flat use factor

C_H	Timber shear stress factor
C_i	Timber incision factor
C_L	Timber beam stability factor
C_M	Timber wet service factor
C_p	Timber column stability factor
C_p	Wind external pressure coefficient
C_r	Timber repetitive member factor
C_s	Snow slope factor
C_t	Snow thermal factor
C_t	Timber temperature factor
C_v	Timber volume factor
D	Dead load
d	depth
$\Delta_{allowable}$	Allowable deflection
Δ_L	Actual deflection
Δ_{max}	Maximum deflection
D_{soil}	Soil load
$d_{nominal}$	nominal depth
Dy	Deflection given by Visual Analysis
E	Earthquake load
E	Modulus of elasticity

E'	Factored modulus of elasticity
F	Load due to fluids with well-defined pressures and maximum heights
F	Number of inches of rise per foot of roof
F_b	Bending parallel to grain
f_b	Actual bending stress
F'_b	Allowable bending stress
F_c	Shear parallel to grain
F_t	Tension parallel to grain
ft	foot or feet
ft^2	feet square
G	Wind gust effect coefficient
GC_{pi}	Wind internal pressure coefficient
H	Load due to lateral earth pressure, ground water pressure, or pressure of bulk material
in^2	inches square
in^3	inches cube
in^4	inches to the fourth
I_s	Snow importance factor
I_x	Moment of inertia
k_d	Wind directionality factor

K_z	Wind velocity pressure exposure coefficient
K_{zt}	Wind topographic coefficient
L	Length
L	Live load
L_0	Unreduced design roof live load
L_r	Roof live load
lb	pounds
lb/ft	pounds per foot
lb/ft^3	pounds per cubic foot
M_{max}	Maximum moment
Mz	Moment given by Visual Analysis
P	Axial compressive force
p_g	Ground snow load
p_s	Slope roof snow load
q_z	Wind velocity pressure
R	Rain load
ρ	Density
R_1	Roof reduction factor when: 200 $ft^2 < A_T <$ 600 ft2
R_2	Roof reduction factor when: $4 < F < 12$
S	Snow load
S_x	Section modulus
T	Self straining force

v	Poisson's ratio
V	Wind velocity
Vy	Shear given by Visual Analysis
W	Wind load

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ABSTRACT

ANALYSIS OF MECHANICAL PROPERTIES OF ALTERNATIVE TIMBER BEAMS FOR A NATIVE AMERICAN EARTH LODGE

FREDDY E. MORAN

2017

To fill a gap in the literature, this thesis explored the mechanical properties for alternative roof beams of a historic Native American Hidatsa earth lodge. The research demonstrates that in those alternative beams, when Moisture Content (MC) increases, Modulus of Elasticity (*E*) decreases and deflection increases. The procedure included obtaining dimensions for alternative beams from scaled sketches created by ethnographers and informants who recorded an actual Hidatsa earth lodge in the early 1800s (confirmed by other sources) although no material properties studies have resulted. After calculating loads, the variations in the *E* were determined using an equation. Using linear analysis, alternative beams were modelled for seven wood types for comparison. The deflection was calculated based on *E* at various percentages of moisture in the wood. By comparing seven wood types of alternative round roof beams, results indicated that Douglas Fir-Western Larch was the most desirable, having the lowest deflection, followed by these types in order of performance: green ash, cottonwood, Ponderosa pine, American elm, and silver maple.

CHAPTER 1 : INTRODUCTION

1.1 Background

There is a gap in the literature concerning material properties of earth lodges of the type that were used prehistorically and historically by some Native American cultures in the upper Missouri Valley in North and South Dakota. The builders of Native American earth lodges were descended from the first "engineers" on the continent, although they used trial and error and word of mouth to pass along their design knowledge. In this thesis, an analysis of the mechanical properties of the main supporting alternative beams was conducted for an early 1900s historic Hidatsa earth lodge that existed in North Dakota (ND).

1.2 Scope of Work and Procedures

The research demonstrates that when Moisture Content (MC) in alternative wood beams increases, Modulus of Elasticity (*E*) decreases and deflection increases. The demonstration was tested for seven different types of wood beams: cottonwood, American elm, combined Douglas Fir and Western Larch (D F-L), green ash, Ponderosa pine, and silver maple at MCs of 4, 8, 12, 18, and 26 percent.

The first procedure was to find an equation to calculate the *E* at various MCs for the alternative roof round wood beams of a Native American earth lodge. This research was based on dimensions provided by scaled drawings recorded by Wilson (1934). A reproduction structure based on Wilson's research exists at Knife River Indian Villages National Historic Site near Stanton, ND (Appendix A). The second procedure was to model alternative beams for the seven types of wood of interest. The third procedure was to calculate deflection based on *E* for selected MCs of interest.

1.3 Overview of Thesis

This thesis is arranged into seven chapters. Chapter 1 provides background, hypothesis, and scope of work and procedures. Chapter 2 includes the literature review, with information about the archaeological and historical sources used to establish dimensions for the beams of the virtual earth lodge. Chapter 3 includes procedures used in this thesis, including calculating loads, the selection of wood types to analyze, selecting the equations needed to model deflections. Chapter 4 presents the analysis of the alternative earth lodge beams and the values of *E* for the alternative beams. Chapter 5 contains the results and discussion, including limitations of the study. Chapter 6 consists of conclusions, and Chapter 7 presents recommendations for future study. This thesis includes Appendices A, B, C, and D. Appendix A includes information about a visit to the Knife River Villages National Historic Site near Stanton, ND. Appendix B includes Wilson's (1934) dimensions and sketches for a Hidatsa earth lodge that existed in the early 1800s. Appendix C includes information about the use of laser imaging at the Knife River Villages site. Appendix D presents general information about various wood properties of interest for timber structures.

CHAPTER 2 : LITERATURE REVIEW

2.1 Archaeological and Historical Sources

Historically, the Northern Great Plains are widely known for nomadic Native American tribes whose cultures were based on buffalo hunting on horseback and living in tipis. Movies and western novels have added to that generalization for all tribes in the locale. There were, however, other tribes such as the Hidatsa who hunted, but they were more sedentary and practiced river bottom gardening along the Missouri River and its tributaries. The agrarian Native Americans, both prehistoric and historic in the Upper Missouri Valley, lived in earth lodges from around 1400 A. D. and into the historic era (until the early 1900s among the Hidatsa, for example [Wilson, 1934], Appendix B). At the time that the written record (i.e., history rather than prehistory) occurs, those earth lodge dwellers on the Upper Missouri River were identified linguistically as Mandan, Arikara, and Hidatsa.

In 2015, the National Park Service (NPS) (2017a) described earth lodges in what is today North Dakota (ND) as follows. Earth lodges, considered sacred, were owned and mostly constructed by women, although men often helped with placing the four large central posts. Most of the timber roof beams were cottonwood poles cut by women. After setting the four central posts with the help of men, women set the perimeter wall posts in a circular pattern. Next, they placed the roof beams. A long narrow entryway of framed with poles extended outwards from the door opening. To the circular roof part of the structure, women added a layer of willow branches, grass, and sod. They left a central roof opening for campfire smoke to escape. Housing from 10 to 20 persons, most such buildings were inhabited for no more than 10 years. Lodges were usually from 30 to 60 ft in diameter and about 15 ft high, although many sites had one larger ceremonial earth lodge.

Many earth lodge sites have been excavated by archaeologists over the years, and much is known about the Native Americans who inhabited earth lodge villages in what later became North and South Dakota (Figs. 2.1 and 2.2) (e.g., Ahler, 1978 and 1984; Hurt, 1974; Sigstad & Sigstad, 1972; Calabrese, 1987) and elsewhere. Some earth lodges were only built to be occupied for a short time, as little as one year; therefore, they vary in structural robustness of construction and in the sizes of timbers. Earth lodge sites on the Missouri River are well known in history because of their association with explorers Lewis, Clark, and Sacajawea, and adventurous artists such as Karl Bodmer (Fig. 2.3) and George Catlin (Fig. 2.4) who included earth lodge scenes in paintings (Gragg, 2003).

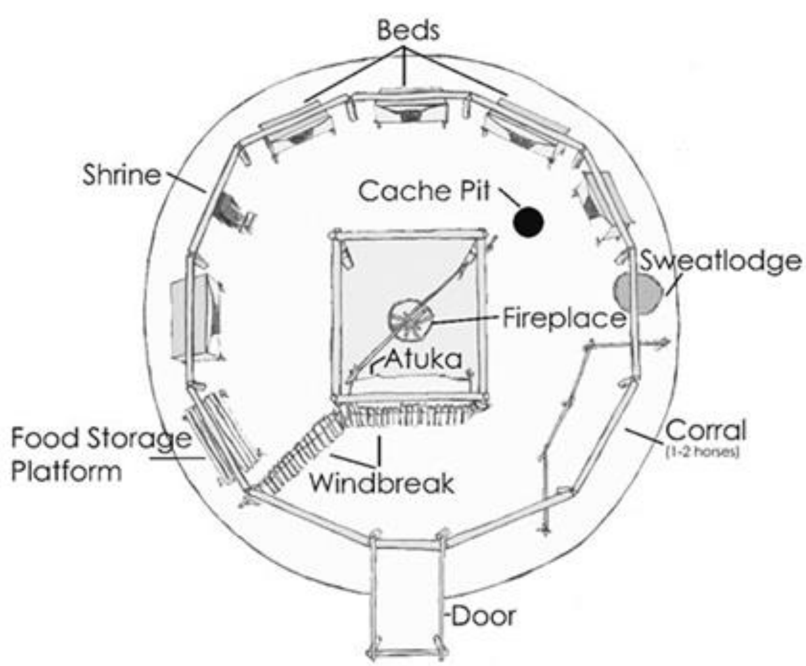

Figure 2.1. Plan view of an earth lodge depicting usage of floor space (after NPS, 2017a).

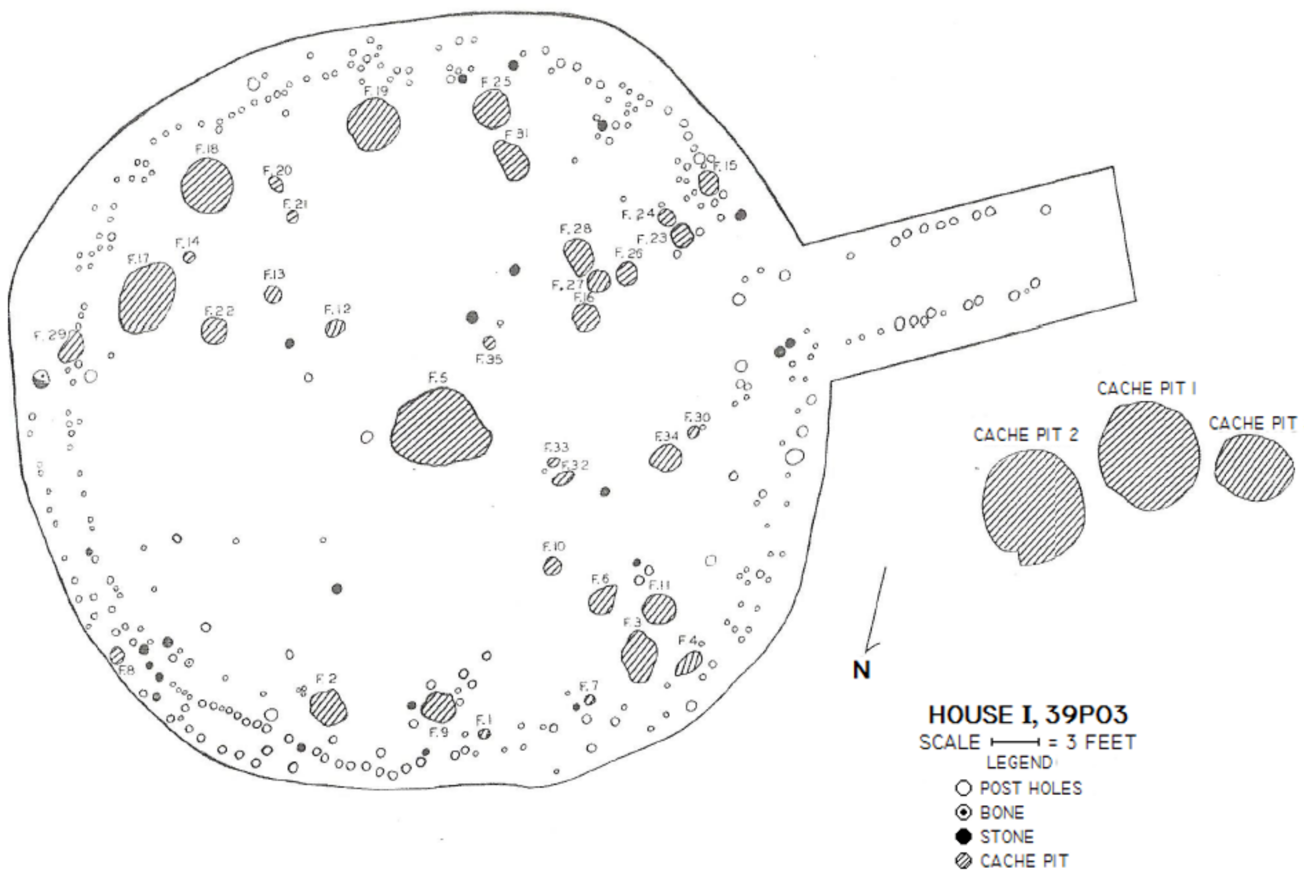

Figure 2.2. Floor plan of a typical domed shaped prehistoric Middle Missouri earth lodge in what is today central South Dakota showing variations in upright pole placement and sizes (after Hurt, 1974).

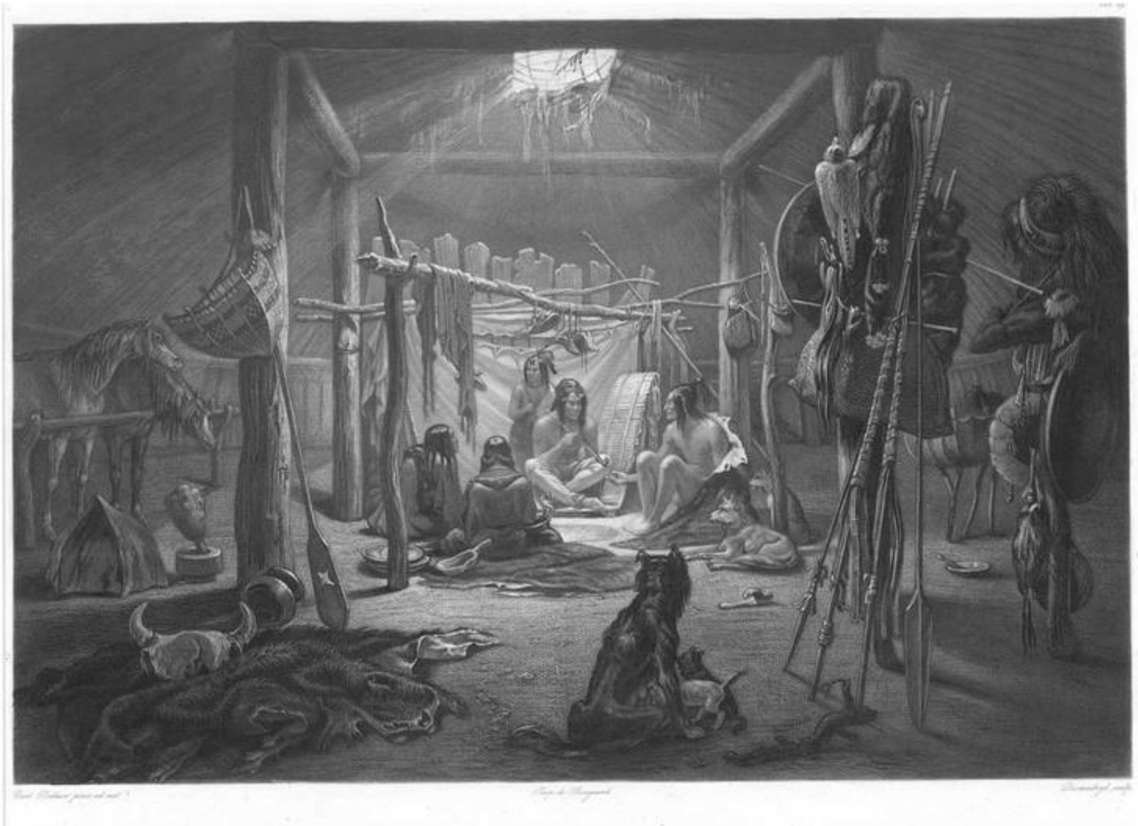

Figure 2.3. Artist Karl Bodmer painted the interior of a Mandan earth lodge in about the 1830s in what later became ND (after Joslyn Art Museum, 2017).

Figure 2.4. Artist George Catlin's painting, The Last Race, Mandan O-Kee-Pa Ceremony, 1832, showing that the Mandan spent time on the roofs of their earth lodges (after George Catlin.org, 2017).

The literature shows that the composition of earth lodges has also been analyzed by an architect, and by educators from North Dakota State University. Architect Dennis R. Holloway (2017) produced a computer model of a Hidatsa earth lodge based on data (Appendix B) collected in the early 1800s by Dr. Gilbert Wilson (1934) and associates at Like-A-Fishhook Village in what later became ND. The computer model was included in the book, *Native American Architecture*, by Nabokov and Easton (1989). North Dakota State University educators Slator (Computer Science) and others (2001) produced a simulation of archaeological features at Like-a-Fish Hook Village, including the structural framework of “Hidatsa Lodge #1” using AutoCAD and "Form Z" software. They modeled structural elements of the virtual earth lodge, including wood posts. They used archaeological reports, as well as historical paintings and sketches by artists such as Bodmer and Catlin to ensure authenticity, although they do not state that Wilson's (1934) scaled drawings were considered (Slator et al., 2001 and North Dakota State University, 2005). Their purpose was to present a system that could be used by archaeology students around the world to conduct a virtual archaeological excavation and to model findings (North Dakota State University Archaeology Technologies Laboratory, 2004).

2.2 Visit to Knife River Indian Villages National Historic Site

The Knife River Indian Villages National Historic Site (National Park Service [NPS], 2017a) was visited by the author and a research team from South Dakota State University (SDSU) on August 7, 2018 as a part of this investigation (Appendix A). The place is an archaeological site that includes historic Hidatsa villages with an NPS interpretive center and staff. The layout of the site includes a series of depressions in the landscape that are the remains of collapsed Hidatsa earth lodges in villages that existed until at least 1837 along the Knife River near what is today Stanton, ND.

As noted, the site also has a modern reproduction Hidatsa earth lodge that was built by the NPS using an accurately detailed description of Wolf-chief’s earth lodge from Like-a-Fishhook Village (Ft. Berthold, currently in ND) based on information gathered by ethnographer Dr. Gilbert Wilson and associates from 1908 to 1918 (although published in 1934). Like-a-Fishhook Village was built beginning in 1852. Wilson’s report, *The Hidatsa Earthlodge (1934)*, provided very detailed information about the materials, dimensions, and construction of Wolf-chief’s earth lodge with sketches by his

Hidatsa associate and informant Edward Goodbird and by F. N. Wilson. Gilbert Wilson's motivation for documenting this information was because only seven earth lodges remained standing at Ft. Berthold in 1908.

To extract information such as materials, member sizes, dimensions, and construction details for the virtual historic Native American earth lodge, several sources were used. They included Wilson's scaled drawings (1934) (Figure 2.5 and Appendix B), the reproduction earth lodge at the Knife River Indian Villages National Historic Site that was built based on Wilson's plans, with details of Upper Missouri earth lodges generally confirmed by various archaeological reports and by historic paintings by Bodmer and Catlin, previously noted.

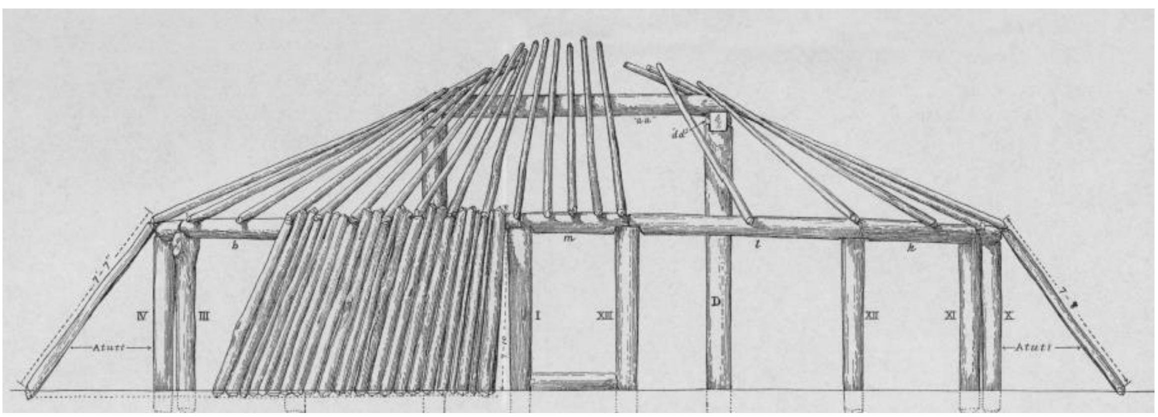

Figure 2.5. Sketch of timber structure with dimensions of Wolf Chief's earth lodge (Hidatsa, Ft. Berthold) early 1800s (after Wilson, 1934, Figure 16, pocket in cover, n. p.).

During the visit to the Knife River Villages site, measurements of the replica earth lodge structural beams were collected by the research team using FARO Focus^{S} 150 (Appendix C). Dimensions of the FARO-derived earth lodge roof beams were not exact, but generally confirmed those from scaled sketches provided by Wilson and associates (1934) upon which the construction of the structure was based.

CHAPTER 3 : PROCEDURES

Prior to conducting the three previously noted procedures: finding an equation to modify *E* properties, modeling alternative beams, and calculating deflection based on *E*, loads were calculated that were applicable to the alternative beam models.

3.1 Loads Applicable to Alternative Beam Models

The load combinations used for the analysis of the alternative earth lodge beams, followed the requirements of ASCE 7-10 (Engineers, 2010), which offers guidelines for minimum design loads for buildings that are subject to code requirements. The ASCE 7-10 presents two fundamental design philosophies:

- Allowable Stress Design (ASD)
- Load and Resistance Factor Design (LRFD)

The differences between the two will not be discussed in this thesis, because it is beyond the scope of this investigation. The use of one or the other is preferential; therefore, for this thesis the ASD method will be adopted since it is widely used for timber design. There are several conditions to determine the serviceability limit state of a building such as: deflection, vibration, corrosion, and fatigue checks. The limit state used for this investigation was deflection. By observing the deflection of the structural members, the efficiency of deflection was determined for the virtual historic Native American earth lodge alternative beams.

3.1.1 Design Loads

Loads for the alternative roof beams were calculated. When designing a structural system, it is important to be aware of all the loads to which a structure will be subjected during the expected service life. The main purpose of any structure is to effectively support the loads applied to it while successfully preventing failure.

Many different loads must be considered for the design of a structure, to properly determine the structural member sizes and to perform an analysis. The direction in which the loading types affect a structure are vertically and horizontally, although some may include one and the other. These loads come in the form of the following: dead, live, snow, and wind.

Depending on the area, seismic loads might need to be calculated. For this investigation, based on the seismic area map provided in the ASCE 7-10 manual (2010), the regions of South Dakota and North Dakota do not require seismic load calculations and, therefore, will not be performed.

The results from the dead, live, snow, and wind uniform loads (Table 3.1) were used to determine the load combination that governed the design and analysis of the virtual earth lodge beams.

Table 3.1. Results for dead, live, snow, and wind uniform loads

Type	Factors		Table	Figure	Section	Page #	Total Value
	Name	Value					
Dead	D						100 psf
Live	L_r						97.5 psf
Snow	C_e	0.9	7-2			73	
	C_t	1	7-3			73	
	C_s	0.76	7-2a			79	
	I_s	1.1	1.5-2			48	
	p_s						26.3 psf
Wind	V	120 mph		26.5-1b		293	
	K_d	0.95	26.6-1			295	
	K_{zt}	1.0			26.8.2	301	
	G	0.85			26.9.1	301	
	GC_{pi}	+0.18 -0.18	26.11-1			305	
	K_z	0.85	27.3-1			308	
	q_z					307	29.77 psf

3.1.2 Load Combinations

After the individual uniform loads were calculated, it was necessary to consider the different loading cases that might affect the structure. These case combinations can be found in ASCE 7-10 in Section 2.4 for Allowable Stress Design (2010, p. 51). The different applicable load combinations for allowable stress design (ASD) are:

1. D
2. $D + L$

3. $D + (L_r \text{ or } S \text{ or } R)$

4. $D + 0.75L + 0.75(L_r \text{ or } S \text{ or } R)$

5. $D + (0.6W \text{ or } 0.7E)$

6a. $D + 0.75L + 0.75(0.6W) + 0.75(L_r \text{ or } S \text{ or } R)$

6b. $D + 0.75L + 0.75(0.7E) + 0.75S$

7. $0.6D + 0.6W$

8. $0.6D + 0.7E$

Because of the radial arrangement of the beams, the tributary area had a triangular shape, and the distributed load will have a trapezoidal shape. Figure 3.1 includes the dimensions for the tributary area; therefore, the load at the Tail end was greater than the load at the Head end. As a result, each tributary section of the roof had two load values.

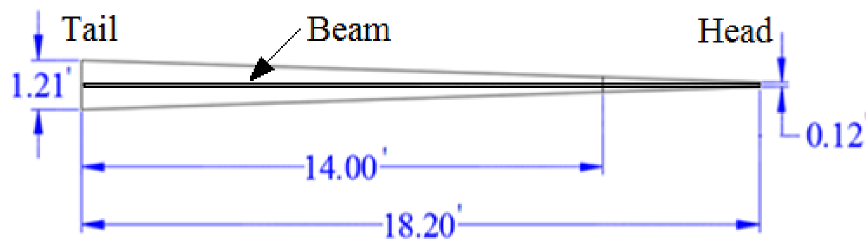

Figure 3.1. Tributary area of roof, plan view

Table 3.2 shows the results from the load combination calculations. The highest load combination (highlighted) was selected to determine the beam deflection and the initial design of the beam.

Table 3.2. Load combination results

Load Case Number	Load Combination	Total (lb/ft)	
		Tail	Head
3	$D + (L_r \text{ or } S \text{ or } R)$	123.83	17.56
6a	$D + 0.75L + 0.75(0.6W) + 0.75(L_r \text{ or } S \text{ or } R)$	85.52	5.81
6b	$D + 0.75L + 0.75(0.6E) + 0.75S$	76.49	14.69

Based on the results shown on Table 3.2, the load combination that governed was:

$D + L_r$ = 124 lb/ft (Tail)

$D + L_r$ = 18 lb/ft (Head)

Those loads were used to determine the external reactions for the alternative beam. The alternative beam was then analyzed by VisualAnalysis, which helped to determine the Maximum Moment (M_{max}) and deflection ($\Delta_{allowable}$). The calculated deflection needed to meet the acceptable code specification limit of L/240 (ASCE, 2010, ASCE 7-10) was used for this investigation. The use of L/240 is frequently implemented when designing in the serviceability state (Breyer, 2007, p. 131) in accordance with the International Building Code (IBC, 2012) in Table 3.3.

Table 3.3 . IBC Deflection Limits
(revised after IBC, 2012, Table 1604.3, p. 271)

CONSTRUCTION	L	S or W	D + L
Roof members:			
Supporting plaster or stucco ceiling	L/360	L/360	L/240
Supporting non-plaster ceiling	L/240	L/240	L/180
Not supporting ceiling	L/180	L/180	L/120

Since the length of the unsupported portion of the beam is 14.0 ft, then the deflection limit based on the code will be:

$$\Delta_{allowable} = \frac{L}{240} = \frac{14.0\, ft * 12}{240} = 0.70\ in.$$

This equation helped determine the deflection for all the beams, girders, and stringers. The result displayed above applies only to the alternative beam and is the maximum beam deflection allowed by the code for this member.

The dimensions used for the alternative beams were derived from Wilson (1934) and generally confirmed as appropriate for Upper Missouri earth lodges by other sources detailed in the literature review (Figures 3.2 and 3.3).

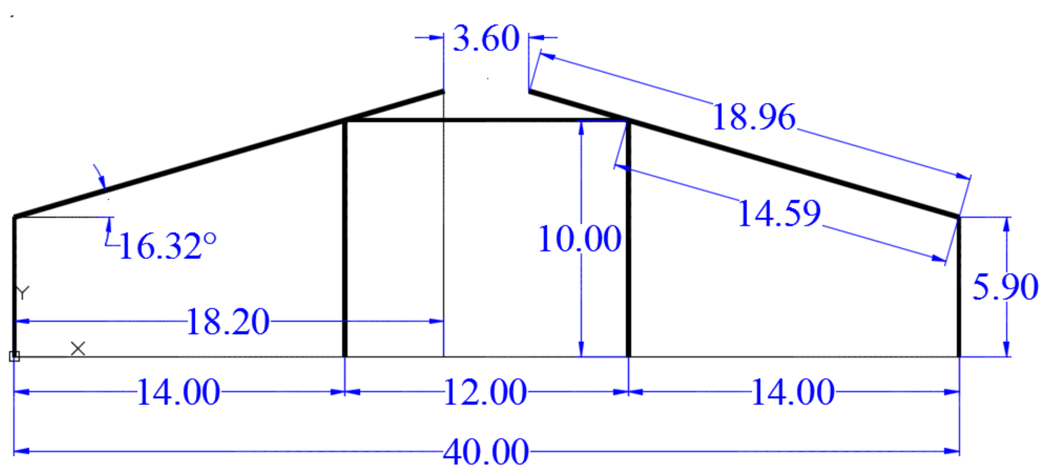

Figure 3.2. This elevation view for both of the alternative earth lodge models was derived from scaled drawings from one of the last remaining Hidatsa earth lodges (Wilson, 1934) and generally confirmed by other sources.

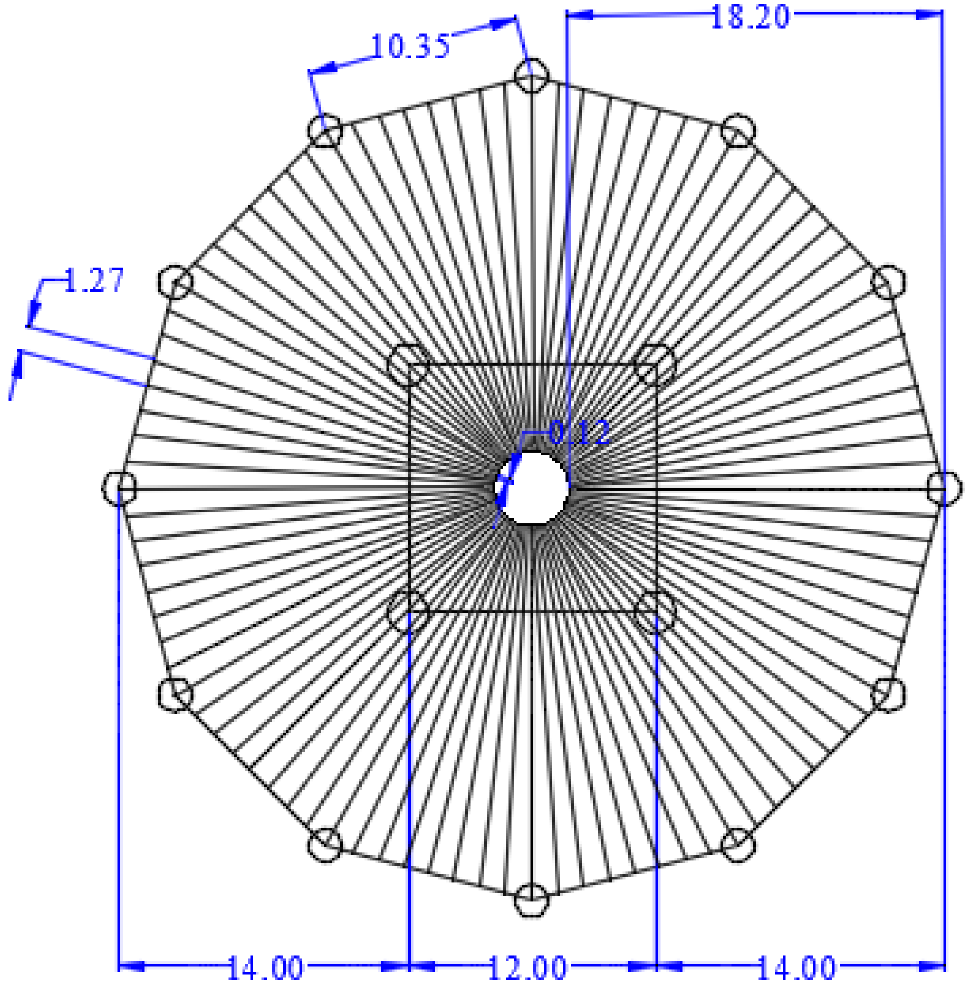

Figure 3.3. This plan view for both of the virtual earth lodge models was derived from scaled drawings from one of the last remaining Hidatsa earth lodges (Wilson, 1934) and other sources.

With the dimensions established, each structural member of the earth lodge was assigned a name, to identify the location of the member during the analysis (Fig. 3.4), although only the beams were of interest for this research.

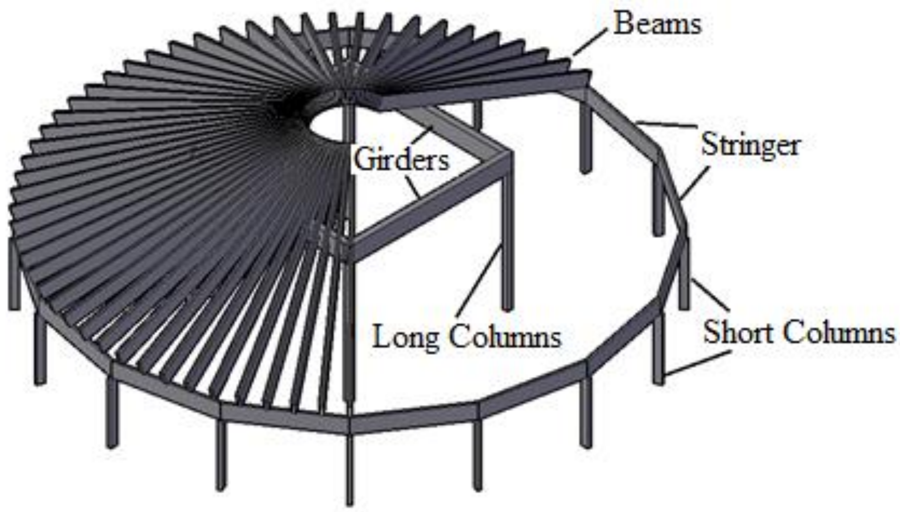

Figure 3.4. Earth lodge member names

3.2 Selecting Types of Woods for Comparison

Some of the types of native wood available for earth lodges at Like-A-Fishhook Village that were in existence from 1906-1918, were noted by Wilson (1934). Those wood types included cottonwood (*Populus deltoides*), green ash (*Fraxinus pennsylvanica)*, American elm (*Ulmus americana)*, diamond willow (*Salix planifolia)*, and peachleaf willow (*Salix Amygdaloides*), as well and driftwood of unidentified species from nearby rivers. According to Wilson (1934) available wood types, but used specifically for temporary hunting lodges included "buckbrush [*Symphoricarpos orbiculatus*,] chokecherry [*Prunus virginiana*], elm, red willow [*Salix*, various species] or other green-cut branches" (p.11). Wilson (1934) noted that in gathering posts and beams for earth lodge construction that,

> *[p]osts and beams were cut by the woman the preceding summer and dried and were brought to the village in winter when snow lay on the ground by the men who dragged them over the snow with rawhide ropes. One informant stated that drift timber [driftwood] stranded on the Missouri sand bars was preferred to freshly cut logs, since the former was said to last longer*. (pp. 358-359)

For purposes of the present research, seven types of wood were selected for deflection comparison when used as roof beams for an earth lodge. Five are native to North or South Dakota, and two types (Douglas fir, Western larch [D F-L]) are native in adjacent states. All are suitable in size for posts and beams for an earth lodge. The seven types of wood included cottonwood, American elm, Douglas fir/western larch *(Pseudotsuga menziesii/Larix occidentalis)*, green ash, Ponderosa pine, and silver maple (*Acer saccharinum)*. Other types of wood noted by Wilson (1934, p. 411) such as willow branches, chokecherry branches and buckbrush were probably only used, along with sod and soil, for cladding the pole framework, particularly in the case of temporary Hidatsa hunting lodges. All Latinized names for plants in this thesis were selected from a United States Department of Agriculture (USDA) webpage (2017).

3.3 Selecting an Equation to Modify the Modulus of Elasticity (*E*) Properties for Alternative Beams

An equation to modify *E* properties for the alternative beams was selected from Forest Products Laboratory (2010, p. 133) as follows.

$$P = P_{12}\left(\frac{P_{12}}{P_g}\right)^{\left(\frac{12-M}{M_p-12}\right)}$$

3.4 Modeling Alternative Beams

Wilson's (1934) scaled drawing dimensions for the actual Hidatsa earth lodge are shown in Table 3.4, although only the beams were of interest for this thesis. To simplify the analysis, the alternative beam diameters and lengths were rounded to the nearest hundredth for ease in calculations (Table 3.5).

Table 3.4. Virtual historic earth lodge dimensions, including beams, as indicated by Wilson's (1934) field research

Virtual historic earth lodge dimensions					
Dimensions	Beam	Girder	Stringer	Long Column	Short Column
Diameter (in)	4.8	9.5	9.0	12.5	10.0
Length (ft)	18.96	12	10.35	10.0	5.9

Table 3.5. Dimensions, after rounding, for timber members of the virtual historic earth lodge

Timber Members					
Dimensions	Beam	Girder	Stringer	Long Column	Short column
Diameter (in)	5.0	10.0	9.0	12.0	10.0
Length (ft)	19.0	12.0	10.4	10.0	5.9

3.5 Calculating Deflection Based on *E*

Finding the material properties was important because they affect the deflection of wood beams. Tables 3.6 through 3.11 include selected material properties for each of the seven types of wood that were of interest (Forest Products Laboratory, 2010) (pages 84 – 88), although Douglas fir and western larch are combined as one type because it is a wood industry standard known as D F-L.

Table 3.6. Cottonwood material properties

E_{12}=	1370000	psi
E_g =	1010000	psi
M =	4, 8, 12, 18, 26	%
M_p=	24	%

Table 3.7. American elm material properties

E_{12}=	1340000	psi
E_g =	1110000	psi
M =	4, 8, 12, 18, 26	%
M_p=	25	%

Table 3.8. Douglas fir and western larch (combined) material properties

E_{12}=	1830000	psi
E_g =	1510000	psi
M =	4, 8, 12, 18, 26	%
M_p=	24	%

Table 3.9. Green ash material properties

E_{12}=	1660000	psi
E_g =	1400000	psi
M =	4, 8, 12, 18, 26	%
M_p=	24	%

Table 3.10. Ponderosa pine material properties

E_{12}=	1300000	psi
E_g =	1000000	psi
M =	4, 8, 12, 18, 26	%
M_p=	21	%

Table 3.11. Silver maple material properties

E_{12}=	1140000	psi
E_g =	940000	psi
M =	4, 8, 12, 18, 26	%
M_p=	25	%

3.6 Model Modification

To perform the analysis required using data from Tables 3.6 through 3.11, modifications were required to create alternative beam models. Some involved adjusting the geometry of the members; while others involved neglecting certain aspects to simplify the analysis while still providing accurate results. An effort was made to keep modifications as parallel as possible because the further the designed model deviated from the original, the greater the likelihood of failing to apply the appropriate modifications.

A fundamental assumption for the use of wood components in load carrying members is, that material properties such as strength, density, and stiffness can be modeled with great accuracy. To achieve a proper level of accuracy, various factors need to be taken into consideration when trying to determine the uncertainties of the behavior of timber material properties. For instance, the unpredictable variability of common weakening elements of natural wood, such as knots and cross grain irregularities, must be carefully considered. The appropriate representation needs to be properly depicted when simplifying physical and mechanical descriptions of timber in the model.

The degree of difficulty increases when trying to predict timber behavior in an historic structure, because it is especially challenging to accurately define the material properties, since wood loses strength over time. Although this thesis goal is to model the deflection of virtual beams based on the effect of MC on an historic structure, the loss of strength over time will not be considered in this paper.

The thesis analysis investigated only how the historic Native American alternative beams compared to NDS code-specified deflections, with the assumption that all beams were made of one particular type of wood under the condition of various specific moisture contents. In other words, the virtual historic Native American alternative beams were analyzed not as historic member components (which would include strength losses), but instead, as they were at the time the earth lodge was inhabited in the early 1800s. In the process, comparisons were made between the mechanical and physical properties of selected types of wood beam performance, including cottonwood, American elm, D F-L, green ash, Ponderosa pine, and silver maple. The historic earth lodge that Wilson (1934) analyzed and recorded may have included several species of trees, although the lodge was probably a combination of driftwood, cottonwood, and willow branches. The reproduction earth lodge at Knife River Villages was built of pine for convenience rather than for historical accuracy.

CHAPTER 4 : ANALYSIS OF ALTERNATIVE BEAMS

To analyze the virtual beams, first an equation to modify the modulus of elasticity (*E*) was used. Second, the Bernoulli-Euler beam theory equation was used to determine the deflection of the alternative beam. Finally, the values of the *E* needed for the Bernoulli-Euler equation were located. Those steps are explained as follows.

4.1 Equation to Modify *E*

This chapter will demonstrate how the analysis of the virtual beams was approached. To analyze the interaction of certain timber material properties, the following equation termed the Constant Percentage Adjustment Model was applied. This analytical equation (after Forest Products Laboratory, 2010) adjusts *E* by a constant percentage, regardless of grade or size when the MC is changed from one level to another. This equation modifies *E* based on MC.

$$E = E_{12}\left(\frac{E_{12}}{E_g}\right)^{\left(\frac{12-M}{M_p-12}\right)}$$

Where:

E_{12} : Modulus of Elasticity at 12% MC

E_g : Modulus of Elasticity at the green stage

M_p : Intersection Moisture Content Value

M : Target Moisture Content (desired)

If a relatively simple model is needed as a basis for general design use, the linear constant percentage adjustment model is appropriate for the modification of E.

4.2 Bernoulli-Euler Beam Theory Equation

Since the structure designed was based on the serviceability limit state, the deflection was critical to determine if the beam would meet the code requirements. To manually determine the beam deflection, the following equation (after Breyer et al., 2007, p. 132) based on the Bernoulli-Euler beam theory for prismatic beams was used. Deflection was then calculated by adjusting *E* on the following equation.

$$\Delta = \frac{5 * W * (L * 12)^4}{384 * E * I}$$

The maximum deflection is found at the center of the span, but the following conditions must be met when applying this equation:

- The beam has a constant cross-section
- The beam undergoes linear elastic deformation only
- The beam is slender (where length to height ratio is greater than 10)
- Only small deflections are considered (where $\Delta_L \leq 1/10$ of span)

All of those conditions were met by the alternative beams. The equation provides the maximum deflection caused by bending in a simply supported beam when a uniformly distributed load is applied to the entire length.

4.3 Values for *E*

The variables or values used to determine the input parameters are crucial to obtain results that closely reflect the behavior of the materials used. Seven types of wood beams were used for the analysis, and each alternative beam was assigned a particular species.

The inclusion of Douglas Fir-Larch as part of this investigation is due to its availability as well as being the most common species used in modern timber frame construction.

The input parameters (Tables 4.1 through 4.6) were especially important for the modeling of the materials, because they are essential to model and perform the analysis properly. The following tables show the various input parameters used to help determine the variation of MOE and the deflections. The values in the tables are assumed to be at a MC of 12%.

Table 4.1. Input parameters used for material properties of cottonwood

Cottonwood beams and columns			
Parameters	Symbol	Value	Units
Modulus of elasticity	E	1380000	lb/in^2
Modulus of rupture	MOR	8733	lb/in^2
Poisson's ratio	v	0.29	
Density	ρ	27	lb/ft^3
Moment of inertia	I_x	35	in^4

Table 4.2. Input parameters used for material properties of American elm

American Elm beams and columns			
Parameters	Symbol	Value	Units
Modulus of elasticity	E	1340000	lb/in^2
Modulus of rupture	MOR	11800	lb/in^2
Poisson's ratio	v	0.32	
Density	ρ	35	lb/ft^3
Moment of inertia	I_x	35	in^4

The data for Table 4.3 was acquired from AWC (2012a), except for the Poisson's ratio, which was obtained from Forest Products Laboratory (2010, p. 78).

Table 4.3. Input parameters used for material properties of Douglas fir and western larch (D F-L) combined

D F-L beams and columns			
Parameters	Symbol	Value	Units
Modulus of elasticity	E	1700000	lb/in^2
Modulus of rupture	MOR	12500	lb/in^2
Poisson's ratio	v	0.29	
Density	ρ	32	lb/ft^3
Moment of inertia	I_x	35	in^4

Table 4.4. Input parameters used for material properties of green ash

Green ash beams and columns			
Parameters	Symbol	Value	Units
Modulus of elasticity	E	1660000	lb/in^2
Modulus of rupture	MOR	14000	lb/in^2
Poisson's ratio	v	0.37	
Density	ρ	40	lb/ft^3
Moment of inertia	I_x	35	in^4

Table 4.5. Input parameters used for material properties of Ponderosa pine

Ponderosa pine beams and columns			
Parameters	Symbol	Value	Units
Modulus of elasticity	E	1290000	lb/in^2
Modulus of rupture	MOR	9400	lb/in^2
Poisson's ratio	v	0.34	
Density	ρ	28	lb/ft^3
Moment of inertia	I_x	35	in^4

Table 4.6. Input parameters used for material properties of silver maple

Silver maple beams and columns			
Parameters	Symbol	Value	Units
Modulus of elasticity	E	1140000	lb/in^2
Modulus of rupture	MOR	8900	lb/in^2
Poisson's ratio	v	0.42	
Density	ρ	33	lb/ft^3
Moment of inertia	I_x	35	in^4

CHAPTER 5 : RESULTS AND DISCUSSION

5.1 Results

As noted in the procedures section of this thesis, the following types of wood were selected for deflection comparisons when potentially used as earth lodge beams. The results follow in Tables 5.1 through 5.6 and in Figure 5.1.

Table 5.1. Results for E and deflection of cottonwood

Cottonwood (*Populus deltoides*)		
MC %	*E* (psi)	Deflection (in)
26	958801	3.74
18	1180593	3.03
12	1380000	2.60
8	1531317	2.34
4	1699225	2.11

Table 5.2, Results for E and deflection of American elm

American Elm (*Ulmus americana*)		
MC %	*E* (psi)	Deflection (in)
26	1094037	3.27
18	1228455	2.92
12	1340000	2.67
8	1419935	2.52
4	1504638	2.38

Table 5.3. Results for E and deflection of D F-L

Douglas, Fir/Western Larch (*Pseudotsuga menziesii*, *Larix occidentalis)*		
MC %	*E* (psi)	Deflection (in)
26	1462395	2.45
18	1662318	2.16
12	1830000	1.96
8	1951083	1.84
4	2080178	1.72

Table 5.4. Results for E and deflection of green ash

Green Ash (*Fraxinus pennsylvanica*)		
MC %	*E* (psi)	Deflection (in)
26	1360812	2.63
18	1524467	2.35
12	1660000	2.16
8	1756985	2.04
4	1859637	1.93

Table 5.5. Results for E and deflection of Ponderosa pine

Ponderosa Pine (*Pinus ponderosa*)		
MC %	*E* (psi)	Deflection (in)
26	864367	4.15
18	1091393	3.28
12	1300000	2.76
8	1460780	2.45
4	1641445	2.18

Table 5.6. Results for E and deflection of silver maple

Silver Maple (*Acer saccharinum*)		
MC %	*E* (psi)	Deflection (in)
26	926155	3.87
18	1042890	3.44
12	1140000	3.14
8	1209713	2.96
4	1283689	2.79

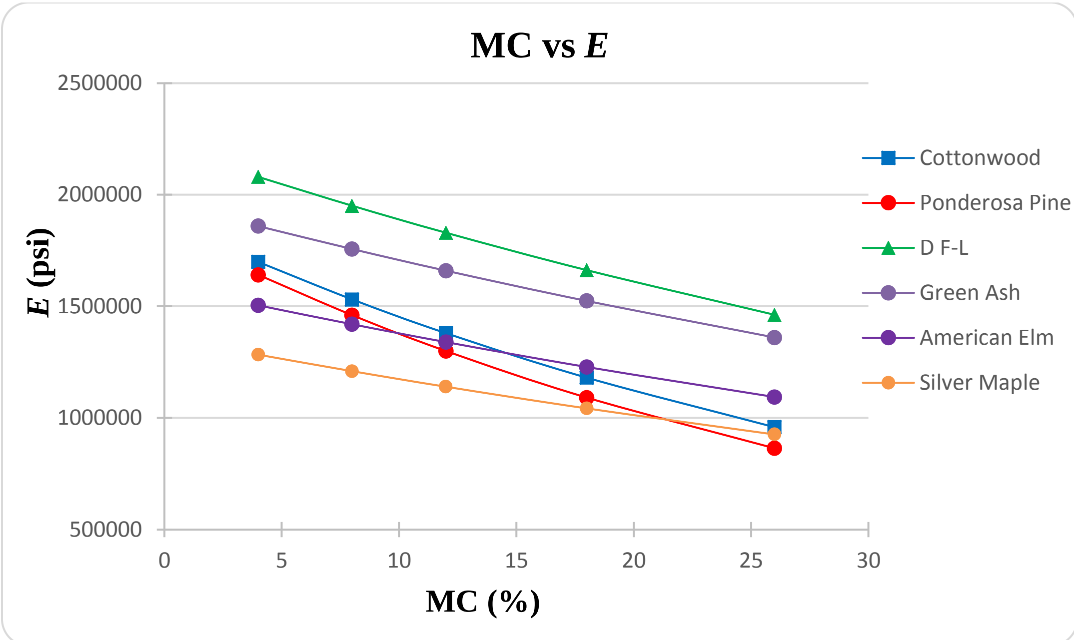

Figure 5.1. Combined graph showing the change of E as MC increases.

5.2 Discussion

In analyzing the seven types of woods of interest, results indicated that the various woods ranked as follows in desirable deflection properties under varying moisture contents of 4, 8, 12, 18, and 26 percent: D F-L, green ash, cottonwood, Ponderosa pine, American elm, and silver maple (Figure 5.2). It is known from the literature that the Hidatsa used ash and cottonwood in building earth lodges in the early 1800s, although they also used and preferred driftwood of unrecorded species. Results indicated that the Hidatsa used at least two of the most desirable woods (considering deflection properties in this thesis) available to them during the historic period (Wilson, 1934), namely elm and cottonwood. They were also aware of the lost-lasting properties of large driftwood logs (especially cottonwood) (Wilson, 1934) which they preferred to all other categories of wood in earth lodge construction.

It is possible that the Hidatsa used a variety of native wood types based on proximity and ease of availability, although the specific names were not recorded by Wilson (1934). Since D F-L is not native in North or South Dakota, it is unlikely that it was used in earth lodge construction by the Hidatsa or their ancestors as they moved north along the Missouri River valley. The D F-L was included in the list, as noted earlier, because it is a modern industry standard against which other wood is ranked. The acronym D F-L refers to Douglas fir and western larch, and the two species of wood often grow in stands side by side in a state adjacent to North Dakota and South Dakota.

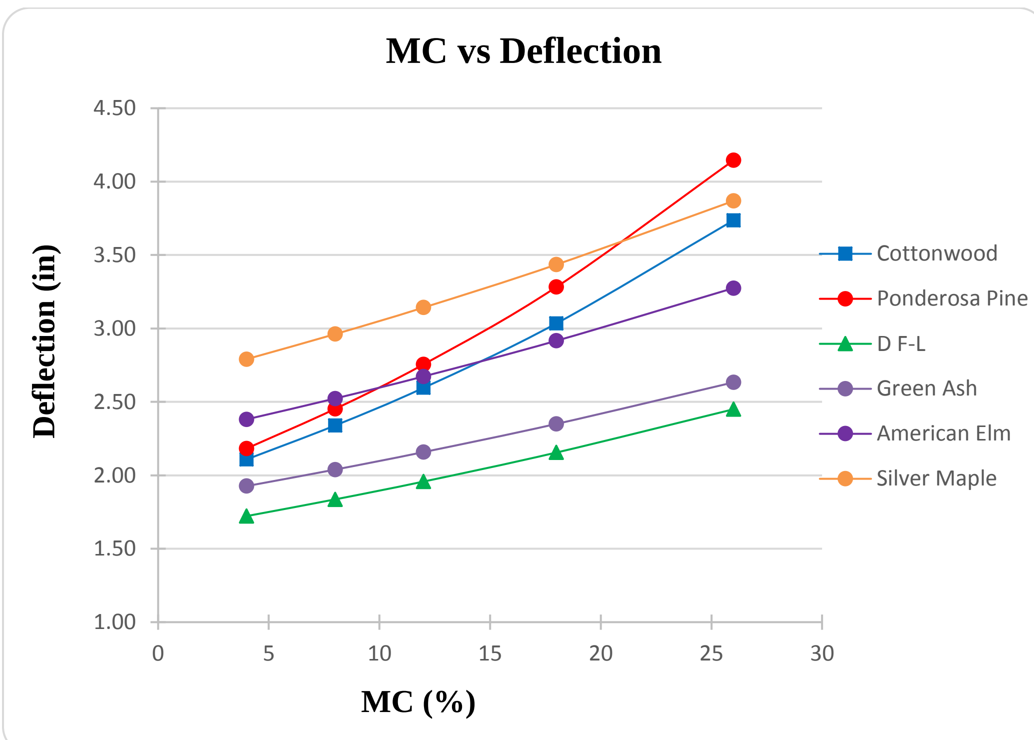

Figure 5.2. Combined graph showing the change in deflection as MC increases.

5.2.1 Limitations of the Study

This investigation offers a glimpse into timber structure engineering ingenuity and structural load capacity among prehistoric and historic Native Americans of the Upper Missouri region of the United States. There are those who would debate whether or not Native American oral traditions of the structural elements of earth lodges actually constitute engineering, although they do, since engineering often involves trial and error and problem solving. Limitations of the study are summarized as follows.

- Wood has complex anisotropic properties because its material composition varies based on its direction (Martin et al., 2011).
- Bracing was assumed to be adequate.
- The assumption was made that all the roof beams were of one wood type, when they may have included various native species.
- It was unlikely that roof beams would have been D F-L because it was not readily available; thus, it was included for comparison to modern timber building.
- The geometry was adjusted to create symmetrical virtual beams, since tree logs are usually larger on one end than the other, although beams were probably not symmetrical in historical earth lodges.
- Strength losses of the beams through time were not considered, since they were assumed to be those used in a newly built earth lodge.

CHAPTER 6 : CONCLUSIONS

While exploring the mechanical properties of alternative roof beans for an historical earth lodge of the type used among the Hidatsa in North Dakota, alternative roof beams were compared based on degree of deflection. Seven types of wood were selected for inclusion in the study, with five being native to North or South Dakota, and one type (D F-L) as a modern wood industry standard. Dimensions for the virtual beams were obtained from ethnographic literature that was confirmed by historical, and archaeological sources. The virtual beams for each selected wood type were analyzed at varying moisture content percentages for comparison. Results indicated that when moisture content increases, *E* decreases and deflection increases, as expected. The wood types with the least deflections in the order of desirability and efficiency included D F-L, green ash, cottonwood, Ponderosa pine, American elm, and silver maple. Historic earth lodges in what is today North Dakota may have been constructed of a combination of native wood types, including driftwood of unknown species. It is known, however, that cottonwood and green ash were used. Those two wood types ranked second and third among readily available wood sources when considering deflection properties, since D F-L was not native to the locale.

CHAPTER 7 : RECOMMENDATIONS FOR FUTURE WORK

Native Americans used trial and error, and oral knowledge passed from one generation to the next when building earth lodges. Without Westernized engineering, they created a structural system that was useful, reliable, and environmentally friendly. This thesis provides information of value for creating a minimalistic structure. Aspects of earth lodge design and materials are expected to be of use to those interested in the highly innovative and entrepreneurial tiny house movement that includes environmentally friendly structures.

This study will be of interest to those producing reconstructions of Native American earth lodges in the Upper Missouri Valley at interpretive sites. Peripherally, the study is also intended to interest related tribal K-12 school students and teachers to increase participation in STEM studies and careers, particularly engineering through the production of related educational vignettes.

Future investigations might include a complete structural analysis of earth lodges of the Upper Missouri Valley, including how cyclic loading changes wood beam behavior over time. There is also potential for a study of notched connectors for earth lodges and resulting non-linear behavior based on Wilson's (1934) scaled sketches.

APPENDICES

APPENDIX A – VISIT TO KNIFE RIVER INDIAN VILLAGES NATIONAL HISTORIC SITE

Figure A-1. Map of Knife River Indian Villages National Historic Site near Stanton, ND. (after NPS, 2017b.)

Figure A-2. (L-R) Alisha Deegan, interpreter; Salvador Caballero, SDSU graduate intern; Suzette Burckhard, Assistant Department Head, Civil and Environmental Engineering, SDSU; Yazen Hindieh, SDSU graduate intern, and Freddy Moran, SDSU graduate intern, 2017 inside the reproduction earth lodge at the Knife River Indian Villages National Historic Site near Stanton, ND. August 2017. (photo: Joanita Kant)

Figure A-3. (L-R) Keely Moriarty, SDSU undergraduate engineering student intern; Freddy Mora, SDSU graduate engineering intern; Yazen Hindieh, SDSU graduate engineering intern; Suzette Burckhard, Assistant Department Head, Civil and Environmental Engineering, SDSU, and Alisha Deegan, Interpreter; inside the reproduction earth lodge at the Knife River site, August 2017. (photo: Joanita Kant)

Figure A-4. (L-R) Yazen Hindieh, SDSU graduate engineering intern, setting tripod for FARO 3D apparatus to scan exterior of reproduction earth lodge at the Knife River site, August 2017. (photo: Joanita Kant)

Figure A-5. (L-R) Freddy Moran, SDSU graduate engineering intern; Keely Moriarty, SDSU undergraduate engineering student; Calvin Wampol, SDSU graduate engineering intern, inspecting and preparing the laser scanner reference sphere set before FARO 3D scan of exterior of reproduction earth lodge at the Knife River site, August 2017.
(photo: Joanita Kant)

Figure A-6. (L-R) Keely Moriarty, SDSU undergraduate engineering student; Freddy Moran, SDSU graduate engineering intern, and Calvin Wampol, SDSU graduate engineering intern, placing the laser scanner reference sphere set around exterior of reproduction earth lodge at the Knife River site, August 2017. (photo: Joanita Kant)

Figure A-7. (L-R) Freddy Moran, SDSU graduate engineering intern; Yazen Hindieh, SDSU graduate engineering intern, and Salvador Caballero, SDSU graduate engineering intern, putting new batteries in FARO 3D scanner before exterior scan of reproduction earth lodge at the Knife River site, August 2017. (photo: Joanita Kant)

Figure A-11. Salvador Caballero, SDSU graduate engineering intern, preparing the FARO 3D for one of the interior scans of the reproduction earth lodge at the Knife River site, August 2017. (photo: Freddy Moran)

APPENDIX B – GILBERT WILSON'S AND ASSOCIATES' PLANS WITH DIMENSIONS FOR EARTH LODGE AT LIKE-A-FISHHOOK VILLAGE.

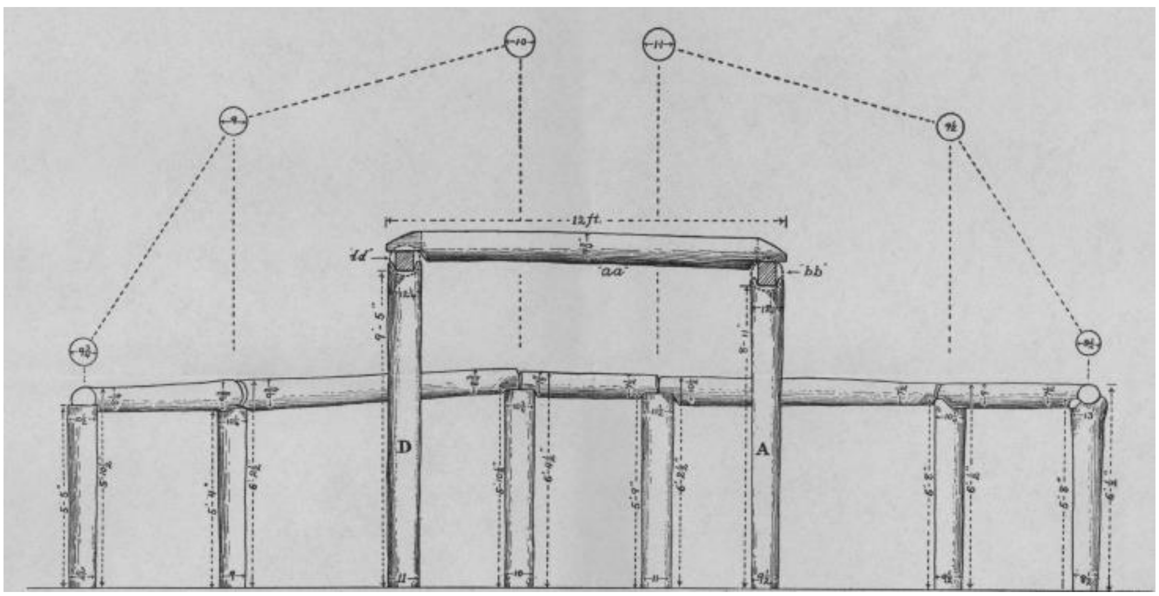

Figure B-1. Sketch of timber structure with dimensions of Wolf Chief's earth lodge (Hidatsa, Ft. Berthold) early 1800s (after Wilson, 1934, Figure 12, pocket in cover, n. p.). These dimensions were used to construct the reproduction earth lodge village at the Knife River site. They were also used to design the virtual historic Native American earth lodge for this thesis.

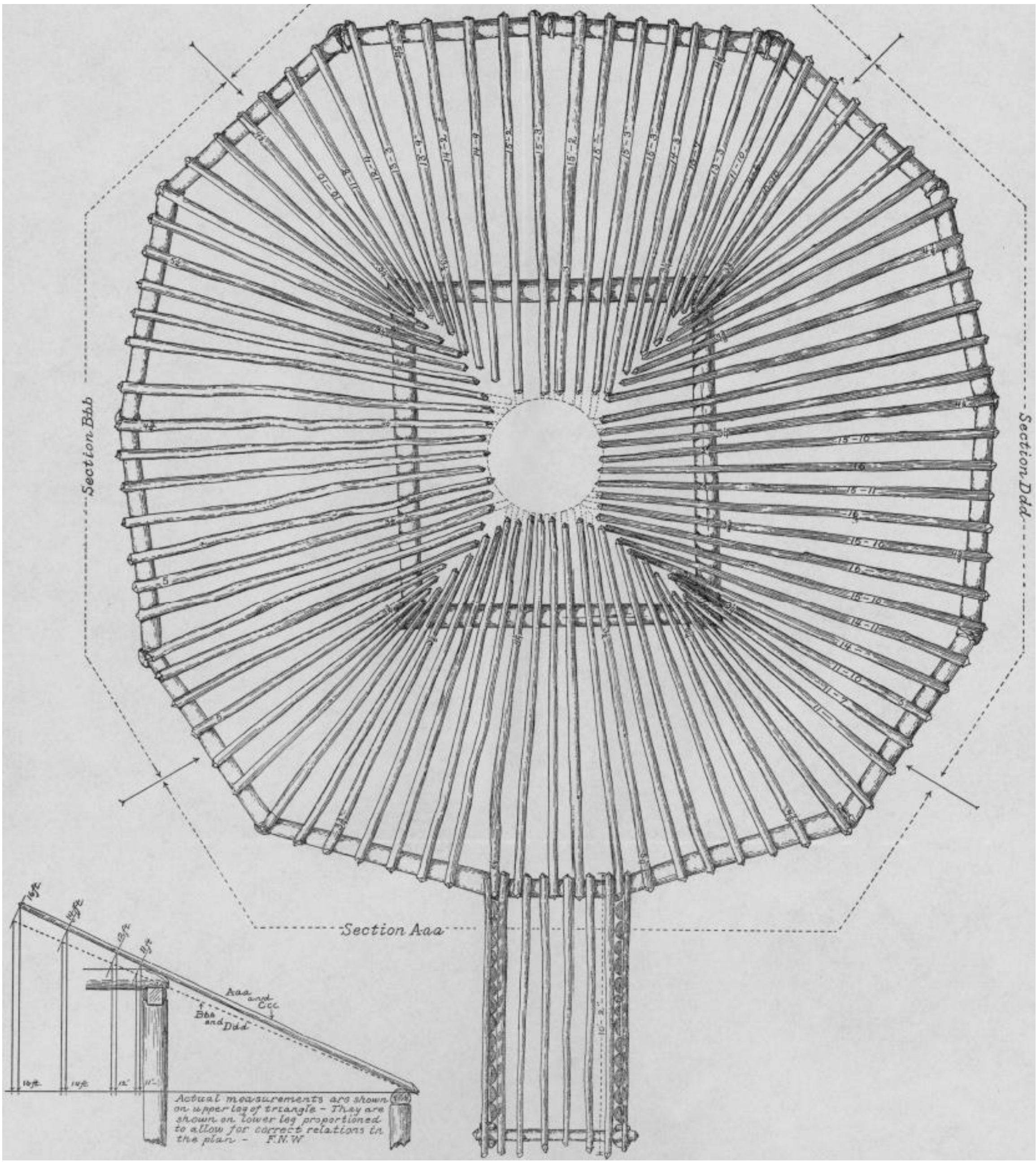

Figure B-2. Sketch of timber structure with dimensions of Wolf Chief's earth lodge (Hidatsa, Ft. Berthold) early 1800s (after Wilson, 1934, Figure 15, pocket in cover, n. p.).

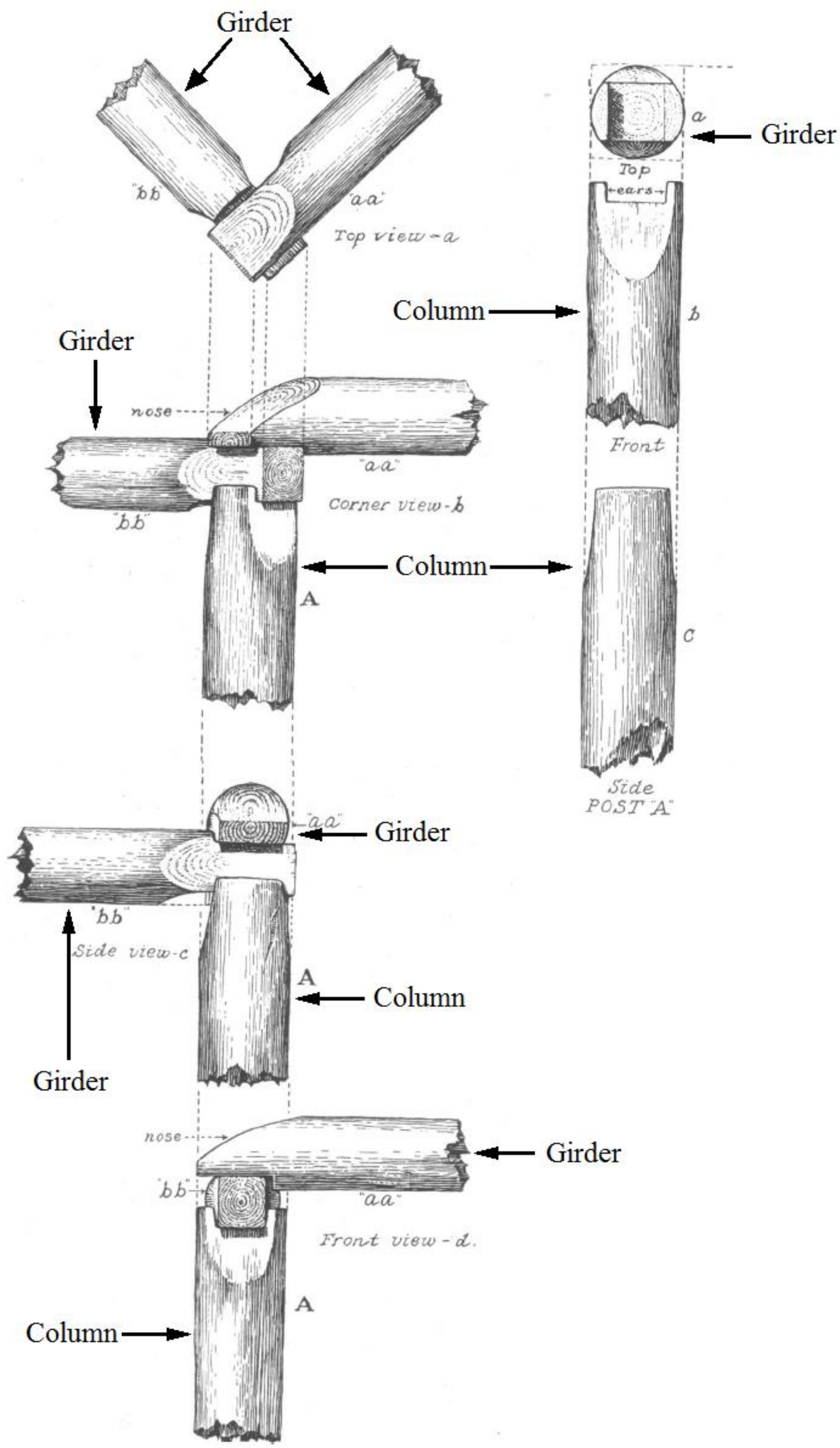

Figure B-3. Sketch of column-girder notched connections of Wolf Chief's earth lodge (Hidatsa, Ft. Berthold) early 1800s (revised after Wilson, 1934, Figure 17, p. 378).

APPENDIX C – FARO LASER 3 D SCANS OF REPRODUCTION EARTH LODGE AT KNIFE RIVERVILLAGES NATIONAL HISTORIC SITE, ND

Figure C-1. Salvador Caballero, SDSU graduate engineering intern, setting FARO 3D scanner to begin scan of exterior of the reproduction earth lodge at the Knife River site, August 2017. (photo: Joanita Kant)

Data collected from a FARO laser scanner was then transferred to the SCENE 5.5 software, which delivered a complete scan reading processing solution to mapping out all correspondent data points provided by FARO. The final step was to transport the SCENE 5.5 output to Autodesk Recap 360 to produce the relevant data, as well as the final rendering. Recap 360 provided the member diameters, lengths and all the building dimensions. Those results generally confirmed that this reproduction structure closely followed Wilson's (1934) scaled sketches, dimensions used in this thesis.

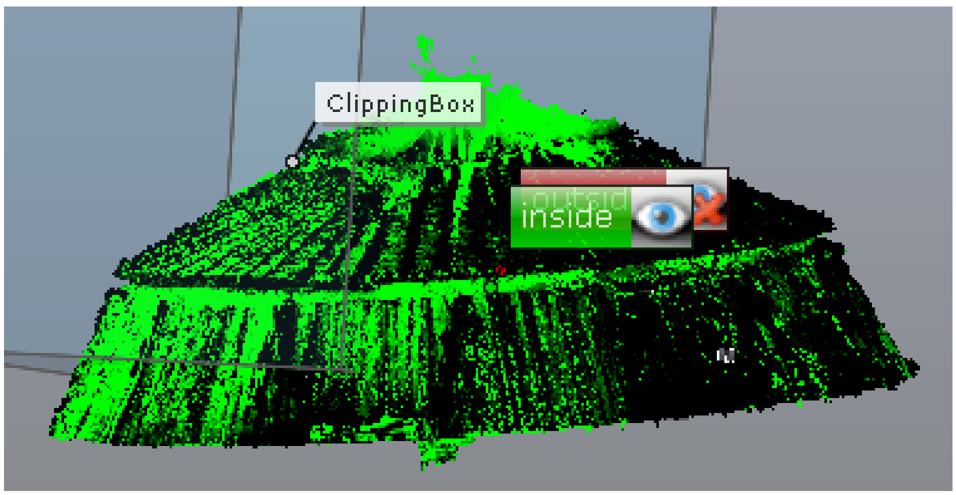

Figure C-2. Image from SCENE 5.5 software showing the correspondent views for the exterior of the reproduction virtual historic earth lodge at Knife River Indian Villages National Historic Site, near Stanton, ND, based on Gilbert Wilson's (1934) and associates' plans from Like-A-Fishhook Village near Ft. Berthold, ND. The Wilson data was sketched from some of the last remaining earth lodges in the early 1900s in what is today North Dakota.

Figure C-3. Final rendering obtained from Autodesk Recap 360, showing detail of roof beams of the reproduction earth lodge at Knife River Villages National Historic Site. This reproduction earth lodge was built based on Wilson's (1934) plans sketched by his associates.

The assistance of FARO, SCENE 5.5, and Autodesk Recap 360 made possible to obtain accurate dimensions from the reproduction Hidatsa earth lodge at the Knife River Indian Villages (Table 3.5).

Table 3.5. Reproduction Hidatsa earth lodge member dimensions

Reproduction Hidatsa earth lodge dimensions: dimensions obtained from FARO					
Dimensions	Beam	Girder	Stringer	Long Column	Short Column
Diameter (in)	5.2	10.0	9.2	12.5	10.0
Length (ft)	18.6	11.5	10.0	10.0	5.6

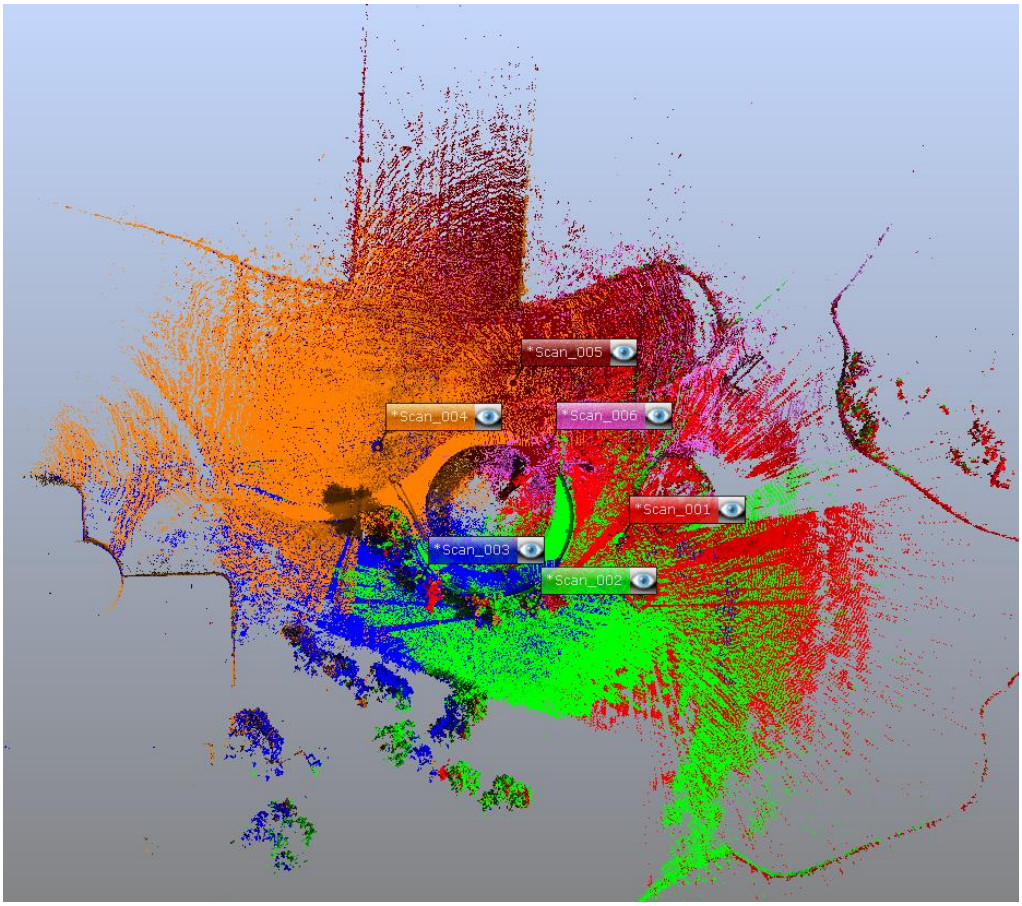

Figure C-4. FARO 3D top view image of reproduction earth lodge at the Knife River site, August 2017.

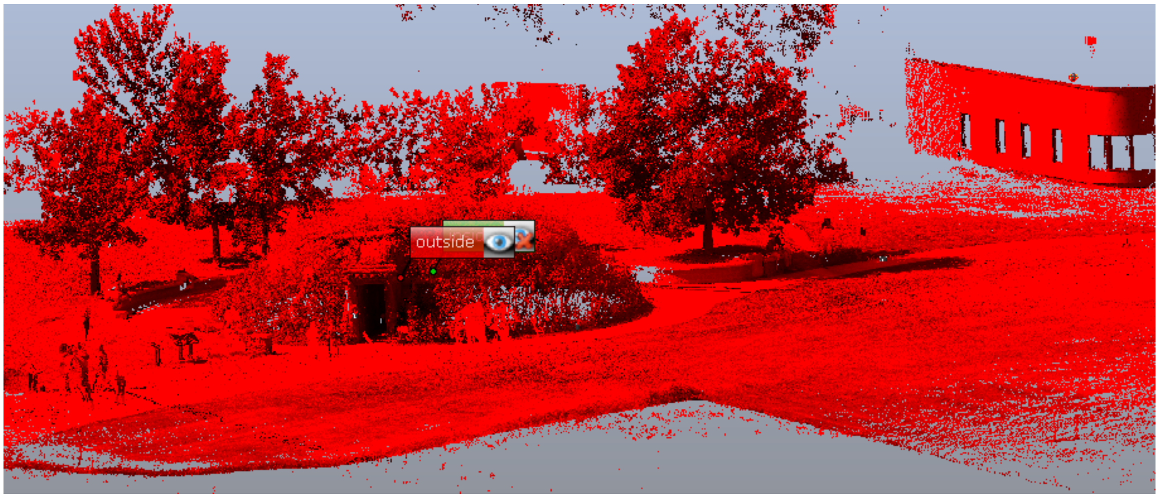

Figure C-5. FARO 3D overall exterior image of reproduction earth lodge at the Knife River site August 2017.

Figure C-6. Autodesk Recap rendering of reproduction earth lodge at the Knife River site. The small green dots are the laser scanner reference spheres positioned to scan this section of earth lodge.

Figure C-7. Autodesk Recap rendering of entrance of reproduction earth lodge at the Knife River Village National Register. The green neon dots represent the laser scanner reference spheres.

Figure C-8. Autodesk Recap rendering of entrance showing where one of the laser scanner spheres was placed (red circle).

Figure C-9. Autodesk Recap rendering showing the interior roof detail of reproduction earth lodge at the Knife River site.

Figure C-10. Autodesk Recap rendering of interior of reproduction earth lodge at the Knife River site showing detail of the short columns and placement of laser scanner spheres (red circles).

APPENDIX D – FACTORS OF WOOD PROPERTIES

Wood engineering has been in a constant process of evolution from the dawn of civilization. Mankind has used wood as a building material to create structures that would offer shelter against predators and environmental conditions. The first timber structures built by mankind were probably simply poles covered with brush and branches. Through time, prehistoric cultures produced stronger and safer timber structures based on trial and error and by passing down oral knowledge from one generation to the next. Today, engineers base designs on engineering principles and written codes and standards. As the understanding of wood improves, timber structures become more economical and have greater structural efficiency.

Safety is of primary concern, and codes and guidelines have become factors in modern wood engineering. The building codes and standards within the *National Design Specification* (NDS) *for Wood Construction* (2012a-d) books published by the American Wood Council (AWC), regulate the design of wood/timber construction. The NDS codes and standards determine the loads applied, and they limit exertion stresses for wood, thus limiting the guess work in expected wood performance. The NDS manuals, based on AWC principles, were used extensively in modeling in this thesis, as an essential component of wood engineering.

The following sections cover many of the important physical and mechanical properties of timber that are factors used by AWC in establishing safe codes and standards known as NDS. They include moisture content, durability, species, size, dressed lumber, rough lumber, full sawn lumber, and size category.

Moisture Content (MC)

This section examines the relationship between wood and Moisture Content (MC), and briefly explains how many mechanical and physical properties are affected by MC. Water is an external component that has a great influence of the strength, shape, and size of wood. Moisture is possibly the most important characteristic when working with wood.   Since wood will absorb or release moisture depending on the surrounding environmental conditions, wood is a "hygroscopic" material (Stalnaker and Harris, 1997). That means that wood's moisture content will aim to reach equilibrium by approaching the temperature and humidity of the coexisting atmosphere. This is called Equilibrium Moisture Content (EMC).

The MC starts to change after a tree is cut. At this stage, the tree is deemed to be in the "green state," containing a substantial moisture. The moisture in the tree at this time is present in two distinct forms: "bound water" which is water existing within the cell walls and "free water" which is water found in the pores or vessels within the wood itself (Stalnaker and Harris, 1997, p. 29).

Right after the tree is felled, it starts losing free water. The fresh log does not show dimensional changes or contract because the fibers are still fully saturated with bound water (trapped in cells). The log will not shrink or contract until all the free water has been essentially depleted, and at this point, the wood will attain the "Fiber Saturation Point" (FSP) (Forest Products Laboratory, 2010, p. 233).

The following equation (after Breyer et al, 2007, p. 216) can be used to determine the moisture content of wood.

$$Moisture\ Content\ \% = \frac{weight\ of water\ in\ wood}{ovendry\ weight\ of\ wood} * 100$$

The size and shape of wood will be modified as MC increases. This occurs only up to the FSP. This is when the cell walls swell and the wood becomes larger. The opposite happens when MC decreases.

The impact of MC is adjusted by NDS, where the strength values for the lumber utilized in environments of high moisture content are lowered. As far as strength, tests have revealed that the strength of wood peaks at about 10 to 15 percent MC (Breyer et al., 2007, p. 34).

Durability

This section presents another factor that has a great influence on the mechanical properties of wood: time. Structures are expected to have a certain lifespan, involving the relationship between time and durability. To be more exact, it is the length of time a structure will last depending on durability in relation to wood and what could affect the life span of the wood. Durability in relation to wood refers to the ability of wood to resist natural decay elements and treatability.

A common misconception about the word durability in relation to wood or timber, is that durability is usually equated to the capacity of wood to resist scratches or dents. Scratches or dents will not destabilize a structure, and although they might be aesthetically unpleasing, they do not threaten the expected service life of a structure.

Decay

Decomposition can occur from microorganisms such as fungi, bacteria, or mold. Other factors include termites or other destructive insects.

Of the all the microorganisms, fungi (wood destroying fungi) is the most damaging because it can greatly affect the strength of a structure. Fungi feeds on the elements existing in the cell walls by destroying the cell walls and drastically undermining the strength of the wood. This type of damage is called decay and it can materialize at any time (Stalnaker & Harris, 1997, p. 369). Fungi can be present when the tree is alive, after it is cut, while in storage, or in the finished structure. There are four necessary elements for fungi to thrive: food supply, ample moisture, appropriate temperature, and oxygen. If any of these requirements is not present, decay will not take place (Breyer et al., 2007, p. 226).

A way to eliminate the food supply is by pressure treating wood, this method poisons the food source by impregnating chemicals into the lumber. This type of treatment is also effective against boring insects.

Decay is of great concern, especially in an existing structure, because even if a small portion of a structural member (e.g., beam or column) is affected, the member would be considered useless (Stalnaker & Harris, 1997, p. 370).

To prevent harm to wood, timber should be properly treated, or preventive construction and maintenance methods must be utilized.

Treatment

The application of wood preservatives, which are chemicals impregnated into the wood, can prevent or be very effective in delaying the decomposition of wood. The treatment methods include pressure and non-pressure applications, and though the non-pressure method is more economical, it is also less effective.

Figure D-1 provides an example of classifications of wood durability when in direct contact with soil. Durability also depends on the treatment or lack of treatment.

Based on Table D-1, the use of untreated cottonwood for Native American earth lodges falls into the classification of non-durable or perishable, but cottonwood was suitable for the purpose because the earth lodges were meant to have a service life of 10 years or less, and some were only occupied for one season. Certain earth lodges were

Table D-1. Wood Durability Classification (after Breyer et al., 2007)

Classification	**Service Life (in years)**
Very Durable	25 +
Durable	15 - 25
Moderately Durable	10 - 15
Non-Durable	5 - 10
Perishable	less than 5

used only as summer houses and some only as winter houses, and some houses were inadvertently lost due to prairie fires or warfare. Some were sturdily built, and others were less robust, depending on the expected usefulness of the earth lodge through time. Archaeologist Jay Sturdevant, acting director of the Knife River Indian Villages National Historic Site, noted that many earth lodges were built using driftwood along the Missouri and Knife Rivers because the wood was already cured, dried, and readily available (personal communication to Freddy Moran, August 7, 2017, Stanton, ND).

Species and species groups

The wood from many tree species that can be used in the production of structural timber, and because of the wide range of properties, it is important to choose the best suitable species for a distinct application. The decision about which type of wood to use is based mostly on what is available in a particular region.

Since there are a great variety of tree species in North America, a common practice for engineers is to use wood from a commercial "species group" instead of a specific species. The likely reason is that" same grading rules, reference design values, and grade stamp are applied to all species in the species group" (Breyer et al, 2007, p. 213).

A species group is composed of several individual species. The reference design values for a species group are tabulated employing statistical methods that provide conservative results for all the species existing in the group.

There are cases where the mark of one or several individual species might be incorporated in the grade stamp. A grade stamp represents the individual species or a group species with similar strengths.

The 2012 NDS Supplements (AWC) include a complete catalog of the species groups with a summary of the many individual species that would be included in each group. Figure E-1 shows examples of typical species groups with individual species.

Species Group Name and *Group Name Mark* that may appear in grade stamp	*Individual Species* that may be included in the Species Group and *Individual Species Mark* that may appear in grade stamp	Notes
Douglas Fir-Larch DOUG. FIR-L	Douglas Fir (D FIR) Western Larch (L)	Individual species mark for Douglas Fir may also appear as "DOUGLAS FIR" or "D. FIR"
Douglas Fir-Larch (N) D. FIR(N)	Douglas Fir[1] Western Larch[1]	(N) - indicates a Canadian species group
Douglas Fir South D FIR S	Douglas Fir South D FIR S	South indicates Douglas Fir grown in Arizona, Colorado, Nevada, New Mexico, and Utah
Hem-Fir HEM FIR	California Red Fir[1] Grand-Fir[1] Noble Fir[1] Pacific Silver Fir[1] Western Hemlock (HEM) White Fir[1]	
Hem-Fir (N) HEM-FIR-N	Amabilis Fir Western Hemlock	(N) - indicates a Canadian species group
Southern Pine SYP	Loblolly Pine[1] Longleaf Pine[1] Shortleaf Pine[1] Slash Pine[1]	Group mark is not used when graded under Southern Pine Inspection Bureau - grade stamp will show: SPIB
Spruce-Pine-Fir S-P-F	Alpine Fir[1] Balsam Fir[1] Black Spruce[1] Englemann Spruce[1] Jack Pine[1] Lodgepole Pine[1] Red Spruce[1] White Spruce[1]	Canadian species group
Spruce-Pine-Fir (S) SPF[S]	Balsam Fir[2] Eastern Spruce[2] Engelmann Spruce (ES) Jack Pine[1] Lodgepole Pine (LP) Red Pine[2] Sitka Spruce (SS)	(S) - indicates USA species group (established 1991). Eastern Spruce is any combination of Black Spruce, Red Spruce, and White Spruce.

Figure D-1. Species and group species (after Breyer et al., 2007)

<u>Size</u>

Size is a very important aspect of wood engineering because structural calculations are performed based on the standard net size from a section of wood. Size does not refer to the length of a piece lumber. Size refers to a cross section. The following figure shows a cross section of lumber displaying the sides that represent the width (height, *h*) and thickness (base, *b*).

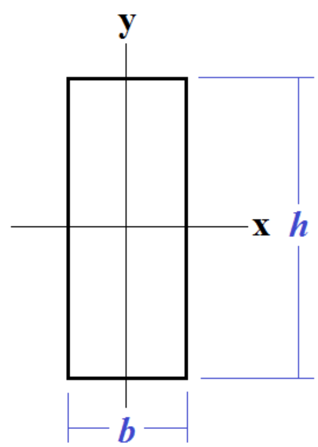

Figure D-2. Cross section components.

The design engineer may need to consider shrinkage when detailing connections, but standard dimensions are consented for stress calculations.

There are three types of lumber sizes: dressed, rough sawn, and full sawn.

<u>Dressed lumber</u>

Most of the wood used for structural design is called "dressed lumber," where the piece of lumber is shaved or surfaced from the nominal (actual) size to the standard net size. The most common method to dress lumber is S4S (the four sides are surfaced).

Here the wood section is placed on a planer machine, this process is used to smooth the surfaces and attain size uniformity.

Rough sawn lumber

Large pieces of lumber are usually rough sawn, where the lumber is not finished, and it is yet to be milled to its final dimensions. The final dimensions are very close to the standard net sizes. Usually the texture of the surface is not smooth, and this is sometimes a condition desired for architectural purposes. There are certain advantages for the use of rough sawn lumber:

- Cross sectional dimensions are approximately 1/8 inch larger than standard dressed sizes (Breyer et al, 2007, p. 231).
- Rustic appearance
- Lower environmental footprint

A problem that may arise when using rough sawn lumber as a structural component is that building to codes may be dimensional; therefore, extra paperwork is needed to prove its structural efficiency.

Full sawn lumber

Full sawn lumber has actual dimensions of the cross section that are the same as the specified. NDS does not include cross sectional properties for rough swan lumber because it is rarely used.

Figure D-3 illustrates the differences between the sizes previously discussed. The size of an 8 x 12 member (nominal size = 8" x 12") is used for purposes of comparison.

- Dressed Lumber:

    Standard net size = 7 ½" x 11 ½"

- Rough Sawn Lumber:

    Approximate size = 7 ⅝" x 11 ⅝"

- Full Sawn Lumber:

    Minimum size = 8" x 12"

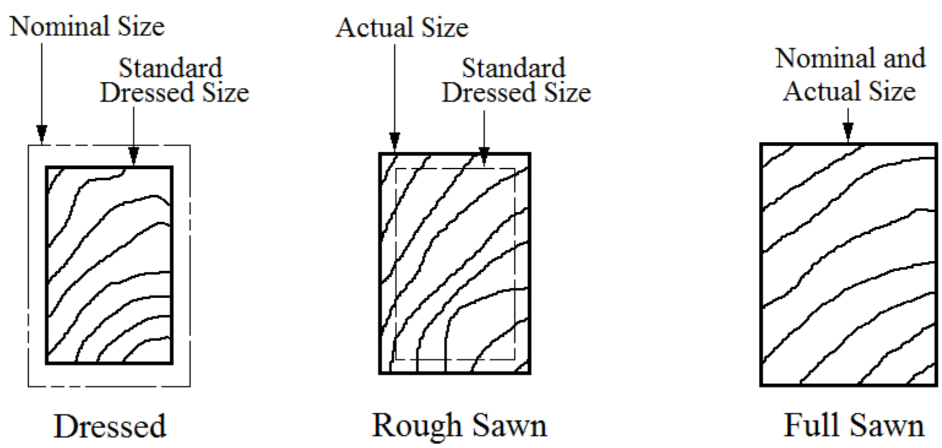

Figure D-3. Lumber size characteristics

<u>Size categories</u>

The mechanical properties of wood are known to change to a great degree between different trees, logs, and at times, even within the same trees or logs (Crocetti and Bergkvist, 2011, p. 53). Lumber is grouped into three size categories based on their cross-sectional dimensions (after Breyer et al., 2007):

- Boards:

    Thickness: 1 to 1 ½ inches

Width: 2 inches and wider

- Dimension Lumber:

  Thickness: 2 to 4 inches

  Width: 2 inches and wider

- Timbers:

  Thickness: 5 inches and thicker

  Width: 5 inches and wider

When considering size categories for structural applications, boards are very seldom used because they are too thin, therefore not ideal for framing.

For reasons of simplicity and economics, lumber of comparable mechanical properties is grouped in categories described as "stress grades". The stress grades are reference design values for the use in structural design. The purpose of this method is to anticipate the application a member would experience in construction. For instance, the moment of inertia depends mostly on the depth of a member, for this reason, a piece of lumber with a rectangular cross-section would be more efficient if intended to use as a beam when compared to a member with a square cross-section. Hence, if the final purpose for the use of the lumber were known, then the grading rules would take into consideration the intended primary purpose of the piece of lumber.

Reference design values for wood construction can be obtained from the 2012 NDS Supplement. Table D-2 containing the Reference Design Values for Visually Graded Dimension Lumber (NDS, 2012) shows the stress grade values for cottonwood, which is the type of wood used for the construction of the NA structures.

Table D-2. Allowable Stresses for Visually Graded Dimension Lumber (after AWC, 2012, Table 4-A).

USE WITH TABLE 4A ADJUSTMENT FACTORS

Species and commercial grade	Size classification	Design values in pounds per square inch (psi)							Specific Gravity[4]	Grading Rules Agency
		Bending	Tension parallel to grain	Shear parallel to grain	Compression perpendicular to grain	Compression parallel to grain	Modulus of Elasticity			
		F_b	F_t	F_v	$F_{c\perp}$	F_c	E	E_{min}	G	
BEECH-BIRCH-HICKORY										
Select Structural	2" & wider	1,450	850	195	715	1,200	1,700,000	620,000	0.71	NELMA
No. 1		1,050	600	195	715	950	1,600,000	580,000		
No. 2		1,000	600	195	715	750	1,500,000	550,000		
No. 3		575	350	195	715	425	1,300,000	470,000		
Stud	2" & wider	775	450	195	715	475	1,300,000	470,000		
Construction	2" - 4" wide	1,150	675	195	715	1,000	1,400,000	510,000		
Standard		650	375	195	715	775	1,300,000	470,000		
Utility		300	175	195	715	500	1,200,000	440,000		
COAST SITKA SPRUCE										
Select Structural	2" & wider	1300	950	125	455	1200	1,700,000	620,000	0.43	NLGA
No. 1/ No. 2		925	550	125	455	1100	1,500,000	550,000		
No. 3		525	325	125	455	625	1,400,000	510,000		
Stud	2" & wider	725	450	125	455	675	1,400,000	510,000		
Construction	2" - 4" wide	1050	650	125	455	1300	1,400,000	510,000		
Standard		600	350	125	455	1100	1,300,000	470,000		
Utility		275	175	125	455	725	1,200,000	440,000		
COTTONWOOD										
Select Structural	2" & wider	875	525	125	320	775	1,200,000	440,000	0.41	NSLB
No. 1		625	375	125	320	625	1,200,000	440,000		
No. 2		625	350	125	320	475	1,100,000	400,000		
No. 3		350	200	125	320	275	1,000,000	370,000		
Stud	2" & wider	475	275	125	320	300	1,000,000	370,000		
Construction	2" - 4" wide	700	400	125	320	650	1,000,000	370,000		
Standard		400	225	125	320	500	900,000	330,000		
Utility		175	100	125	320	325	900,000	330,000		

The Table D-2 shows the allowable stresses that should never be exceeded because of potential failure of the member. For this reason, Table D-2 requires Adjustment Factors.

Adjustment factors

The strength of wood members is affected by conditions such as moisture content, temperature, shrinkage, member size, and several other factors. The numbers given in the Reference Design Value tables are primarily a beginning point to determine the allowable stress for a particular member. To account for the factors affecting the strength and mechanical properties of wood, the initial design values need to be adjusted to remain under the allowable stress.

The effect of the adjustment factors can provide different results on the reference design values, sometimes it will cause the reference design values to decrease, and some others to increase. This is of great importance, because if the adjustment factors reduce the strength, then a larger size member will be needed to support the initial calculated load.

The NDS Specification lists fourteen types of adjustment factors, the large number is intended to remind the engineer not to neglect something that may impede the optimum performance of a structural member.

The following are the fourteen adjustment factors listed in the NDS Specification (after Stalnaker & Harris, 1997).

C_M : wet service factor

C_D : load duration factor

C_F : size factor

C_r : repetitive member factor

C_{fu} : flat use factor

C_t : temperature factor

C_i : incising factor

C_v : volume factor

C_L : beam stability factor

C_p : column stability factor

C_c : curvature factor

C_f : form factor

C_H : shear stress factor

C_T : buckling stiffness factor

C_b : bearing area factor

The adjustment factors do not always apply to all the reference design values. A brief description of each factor will be given in this paper.

Wet Service Factor, C_M

Moisture content of wood was previously described in subchapter 2.2.2.

Load Duration Factor, C_D

The strength of wood changes with the duration of a load. Because of the unique structural property of wood, it may support higher stresses if the load is placed for a short period.

Size Factor, C_F

As a general rule, a smaller member has a greater unit of strength than a larger member. The size factor is based on the size classification.

Repetitive Member Factor, C_r

Repetitive members are those that are placed closely together, parallel to each other. This arrangement enables the members to share the load, where if a weaker member cannot carry the load, and adjacent stiffer, stronger member can help. Certain conditions need to be met:

- No less than three members arranged in parallel sequence
- Members spaced at no more than 24 inches
- Members are joined by roof, floor, or other form of load distributing system.

Flat Use Factor, C_{fu}

This factor is considered when a member is placed edgewise, when dimension lumber is placed in this manner and the load is applied perpendicular to the wide side, a flat use factor is used to only the bending value.

- Temperature Factor, C_t

Temperature factor applies only when members are exposed to temperatures greater than 100°F for long periods of time. Allowable stress and modulus of elasticity will be adjusted,

Incising Factor, C_i

Some species easily accept pressure treatment, while others may not. This factor is applied when incising is used to increase the penetration of the protective chemicals, in this case, design values for Dimension Lumber need be adjusted.

Volume Factor, C_v

This only applies to glulam members. Instead of using the size factor, a volume factor is applied to adjust the design value for allowable bending stress (F_b).

Beam Stability Factor, C_L

This factor applies only when a beam is not properly laterally supported to prevent lateral buckling.

Column Stability Factor, C_p

This is a reducing factor that considers the potential for buckling on slender columns.

Curvature Factor, C_c

Only applies to glulam members.

Form Factor, C_f

Applies to bending members with circular or diamond shape cross-sections.

Shear Stress Factor, C_H

This factor adjusts the allowable horizontal shear stress for sawn lumber and timber sections.

Buckling Stiffness Factor, C_T

This factor applies exclusively to the modulus of elasticity of some specific trusses.

Bearing Area Factor, C_b

Applies only to the allowable compressive stress ($F_{C\perp}$) when perpendicular to the grain.

REFERENCES

Ahler, S. A. (1978). A research plan for investigation of the archaeological resources of the Knife River Indian Villages National Historic Site. Ms. on file, National Park Service, Midwest Archaeological Center, Lincoln, NE

Ahler, S. A. (1984). Archaeological research at the Knife River Indian Villages National Historic Site. Progress report for the period October 1 through December 31, 1983. Ms. on file, National Park Service, Midwest Archaeological Center, Lincoln, NE

American Society of Civil Engineers (ASCE) (2010). Minimum design loads for buildings and other structures: sei/asce 7-10. ASCE, Reston, VA. https://doi.org/10.1061/9780784412916

American Wood Council (2012a). ASD/LRFD [Allowable Stress Design/Load and Resistance Factor Design]. ASD/LRFD manual for engineered wood construction. American Wood Council, Leesburg, VA. www.awc.oorg/codes-standards/publications/nds-2012

American Wood Council (2012b). ASD/LRFD [Allowable Stress Design/Load and Resistance Factor Design].ASD/LRFD NDS [National Design Specifications] for wood construction. American Wood Council, Leesburg, VA. www.awc.oorg/codes-standards/publications/nds-2012

American Wood Council (2012c). ASD/LRFD [Allowable Stress Design/Load and Resistance Factor Design]. Supplement NDS [National Design Specifications] design values for wood construction. American Wood Council, Leesburg, VA. www.awc.oorg/codes-standards/publications/nds-2012

American Wood Council (2012d). ASD/LRFD [Allowable Stress Design/Load and Resistance Factor Design] ASD/LRFD wind & seismic special design provisions with commentary. American Wood Council, Washington, DC. www.awc.oorg/codes-standards/publications/nds-2012

Breyer, D. E., Fridley, J. F., Cobeen, K. E., & Pollack Jr., D. G. (2007). Design of wood structures, ASD/LRFD. McGraw-Hill, New York, NY.

Calabrese, F. A., "Knife River Indian Villages Archaeological Program: An Overview" (1987). *Anthropology Faculty Publications.* Paper 110. http://digitalcommons.unl.edu/anthropologyfacpub/110

Crocetti, R. and Bergkvist, P. (2011). Design of timber structures. Swedish Forest Industries Federation, Stockholm, Sweden.

Energy - American Petroleum Institute (API) (2008, June). Spring ballot results. Subcommittee on Aboveground Storage Tanks. Modified November 24, 2009 by gvyoung@api.gov. http://mycommittees.api.org/standards/cre/scast/Meeting%20Materials/Spring08/08spring620ballotresults.zip

Forest Products Laboratory (2010). Wood handbook—Wood as an engineering material. General Technical Report FPL-GTR-190. U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, WI. www.woodweb.com/Resources/wood_eng_handbook/wood_handbook_fpl_2010.pdf

George Catlin.org (2017). George Catlin. http://www.georgecatlin.org/the-complete-works.html

Holloway, D. R. (2017). Dennis R. Holloway, Architect; Earth lodge prototype, Mandan-Hidatsa-Arikara cultures, North Dakota. www.dennisrhollowayarchitect.comj/mandanarikarahidatsa .html

Hurt, W. (1974). The Rosa Site (revised ed.) Sigstad, J. S. and Sigstad, J. K., eds. Archaeological Circular No. 9. Archaeological Research Center, Department of Education and Cultural Affairs, Vermillion, SD.

International Building Code (IBC). (2012). IBC: 2012. IBC, Country Club Hills, IL.

Joslyn Art Museum (2017). Images and descriptions [Karl Bodmer]. https://www.joslyn.org/Post/sections/400/Files/Image%20Descriptions.pdf

Martin, K. G., Gupta, R., Prevatt, D. O., Datin, P. L., & Lindt, J. W. (2011). Modeling System Effects and Structural Load Paths in a Wood-Framed Structure. Journal of Architectural Engineering,*17*(4), 134-143. doi:10.1061/(asce)ae.1943-5568.0000045

Nabokov, P and Easton, R. (1989). Native American architecture. London, EN: Oxford University Press.

National Park Service (2017a). Knife River Indian Villages National Historic Site North Dakota. https://www.nps.gov/knri/index.htm

National Park Service (2017b). Map, Knife River Indian Villages National Historic Site North Dakota. https://www.nps.gov/maps/embed.html?alpha=knri&mapId=d227494d-87cc-489c-ad4e-7a861cec6ca6

North Dakota State University Archaeology Technologies Laboratory (2005). Like-A-Fishhook/Fort Berthold reconstruction. North Dakota State University, Fargo, ND. http://fishhook.ndsu.edu/home/

Sigstad, J. S. and J. K. (1972). Archaeological field notes of W. H. Over. Research Bulletin Number 1. Vermillion, SD: State Archaeologist, Department of Education and Cultural Affairs, State of South Dakota.

Slator, B., Clark, J., Landrum, J., Bergstrom, A., Hawley, J., Johnston, E., & Fisher, S. (2001). Teaching with immersive virtual archaeology. Proceedings Seventh International Conference on Virtual Systems and Multimedia. doi:10.1109/vsmm.2001.969679

Stalnaker, J. J., & Harris, E. C. (1997). Structural design in wood. Chapman and Hall, New York, NY.

Wilson, G. L. (1934). The Hidatsa earthlodge. B. Wietzner (Arranger and Editor). *Anthropological Papers of the American Museum of Natural History, 33*(pt.5), pp 341-420 (with pocket in cover sketches, Figures 1-27, n. p.). New York City, NY. http://hdl.handle.net/2246/137