

NONDESTRUCTIVE EVALUATION OF OKLAHOMA
STATE UNIVERSITY COLVIN CENTER ANNEX
DECAYED TIMBER ARCHES

By

SARAH REBECCA MARKES

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1999

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2001

COPYRIGHT

By

Sarah Rebecca Markes

December, 2001

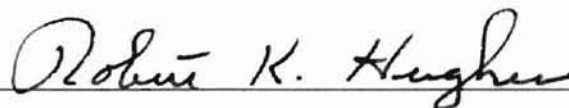
NONDESTRUCTIVE EVALUATION OF OKLAHOMA
STATE UNIVERSITY COLVIN CENTER ANNEX
DECAYED TIMBER ARCHES

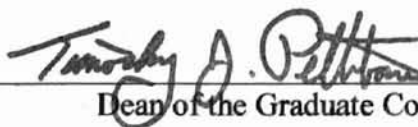
Thesis Approved:



Thesis Advisor







Dean of the Graduate College

PREFACE

This study was conducted to evaluate the condition of the Oklahoma State University Colvin Center Annex glued-laminated arches. Throughout the 27-year lifespan of the building, many adverse weather conditions have caused decay throughout the exposed ends of the arches. The objective of this study was to determine the amount of decay in individual laminations of each arch by employing through-transmission stress wave technology. From this data collection, recommendations were made to Oklahoma State University officials regarding possibilities for restoration of the existing structure considering economical issues as well as safety. This information will help the university make a final decision on the issue.

I would sincerely like to thank Dr. Robert Emerson for his unconditional help through all of my thesis work. He has been an excellent mentor, as well as a friend. Not only have I learned a great deal of knowledge from him, but I have also learned patience and perseverance. Also, thanks to my committee, Dr. Robert Hughes and Dr. Steve Gipson, for responding quickly when I needed them. Finally, I want to thank the Oklahoma State University Physical Plant, especially John Houck, for their trust in my abilities of completing this undertaking, and for their financial backing throughout the project.

TABLE OF CONTENTS

Chapter	Page
1 HISTORY.....	1
1.1 Environmental Exposure.....	1
1.2 Uses of Colvin Center Annex.....	2
1.3 Objectives.....	2
2 TESTING PROCEDURES.....	3
2.1 Layout of Test Spots.....	3
2.2 Testing Techniques.....	4
2.3 Effect of Decay on Material Properties.....	5
2.4 SigmaPlot 2000.....	7
2.5 Microsoft Excel Worksheets.....	8
3 ANALYSIS OF NORMALIZED GLULAMS.....	10
3.1 Summary.....	10
4 INDIVIDUAL ANALYSIS OF EACH GLULAM.....	11
4.1 Glulam 0.....	11
4.2 Glulam 1.....	13
4.3 Glulam 2.....	15
4.4 Glulam 3.....	17
4.5 Glulam 4.....	19

Chapter	Page
4.6 Glulam 5.....	21
4.7 Glulam 6.....	23
4.8 Glulam 7.....	25
4.9 Glulam 8.....	27
4.10 Glulam 9.....	29
4.11 Glulam 10.....	31
4.12 Glulam 11.....	33
4.13 Glulam 12.....	35
4.14 Glulam 13.....	37
4.15 Glulam 14.....	39
4.16 Glulam 15.....	41
4.17 Glulam 16.....	43
4.18 Glulam 17.....	45
4.19 Glulam 18.....	47
4.20 Glulam 19.....	49
4.21 Glulam 20.....	51
4.22 Glulam 21.....	53
4.23 Glulam 22.....	55
4.24 Glulam 23.....	57
4.25 Glulam 24.....	59
4.26 Glulam 25.....	61
5 CONCLUSIONS.....	63
5.1 Summary.....	63

Chapter	Page
5.2 Recommendations.....	63
5.3 Conclusions.....	65
BIBLIOGRAPHY.....	66

LIST OF TABLES

Table	Page
2.2 Strength Capacity Remaining in Wood as Decay Level Increases.....	7
2.5 Excerpt of Excel Worksheet Calculations for Glulam 21.....	9
4.1 Test Conditions of Glulam 0.....	11
4.2 Test Conditions of Glulam 1.....	13
4.3 Test Conditions of Glulam 2.....	15
4.4 Test Conditions of Glulam 3.....	17
4.5 Test Conditions of Glulam 4.....	19
4.6 Test Conditions of Glulam 5.....	21
4.7 Test Conditions of Glulam 6.....	23
4.8 Test Conditions of Glulam 7.....	25
4.9 Test Conditions of Glulam 8.....	27
4.10 Test Conditions of Glulam 9.....	29
4.11 Test Conditions of Glulam 10.....	31
4.12 Test Conditions of Glulam 11.....	33
4.13 Test Conditions of Glulam 12.....	35
4.14 Test Conditions of Glulam 13.....	37
4.15 Test Conditions of Glulam 14.....	39
4.16 Test Conditions of Glulam 15.....	41
4.17 Test Conditions of Glulam 16.....	43
4.18 Test Conditions of Glulam 17.....	45

Table	Page
4.19 Test Conditions of Glulam 18.....	47
4.20 Test Conditions of Glulam 19.....	49
4.21 Test Conditions of Glulam 20.....	51
4.22 Test Conditions of Glulam 21.....	53
4.23 Test Conditions of Glulam 22.....	55
4.24 Test Conditions of Glulam 23.....	57
4.25 Test Conditions of Glulam 23.....	59
4.26 Test Conditions of Glulam 25.....	61

LIST OF FIGURES

Figure	Page
2.1. Layout of Test Spots for Each Glulam.....	4
2.2. Captured Stress Wave on <i>Fluke</i> 192 Scopemeter.....	5
4.1.1 Field Picture of Glulam 0.....	11
4.1.2 Glulam 0 Graphs.....	12
4.2.1 Field Picture of Glulam 1.....	13
4.2.2 Glulam 1 Graphs.....	14
4.3.1 Field Picture of Glulam 2.....	15
4.3.2 Glulam 2 Graphs.....	16
4.4.1 Field Picture of Glulam 3.....	17
4.4.2 Glulam 3 Graphs.....	18
4.5.1 Field Picture of Glulam 4.....	19
4.5.2 Glulam 4 Graphs.....	20
4.6.1 Field Picture of Glulam 5.....	21
4.6.2 Glulam 5 Graphs.....	22
4.7.1 Field Picture of Glulam 6.....	23
4.7.2 Glulam 6 Graphs.....	24
4.8.1 Field Picture of Glulam 7.....	25
4.8.2 Glulam 7 Graphs.....	26
4.9.1 Field Picture of Glulam 8.....	27
4.9.2 Glulam 8 Graphs.....	28
4.10.1 Field Picture of Glulam 9.....	29
4.10.2 Glulam 9 Graphs.....	30
4.11.1 Field Picture of Glulam 10.....	31
4.11.2 Glulam 10 Graphs.....	32

Figure	Page
4.12.1 Field Picture of Glulam 11.....	33
4.12.2 Glulam 11 Graphs.....	34
4.13.1 Field Picture of Glulam 12.....	35
4.13.2 Glulam 12 Graphs.....	36
4.14.1 Field Picture of Glulam 13.....	37
4.14.2 Glulam 13 Graphs.....	38
4.15.1 Field Picture of Glulam 14.....	39
4.15.2 Glulam 14 Graphs.....	40
4.16.1 Field Picture of Glulam 15.....	41
4.16.2 Glulam 15 Graphs.....	42
4.17.1 Field Picture of Glulam 16.....	43
4.17.2 Glulam 16 Graphs.....	44
4.18.1 Field Picture of Glulam 17.....	45
4.18.2 Glulam 17 Graphs.....	46
4.19.1 Field Picture of Glulam 18.....	47
4.19.2 Glulam 18 Graphs.....	48
4.20.1 Field Picture of Glulam 19.....	49
4.20.2 Glulam 19 Graphs.....	50
4.21.1 Field Picture of Glulam 20.....	51
4.21.2 Glulam 20 Graphs.....	52
4.22.1 Field Picture of Glulam 21.....	53
4.22.2 Glulam 21 Graphs.....	54
4.23.1 Field Picture of Glulam 22.....	55
4.23.2 Glulam 22 Graphs.....	56
4.24.1 Field Picture of Glulam 23.....	57
4.24.2 Glulam 23 Graphs.....	58
4.25.1 Field Picture of Glulam 24.....	59
4.25.2 Glulam 24 Graphs.....	60
4.26.1 Field Picture of Glulam 25.....	61
4.26.2 Glulam 25 Graphs.....	62

LIST OF EQUATIONS

Equation	Page
2.1 $V = \sqrt{\frac{E * g}{\rho}}$	5

1. INTRODUCTION

In this thesis project, glued-laminated arches on the Oklahoma State University Annex were analyzed to determine the amount of decay present in each. A previous visual inspection of the beams by an outside source found serious amounts of decay throughout each glulam. The idea of this research is to prove or disprove the amount of decay present in these members by performing a nondestructive analysis of the internal conditions of the beams. From this information, Oklahoma State University Officials can make a final decision to keep or discard the structure.

1.1 Environmental Exposure

The Colvin Center Annex, located on the Oklahoma State University Campus, has been subjected to many adverse and differing Oklahoma weather conditions. When the structure was constructed, the 13 wood glued-laminated (glulam) arches were built with the bottom 7-feet of each end exposed to the environment. Water runs off the roof directly onto this exposed area and collects in the steel casing at the base of each glulam. Due to the ever-changing weather and above-mentioned lack of protection from precipitation, these members of the building have become decayed. Almost all of the glulams have some amount of decay, and that level is the desired information found using the following procedure.

1.2 Uses of Colvin Center Annex

The Annex has been used for many activities within the university, therefore historical and sentimental significance have been placed on the structure. Intramural sports, varsity athletic training, and summer camps are just a few of the numerous activities that take place in the building every year. With the growing demand for athletic facilities, the Annex has much physical importance as well. For these reasons, a structure of this nature is needed for the Oklahoma State University community, and, if the existing building can be salvaged, money could be saved for OSU.

1.3 Objectives

The goal of this study is to nondestructively identify the amount of decay present in each exposed glulam arch and to pinpoint specific areas of major concern. A previous visual analysis by a contracted company showed that decay existed throughout the length of the exposed glulams. The results of this research on the Annex will prove or disprove this spectral evaluation and will allow Oklahoma State University officials to effectively retrofit the structure by concentrating on the problematic areas. This protection should elongate the existence of the structure allowing the building to remain in service, and the university can postpone the cost of a new structure.

© 2014 by S. J. D. Inc.

2. TESTING PROCEDURE

Twenty-six exposed glued-laminated timber segments were nondestructively inspected to locate and quantify decay. Inspection points were marked along each lamination being inspected. Through-transmission stress waves were sent through the wood at each of these locations. The apparent velocity of each wave was captured using a hand held digital oscilloscope (*Fluke 192 Scopemeter*,) and these values were then graphed on color and black-and-white contour diagrams, where decayed regions could be easily identified.

2.1 Layout of Test Spots

To begin evaluating the decay in the arches, a grid of proposed test spots was delineated. Each glued-laminated timber arch is composed of 2x10 pieces of dimension lumber in 21 laminations. Four-inch increments along each lamination were used for the 80-inches of exposed wood on each lamination to give an accurate but efficient sampling of the material throughout each exposed arch section. Therefore, 20 different spots were analyzed on each of the 21 laminations, totaling 420 test locations per member. When constructing the graphs used for analysis, this amount of test locations depicted the decayed regions precisely. As mentioned above, a total of 26 different segments of glulam were evaluated using the layout depicted in Figure 2.1.

A1	A2	A3	A4	A5	A6	A7	A8	A9	A10	A11	A12	A13	A14	A15	A16	A17	A18	A19	A20
B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	B11	B12	B13	B14	B15	B16	B17	B18	B19	B20
C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20
D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14	D15	D16	D17	D18	D19	D20
E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	E17	E18	E19	E20
F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11	F12	F13	F14	F15	F16	F17	F18	F19	F20
G1	G2	G3	G4	G5	G6	G7	G8	G9	G10	G11	G12	G13	G14	G15	G16	G17	G18	G19	G20
H1	H2	H3	H4	H5	H6	H7	H8	H9	H10	H11	H12	H13	H14	H15	H16	H17	H18	H19	H20
I1	I2	I3	I4	I5	I6	I7	I8	I9	I10	I11	I12	I13	I14	I15	I16	I17	I18	I19	I20
J1	J2	J3	J4	J5	J6	J7	J8	J9	J10	J11	J12	J13	J14	J15	J16	J17	J18	J19	J20
K1	K2	K3	K4	K5	K6	K7	K8	K9	K10	K11	K12	K13	K14	K15	K16	K17	K18	K19	K20
L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16	L17	L18	L19	L20
M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	M15	M16	M17	M18	M19	M20
N1	N2	N3	N4	N5	N6	N7	N8	N9	N10	N11	N12	N13	N14	N15	N16	N17	N18	N19	N20
O1	O2	O3	O4	O5	O6	O7	O8	O9	O10	O11	O12	O13	O14	O15	O16	O17	O18	O19	O20
P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20
Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Q13	Q14	Q15	Q16	Q17	Q18	Q19	Q20
R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20
S1	S2	S3	S4	S5	S6	S7	S8	S9	S10	S11	S12	S13	S14	S15	S16	S17	S18	S19	S20
T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19	T20
U1	U2	U3	U4	U5	U6	U7	U8	U9	U10	U11	U12	U13	U14	U15	U16	U17	U18	U19	U20

Figure 2.1: Layout of Test Spots for Each Glulam (not to scale)

2.2 Testing Technique

The amount of decay in a wood beam can be determined nondestructively using several methods. Some of these include visual inspection, sounding, drill resistance, stress wave, ultrasound, radiography, microwave/ground penetrating radar, and vibration. The technique selected in this research was stress wave technology, using a *Fluke192* Scopemeter digital oscilloscope and metriguard stress wave timing equipment. These instruments were employed with “through-transmission” technology, where a wave is generated on one surface of the member, propagates through the member, and is recorded on the opposite surface. A hammer instrumented with an accelerometer was used to impose an initial stress wave. The accelerometer in the hammer senses the imposed stress wave and activates recording in the digital oscilloscope. The stress wave traveled

through the material, and the receiving accelerometer captured and converted the stress wave's mechanical energy into electrical energy that was sent to the oscilloscope. As

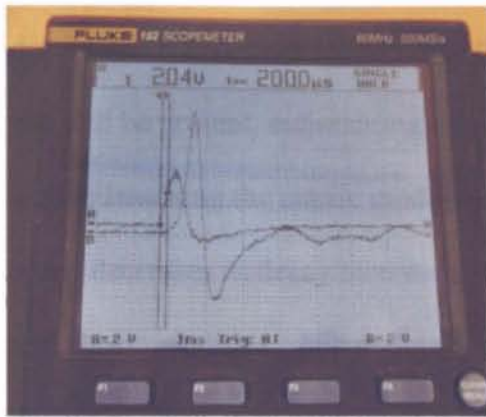


Figure 2.2: Captured Stress Wave on Fluke 192 Scopemeter

shown in Figure 2.2, the initial strike began a stress wave for both the hammer and its accelerometer, with the hammer's wave, wave A, rising as the signal was sent. When the accelerometer in the receiver sensed the wave, the second wave, wave B, ascended similarly to the hammer's wave. The time between the fronts of the waves shown as the time between the two

vertical lines in Figure 2.2 was recorded for each test spot. This wave travel time for each location was then divided by the distance through which the wave traveled giving the velocity of the stress wave. The calculated velocity provided the necessary information to locate and predict the amount of decay present throughout each glulam.

2.3 Effect of Decay on Material Properties

The travel time of each wave is dependent on the material properties of the wood. The velocity (V) of a stress wave in a material is proportional to the material density (ρ) and elastic modulus (E), as seen in Equation 2.1.

Equation 2.1
$$V = \sqrt{\frac{E * g}{\rho}}$$

where g is acceleration due to gravity.

Decay in wood decreases both the density and elastic modulus. The elastic modulus is defined as the force needed to elongate a material, and the density is the amount of substance contained within a specific area. In a decaying material, elastic modulus diminishes much more rapidly than the density because the substance, in this case, wood, can still be present, maintaining the density, but the decay fungi make the wood more brittle, lessening the elastic modulus. Therefore, the velocity of a stress wave through wood decreases as decay increases. Wood containing early decay has diminished density and elastic modulus while maintaining the physical wood structure. Wood having advanced decay may have voids due to complete degradation of internal wood structure. Adjacent regions of early to moderate decay usually accompany these fully decomposed areas, which can be seen later in the color contour diagrams of each glulam. Severely decayed wood contains voids, which the wave must travel around, creating a longer travel time, and consequently, a smaller apparent velocity. In comparison, sound wood allows the wave to travel in a straight line, resulting in a shorter travel time and higher velocity. Hues of light blue, green, and yellow frequently surround areas of red and orange, indicating the above-mentioned levels of decay.

When considering the different levels of decay, early, moderate, advanced, or severe decay were the tiers chosen for comparison. In each of these tiers, a corresponding change in modulus of elasticity (MOE) and in compressive strength has been determined based on previous studies by Emerson (1999), and Ross (1982). These approximate values in Table 2.2 give an idea of the strength capacity remaining in the wood.

% Change in Velocity	Stage of Decay	% Change in MOE	% Change in Comp. Strength
0	Sound Wood	0	0
-5 to -24	Early	< -5	< -15
-25 to -74	Moderate	< -60	< -40
-75 to -99	Advanced	< -80	< -80
< -100	Severe	< -100	< -100

Table 2.2: Strength Capacity Remaining in Wood as Decay Levels Increase

Various levels of decay were identified during this investigation. In some cases, the wood was completely decayed resulting in severe decay, and, consequently, 100% reduction in compressive strength. As seen later, much of the decay is early or moderate, so a 15% to 40% loss in compressive strength results; but this deficit does not result in imminent structural failure, especially since the decay is spaced sporadically throughout each member and surrounded by structurally sound members, in most cases.

2.4 SigmaPlot 2000

After all the wave travel time information was collected for each glulam, the numbers were entered into a program, SigmaPlot 2000 (SPSS Inc., 2000). Three columns of data were used: horizontal and vertical locations on the grid, and stress wave travel time. All 420 grid locations were entered on this program for each individual glulam, and color and black-and-white contour graphs were plotted using the three columns of data. On the graphs, the appropriate axes are labeled in inches with the vertical and horizontal locations. The measured travel times ranged from just under 100 seconds up to 5000 seconds, where a value was merely assigned for completely decayed wood. When these numbers were plotted in SigmaPlot 2000, the graphs did not accurately display the

information comparatively to the other arches. In some of the color contour diagrams, a red area could indicate a very high travel time in comparison with all of the glulams; on another diagram, a red area could merely suggest a high travel time on that glulam when the area might not actually have that significant of a travel time. This flaw in the program could have been avoided if one color could be assigned to a certain travel time value. However, since this problem could not be resolved, the dilemma was accounted for when analyzing the diagrams by concentrating primarily on Microsoft Excel Worksheets, where algorithms were entered to identify levels of decay in specific regions.

2.5 Microsoft Excel Worksheets

After the travel times were put into SigmaPlot 2000, a comparison of travel times to loss in material properties was performed. To do this, all times were put into Microsoft Excel, where the velocity was calculated by dividing the width of the arch, 9.5-inches, by the travel time. A sample of the excel worksheets is outlined in Table 2.5. After calculating the individual velocities, these velocities were compared to the velocities through sound wood, which was assumed to be located in the last 4-inches of each arch closest to the building. The location of the sound wood areas is apparent in the last column, column 20, of Table 2.5. This area was chosen as a sound wood comparison since little to no precipitation reaches the region that would result in decay.

A percent change in velocity was the desired information in these charts because, from this data, a comparison could be made between loss in modulus of elasticity, and, finally,

loss in compressive strength. In the Excel charts, the percent change in velocity, for example, at location A1, was calculated by subtracting the velocity of A20 from the velocity of A1, giving the change in decay from sound wood to decayed wood; that value was then divided by the velocity of A20. To give a percent change in velocity, this result was multiplied by 100. A stage of decay was assigned, based on Table 2.2, to the percent change in velocity depending on how much or how little the change. The differences between these decayed velocities versus sound wood velocities were correlated with the loss in material properties outlined in Table 2.2. In this example, three of the four levels of decay are present in the first 4-inches of the glulam. The correlating changes in compressive strength and modulus of elasticity show up to 80% reduction, which is cause for alarm. All of the individual glulam analysis is seen in Section 4 where all glulams are analyzed in depth.

Location	Time (ms)	Time (s)	Distance (in)	Velocity (in/s)	% Change in Velocity	Stage of Decay	Change in MOE	Change In Comp. Strength
A1	176	0.000176	9.5	53977	-11.36	E	5	15
B1	192	0.000192	9.5	49479	-33.33	M	60	40
C1	208	0.000208	9.5	45673	-38.46	M	60	40
D1	360	0.00036	9.5	26389	-58.89	M	60	40
E1	364	0.000364	9.5	26099	-56.04	M	60	40
F1	324	0.000324	9.5	29321	-53.09	M	60	40
G1	1000	0.001	9.5	9500	-86.00	A	80	80
H1	1000	0.001	9.5	9500	-86.00	A	80	80
I1	516	0.000516	9.5	18411	-72.87	M	60	40
J1	508	0.000508	9.5	18701	-72.44	M	60	40
K1	484	0.000484	9.5	19628	-70.16	M	60	40

Table 2.5: Excerpt of Excel Worksheet Calculations for Glulam 21

3. ANALYSIS OF NORMALIZED GLULAMS

3.1 Summary

An aspect of consideration when analyzing glulams is the wood grain orientation of each individual lamination. Different directions of wood grains can alter stress wave travels, therefore varying travel times. To combat this discrepancy, all test locations were normalized to create an accurate comparison between laminations. To normalize a glulam, each individual travel time was divided by the travel time through sound wood of that lamination. For example, in lamination A, travel times through locations A1 through A19 are divided by travel time through location A20. This procedure is repeated for each individual location on every lamination. This step resulted in a value that compares to every other test spot on the glulam. Most areas maintain some amount of decay, which results in a normalized value greater than one. All normalized color and black-and-white contour diagrams can be seen following the regular diagrams of each glulam. A direct correlation can be seen between the areas of decay explained in the discussion of each glulam and the normalized graphs. The reason for this is due to the normalization of every test location. By normalizing the glulams, an even comparison is created between each lamination as opposed to the regular diagrams where inherent variation between laminations result in stress waves traveling at varying speeds from lamination to lamination. This normalizing of the glulams eliminates this discrepancy.

4. INDIVIDUAL ANALYSIS OF EACH GLULAM

4.1 Glulam 0

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
0	09/19/00	95	none	13

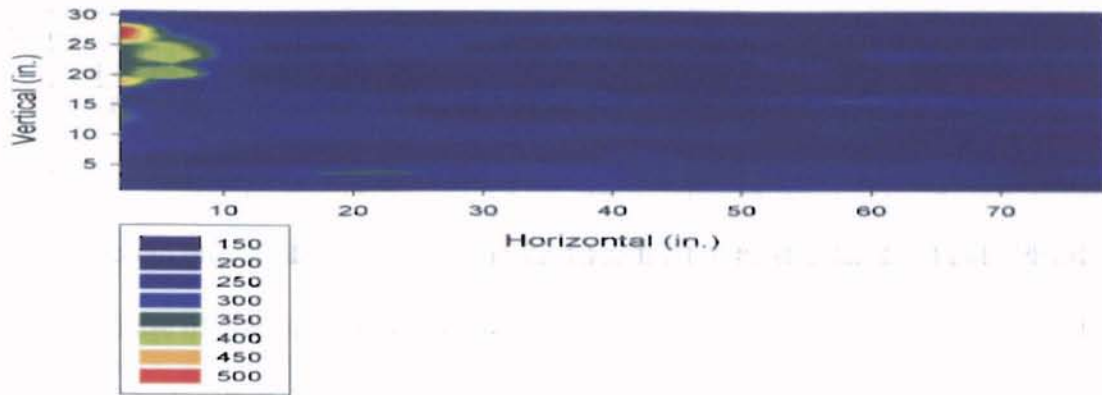
Table 4.1: Test conditions of Glulam 0.

In Glulam 0, a small amount of decay is present throughout most of the member. In the first eight inches, a pocket of advanced decay exists. This critical area can be seen as completely decomposed areas in the field picture. This advanced area is surrounded by regions of moderate and early decay and should be flagged since the connection between the member and the ground is made in this locale. Throughout the remainder of this component, early to moderate decay is often present, but few areas of concern exist. Lamination O is an exception, though, because moderate decay exists throughout the mid-section of the entire piece up to about 20-inches from the top. This decay is indicated on the color contour diagram as a light blue region just above the 10-inch vertical mark. Sometimes these middle areas of slower travel time indicate a natural knot in the wood, but, in this case, the entire lamination is affected, so decay is most likely present.

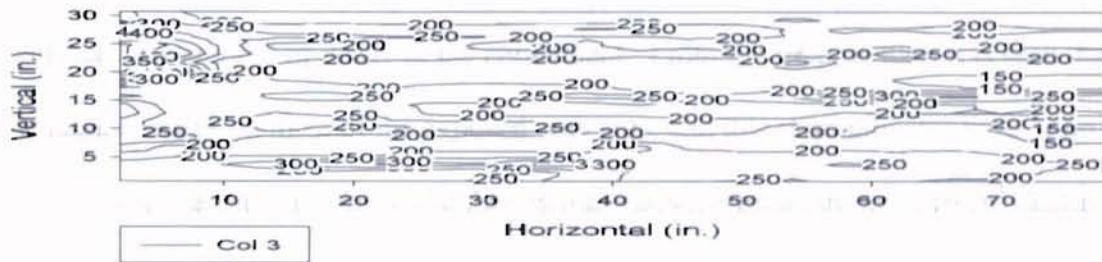


Figure 4.1.1: Field picture of Glulam 0.

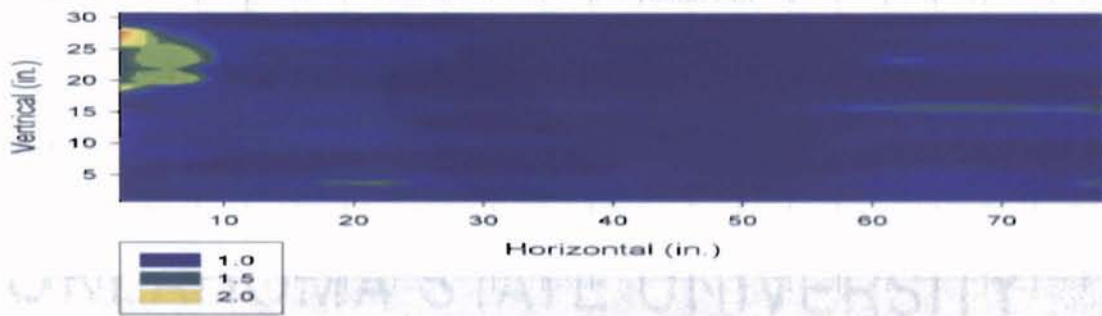
Glulam 0 Graph



Glulam 0 Contour



Glulam 0 Normalized



Glulam 0 Normalized Contour

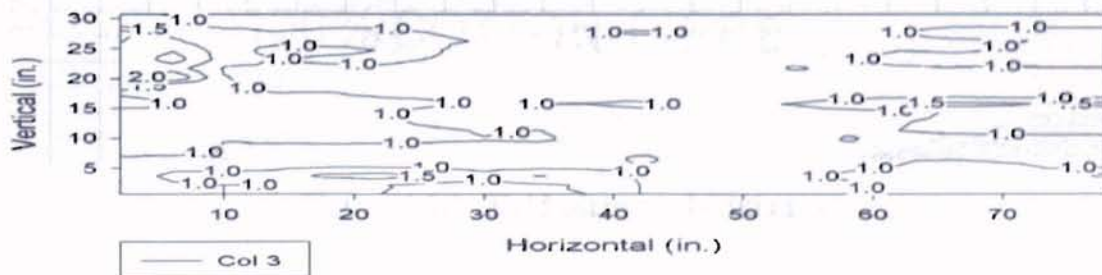


Figure 4.1.2: Glulam 0 Graphs

4.2 Glulam 1

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
1	08/09/00	90	none	14

Table 4.2: Test conditions of Glulam 1.

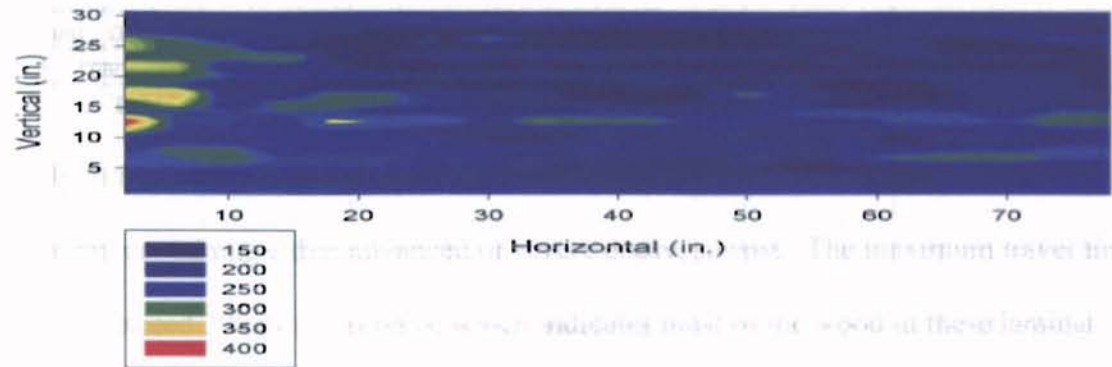
Glulam 1 seems to have very little decay throughout, with patches of early to moderate decay present only in the top half of the member and not extending much past 16-inches from the base of the arch. No advanced or severe decay exists throughout any of the glulam. The location of this member is such that it is protected on both sides by brick walls. These structures have helped in deterring weather from glulam 1 and have, in turn, decreased the amount of decay in the constituent. From the field picture, it is seen that the paint remains on most of the exposed arch area, and this sign indicates little or no decay, since the paint peeling is the first step to allowing moisture to reach the depths of the beam. The contour diagrams for this member show decay throughout its entirety, which is misleading. The maximum travel times reach only to 400- μ s, which is relatively small, so every little change in travel time is magnified, since there are no large times present.



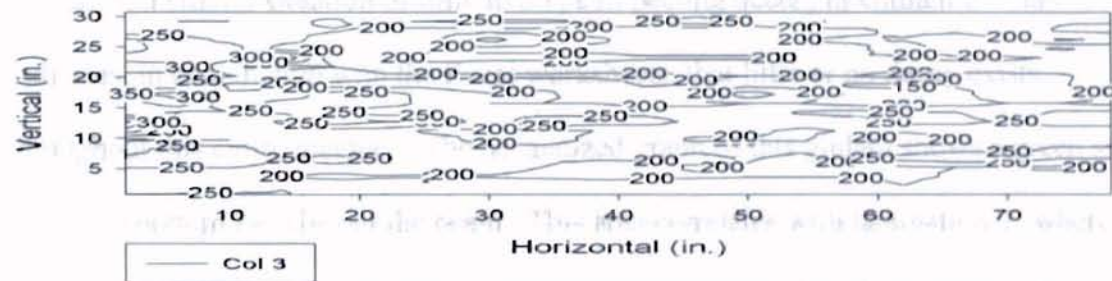
Figure 4.2.1: Field picture of Glulam 1.

4.2.2 Glulam 2

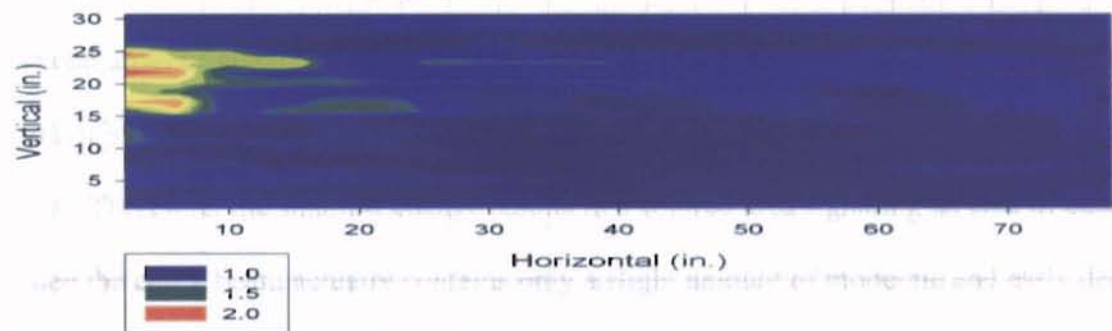
Glulam 1 Graph



Glulam 1 Contour



Glulam 1 Normalized



Glulam 1 Norm. Contour

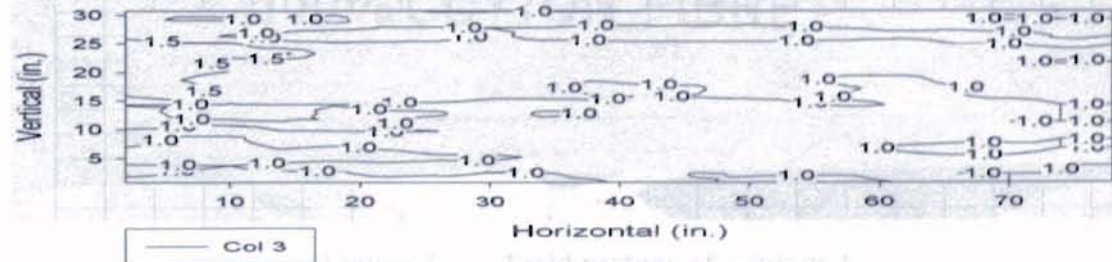


Figure 4.2.2: Glulam 1 Graphs

4.3 Glulam 2

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
2	08/10/00	92	none	16

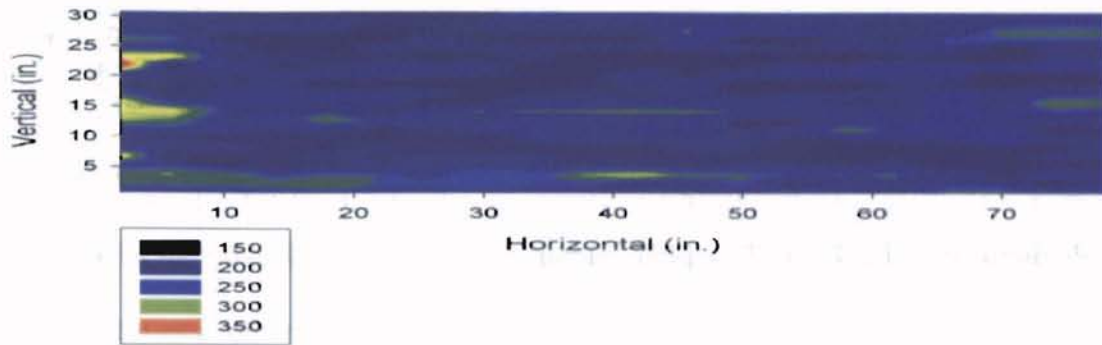
Table 4.3: Test conditions of Glulam 2.

Early to moderate decay exists throughout areas of Glulam 2, but no major areas of concern, containing either advanced or severe decay, subsist. The maximum travel time did not exceed 300 microseconds, which indicates most of the wood in these laminations is sound. This satisfactory state can be seen in the field picture below. As mentioned in Glulam 1, a similar situation of little to no paint peeling occurs in Glulam 2. This indicates, in conjunction with the Excel worksheets, that little or no decay exists throughout this entire member. The normalized graph of this glulam shows a green area along the bottom 8-inches of the beam. This area correlates with lamination T, where moderate and early decay exist throughout the entire beam. This demonstrates the accuracy of the normalized graphs. Another reason the normalized graph contains several areas of green coloration is because the variance of the time travels is so slight, similar to glulam 1, that the normalized graph has very little change from one area to the next. Therefore, the smallest change results in a colored area signaling an area of decay, when the entire beam actually contains only a slight amount of moderate and early decay.

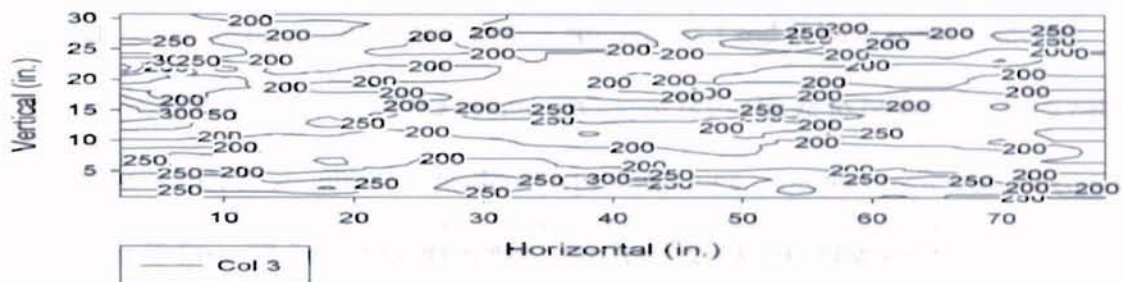


Figure 4.3.1: Field picture of Glulam 2.

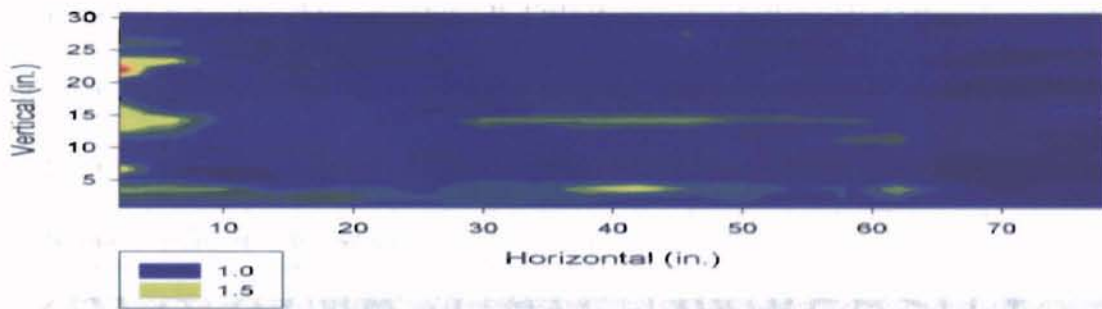
Glulam 2 Graph



Glulam 2 Contour



Glulam 2 Normalized



Glulam 2 Normalized Contour

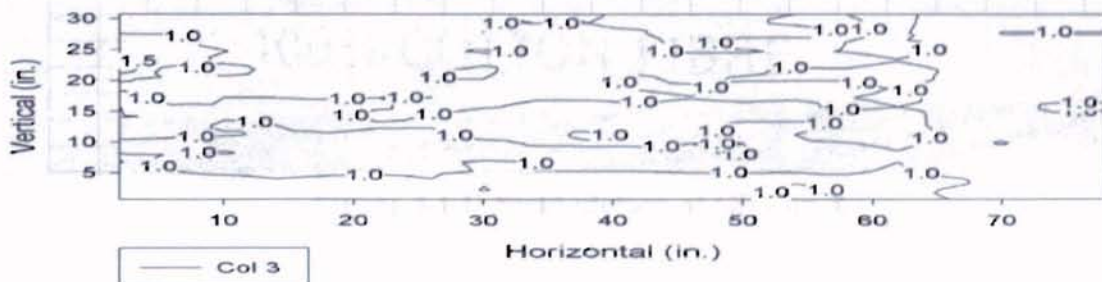


Figure 4.3.2: Glulam 2 Graphs

4.4 Glulam 3

Glulam 3 Graph

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
3	08/16/00	89	none	15

Table 4.4: Test conditions of Glulam 3.

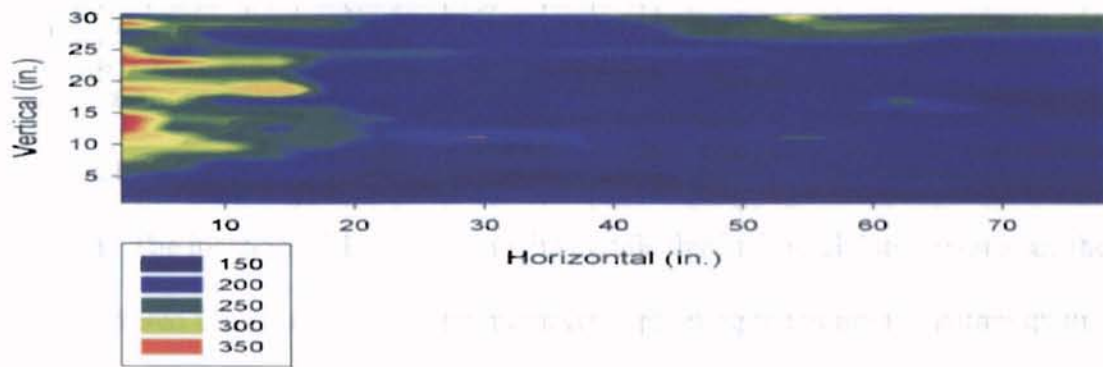
Glulam 3 has a large concentration of moderate decay in the first 16-inches, although very few of the travel times approach or surpass 350- μ s. This value is comparatively low to travel times in other arches. Yet, the effects of weather and wood grain orientation could be the reason for this difference, which was discussed previously. Throughout this member, some areas of concern do exist. Laminations J and K have some moderate decay existing through most of the beam. This spot is too large to be considered a natural knot in the wood, so should be considered a problem area. Another region of concern is lamination T from 32-inches to 40-inches. Moderate decay is shown in this locale, but due to the relatively small size of the area, a natural knot in the wood is probably the cause of the large travel times. Overall, little decay occurs throughout the expanse of this member, but the first foot is of a primary concern. The graphs below show many areas of high decay, yet, as mentioned above, the travel times are relatively low, and the Excel worksheets indicate otherwise.



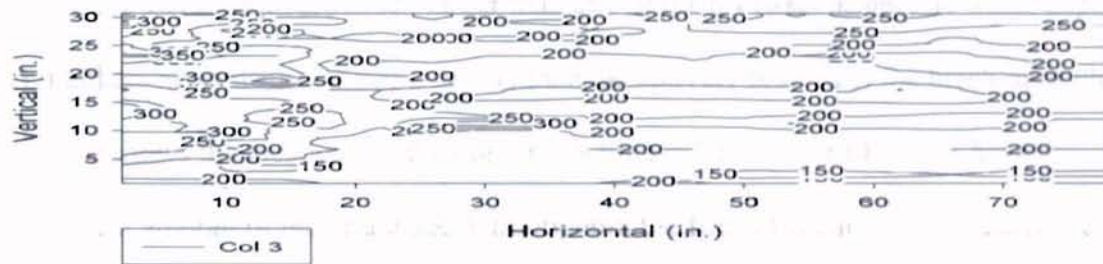
Figure 4.4.1: Field picture of Glulam 3.

Figure 4.4.2: Glulam 3 Graphs

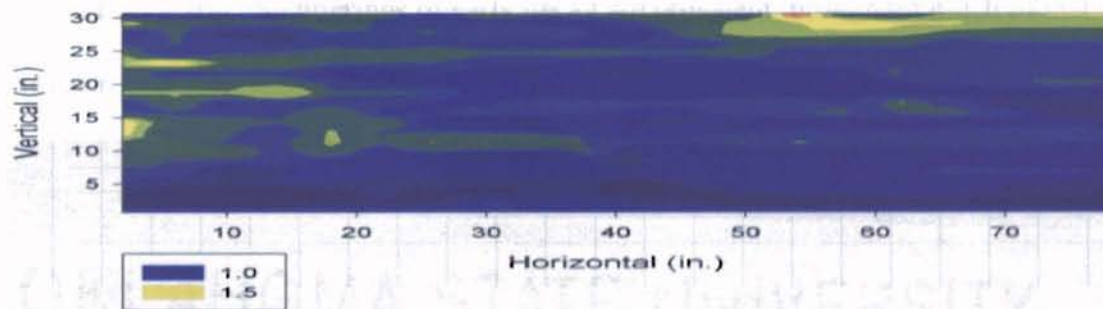
Glulam 3 Graph



Glulam 3 Contour



Glulam 3 Normalized



Glulam 3 Normalized Contour

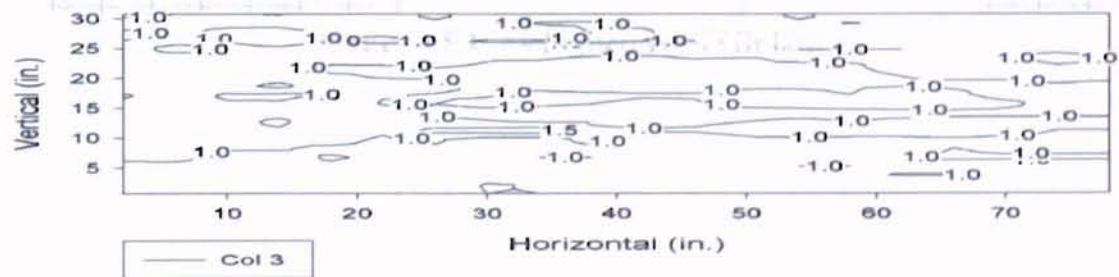


Figure 4.4.2: Glulam 3 Graphs

4.5 Glulam 4

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
4	08/17/00	93	none	16

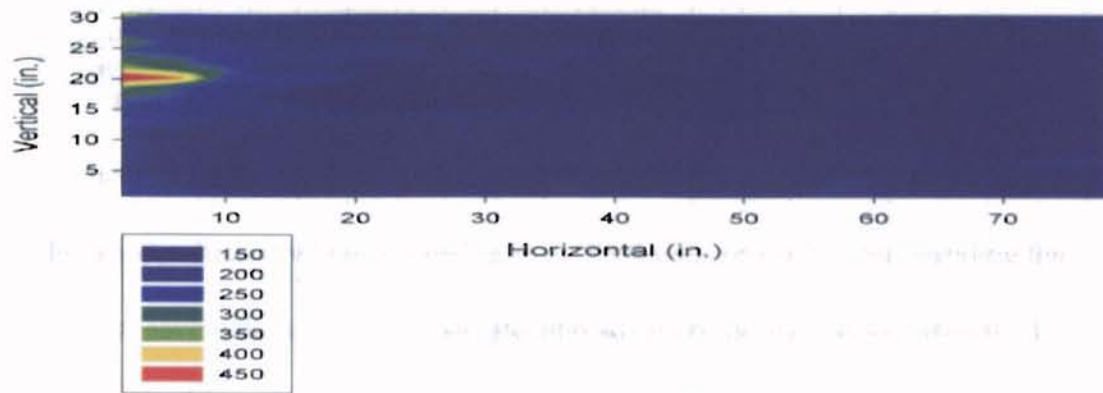
Table 4.5: Test conditions of Glulam 4.

Glulam 4 has solid amounts of early and moderate decay throughout the first 12-inches of the arch. The location of the beam is in the middle third of the glulams, which are the least sheltered from the environment members supporting the building. Although the color contour diagram of this member does not show a large portion of orange and red zones, the travel times are much larger than any of the previous beams. A wider expanse of numbers is occurring, making the diagram deceptively blue. Yet the black-and-white contour shows the locations of the high travel times. Laminations E and F have a consistent amount of moderate decay throughout the first 44-inches of the beam, with a concentration in the first 20-inches, which is indicated by the red and orange areas on the normalized graph. Smatterings of early decay are prevalent throughout much of this member.

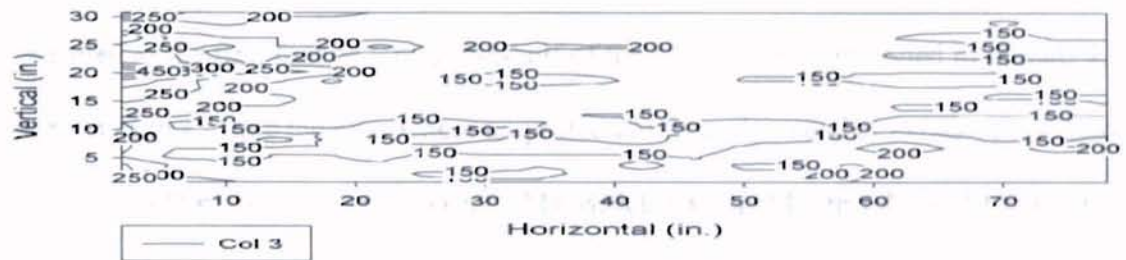


Figure 4.5.1: Field picture of Glulam 4.

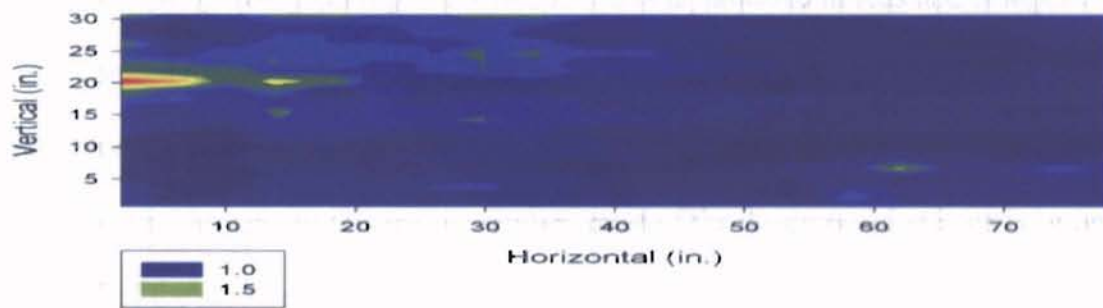
Glulam 4 Graph



Glulam 4 Contour



Glulam 4 Normalized



Glulam 4 Normalized Contour

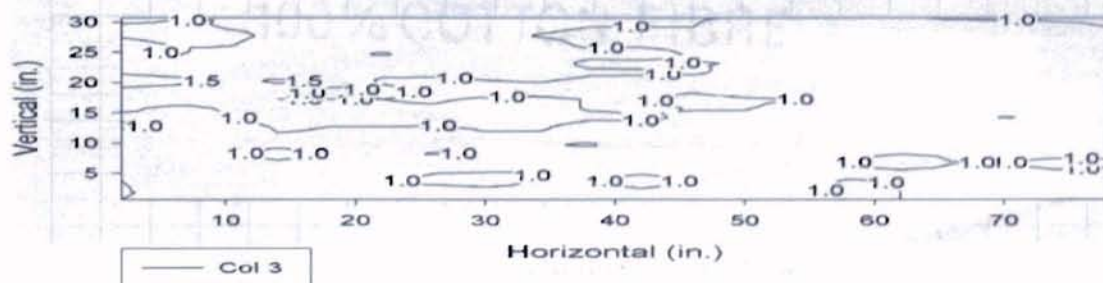


Figure 4.5.2: Glulam 4 Graphs

4.6 Glulam 5

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
5	08/21/00	95	none	13

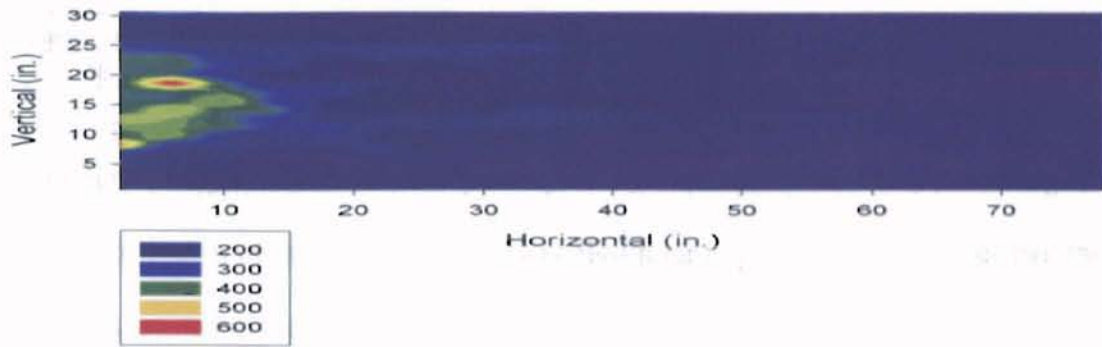
Table 4.6: Test conditions of Glulam 5.

Large pockets of severe decay occur in the first 8-inches of glulam 5. Actual holes exist in the wood, which is where a travel time of 5000- μ s is recorded. Surrounding the pockets of severe decay, early, moderate, and advanced decay is also rampant. Yet, past 20-inches, nothing more than early and some moderate decay exists, although moderate decay is quite prevalent in this area. Primary spots of advanced and severe decay are restricted to the first foot or foot-and-a-half of the glulam. As mentioned in glulam 4, this member is in a prime location where no protection from the weather exists. This factor has a large effect on the decay present. The widespread and large values of travel time can be seen in the black-and-white contour diagram. Other than the 5000- μ s recording, a travel time of up to 600- μ s is present, and this area is indicated in reds and oranges on the color contour diagram. The normalized graphs are similar to the regular graphs, yet more light blue exists throughout the member, representing the moderate decay. Although decay occurs throughout this entire member, most of the decomposition is early or on the low end of the moderate decay.

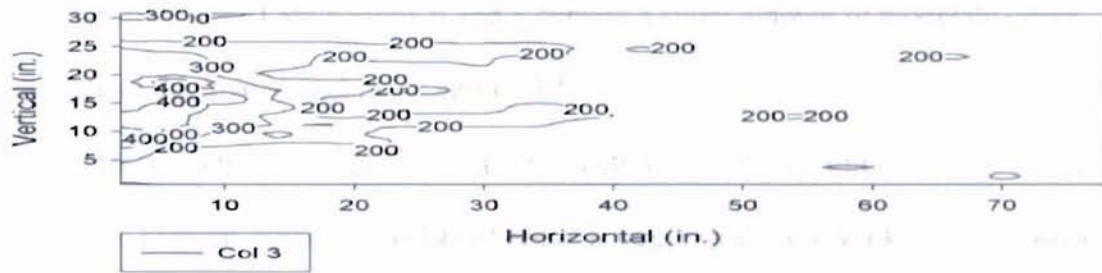


Figure 4.6.1: Field picture of Glulam 5.

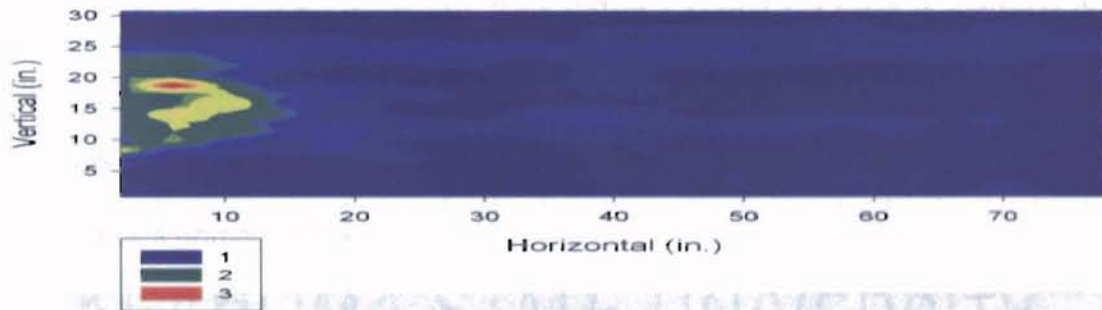
Glulam 5 Graph



Glulam 5 Contour



Glulam 5 Normalized



Glulam 5 Normalized Contour

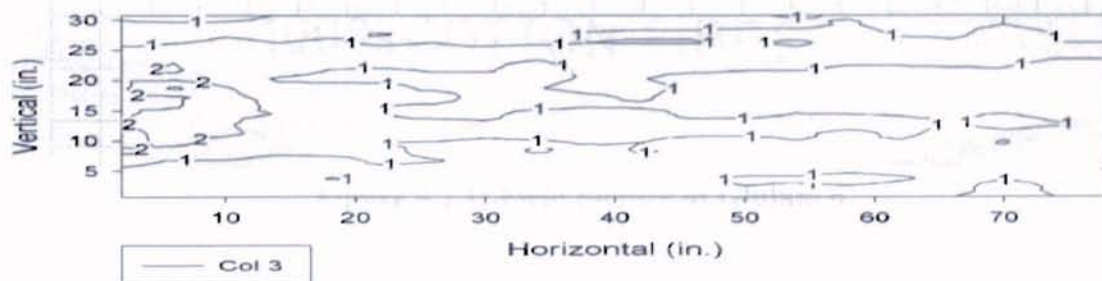


Figure 4.6.2: Glulam 5 Graphs

4.7 Glulam 6

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
6	08/22/00	96	none	19

Table 4.7: Test conditions of Glulam 6.

In glulam 6, only moderate and early decay exist, with little or no decay subsiding beyond 20-inches of the beam. This data is dissimilar to previous conjectures that the members located in the middle third of the structure have large amounts of decay throughout. Yet, the first 8-inches has a solid mix of early and moderate decay, similar to all other members. Laminations E and F contain a slight amount of moderate decay throughout the first 56-inches, or almost 5-feet, but this area is of little concern since the rest of the beam is in such good condition structurally. These laminations should be taken into account, since the pocket of decay is larger than merely a knot in the wood. Yet, since little other decay exists throughout the arch, one small decayed area should not cause too much structural instability. This glulam's normalized graph is similar to the regular graph but with more light blue scattered about the whole. This indicates the small amounts of moderate decay throughout the length of the member, but not enough for the beam to be a primary concern.



Figure 4.7.1: Field picture of Glulam 6.

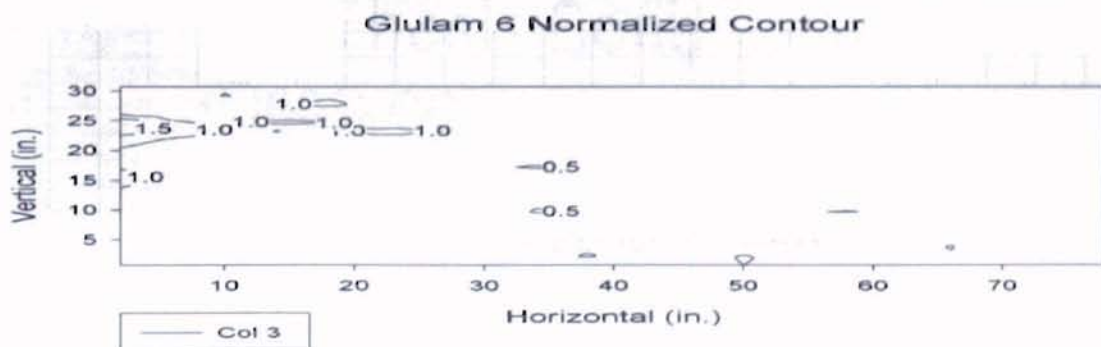
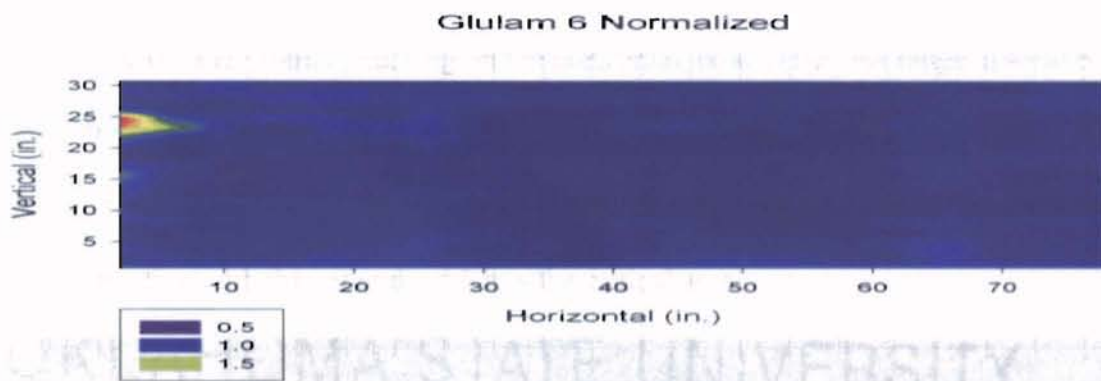
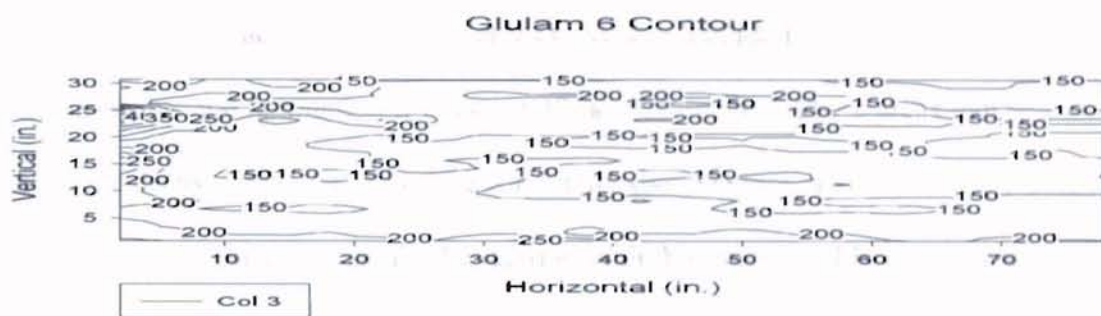
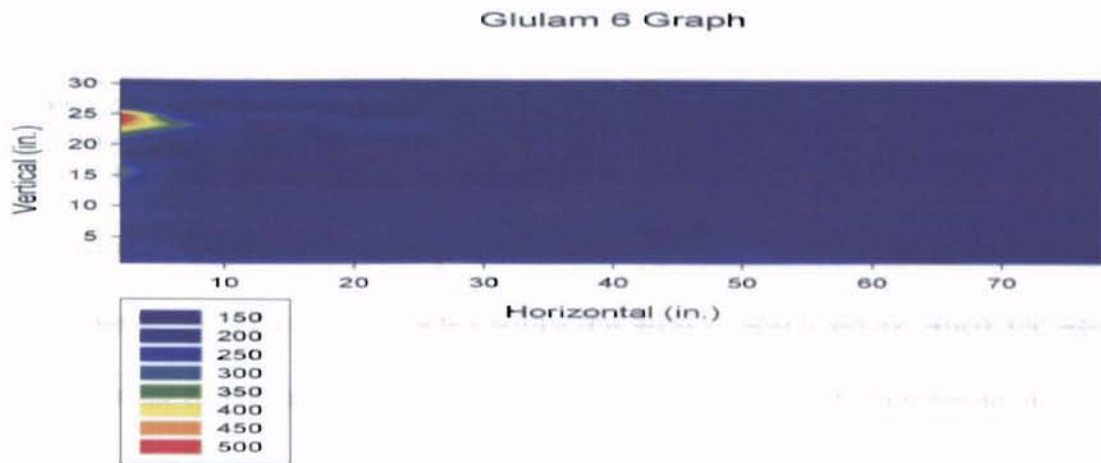


Figure 4.7.2: Glulam 6 Graphs

4.8 Glulam 7

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
7	08/23/00	93	none	14

Table 4.8: Test conditions of Glulam 7.

Following in a typical manner as previous arches, glulam 7 also has a concentration of moderate decay in the first 16-inches with a few areas of severe decay, where the wood is actually nonexistent due to complete rotting. After this area, only minimal amounts of moderate and early decay exist, and the decomposition diminishes as the test spots become closer to the building. Two areas to look at include lamination O between 20- and 28-inches and lamination R between 28- and 36-inches. These areas indicate moderate decay, when the rest of the beam only shows minor amounts of early decay. Yet, since the areas are so small, the regions could be, and probably are, natural knots in the wood. The severe decay areas are identified in red and orange and are obviously located before the 10-inch marking on the horizontal axis. After this range, a solid blue color exists with interspersed areas of light blue, all of which indicate moderate or early decay. Overall, this beam does not have a continual problem throughout, but merely at the connection with the ground, which is the critical area.

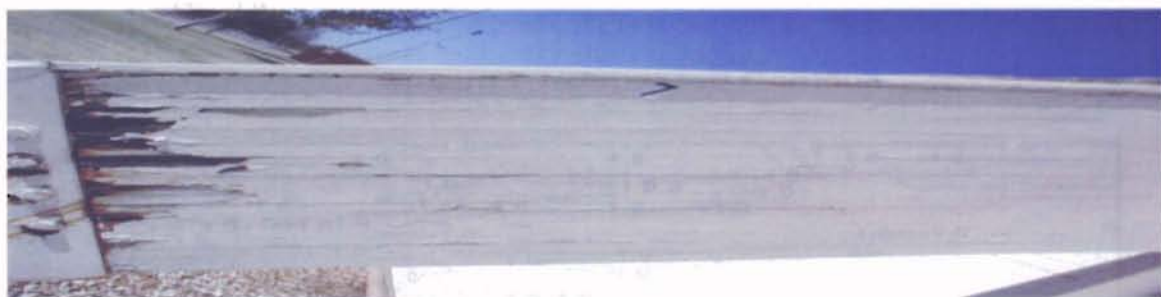
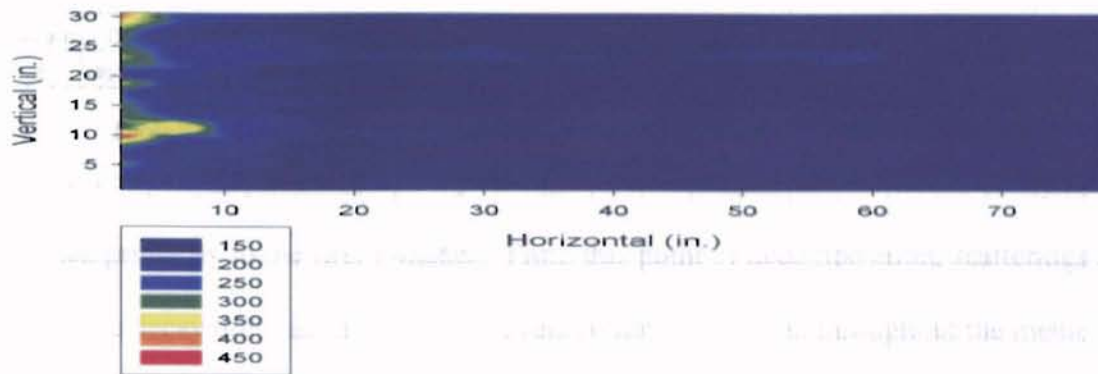
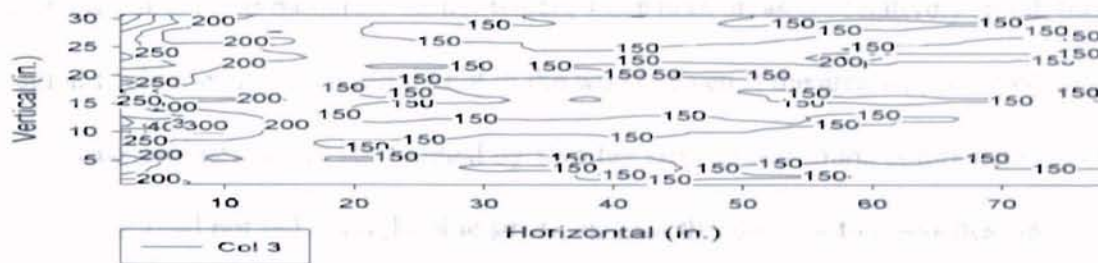


Figure 4.8.1: Field picture of Glulam 7.

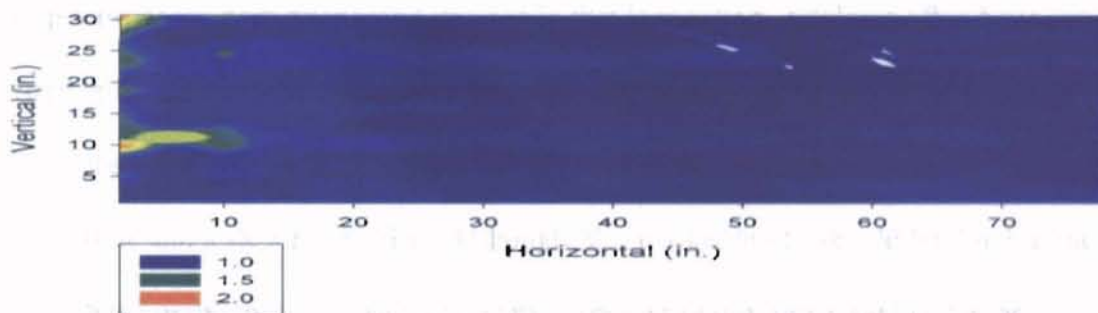
Glulam 7 Graph



Glulam 7 Contour



Glulam 7 Normalized



Glulam 7 Normalized Contour

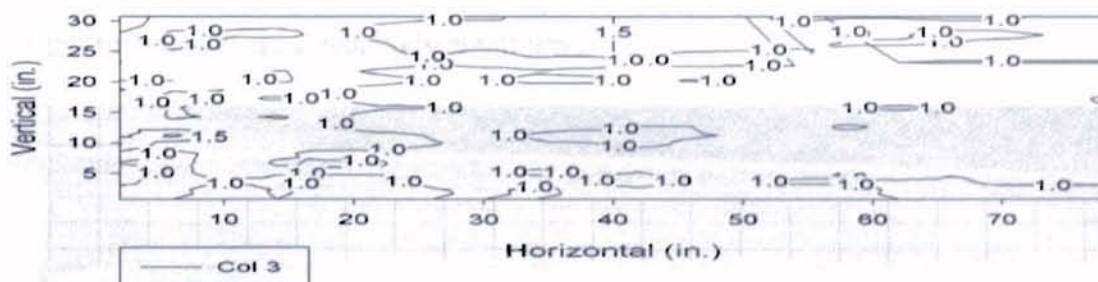


Figure 4.8.2: Glulam 7 Graphs

4.9 Glulam 8

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
8	08/25/00	98	none	13

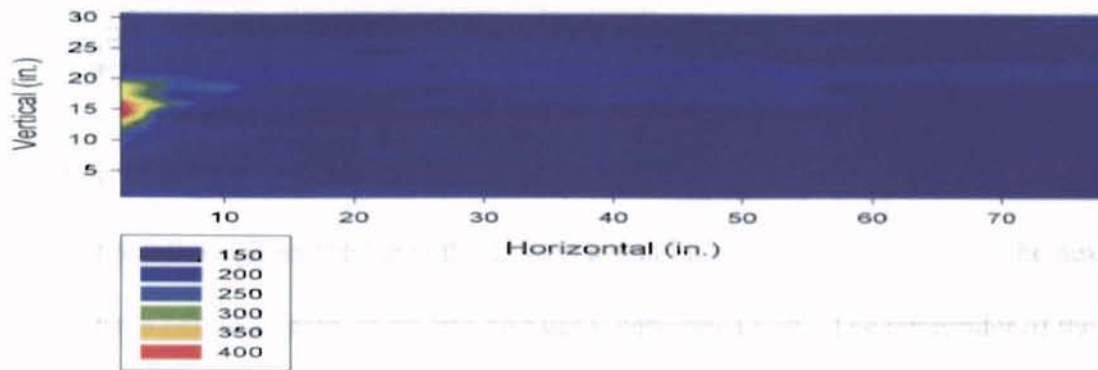
Table 4.9: Test conditions of Glulam 8.

Glulam 8 does not have much decay throughout the laminations. Moderate decay is limited primarily to the first 8-inches. From this point of decomposition, scatterings of moderate decay diminishing to decay levels continue scattered throughout the member, but few areas of concern exist other than laminations N and T. These laminations have a continual amount of moderate decay, which, since both areas are relatively small, this region could merely be a natural knot in the wood. Even if the area was decayed, since these two laminations are surrounded by 19 other structurally sound components, the member should not fail. A light blue streak extends through 20- to 25-inches, and a reason for this light blue streak through laminations could be due to the material properties of the particular wood utilized in that lamination. Glulams often have varying wood grain orientations throughout, and these differing patterns can cause an alteration in the stress wave sent through the individual lamination, resulting, in this case, in a larger travel time and a slower velocity. Although, this discontinuity should be fixed in the normalized graph, but the area still occurs. Another reason this might be happening is the relatively small travel times which appear to be drastic in the graphs, when, actually, the largest time is 400- μ s, a relatively small time.

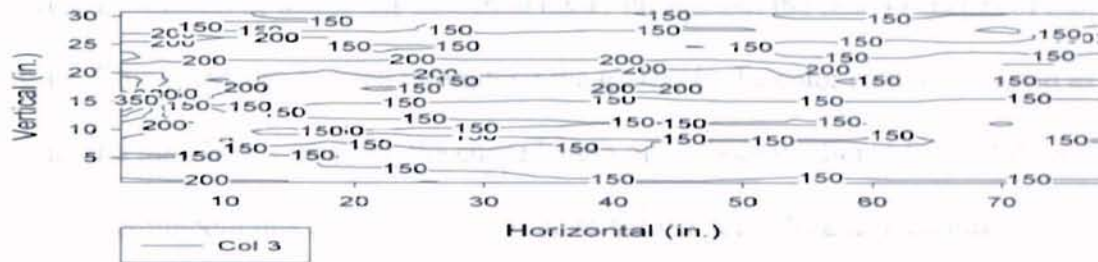


Figure 4.9.1: Field picture of Glulam 8.

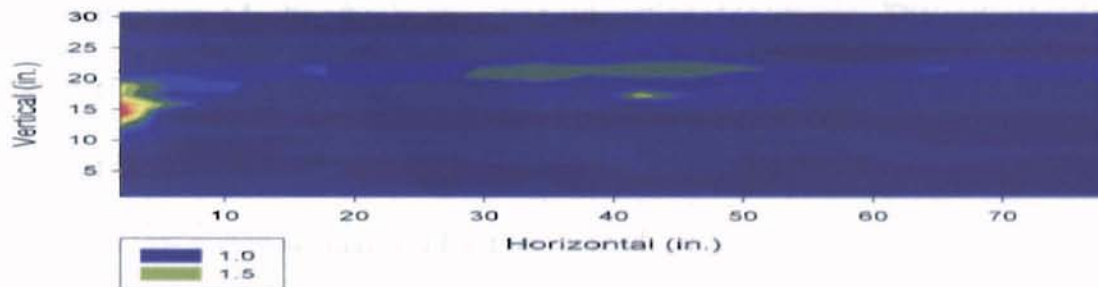
Glulam 8 Graph



Glulam 8 Contour



Glulam 8 Normalized



Glulam 8 Normalized Contour

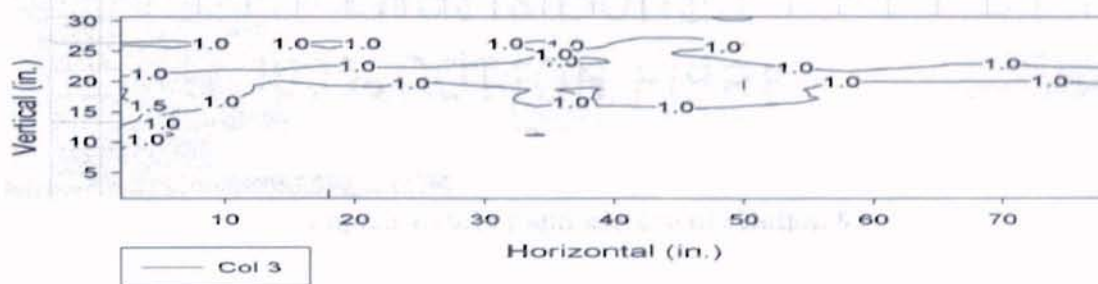


Figure 4.9.2: Glulam 8 Graphs

4.10 Glulam 9

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
9	08/30/00	95	none	11

Table 4.10: Test conditions of Glulam 9.

The first 12-inches of glulam 9 has a high concentration of damaging moderate decay interspersed throughout the laminations with a small amount of early decay. The next 4-inches have half moderate decay and half early decomposition. The remainder of the member has relatively small amounts of moderate decay interspersed with early decay, except lamination S, which has moderate decay throughout the first 44-inches of the beam. This decay can be seen throughout the glulam in the color contour diagram as the green and light blue area along the entire length of the bottom. Some form of decay is present throughout this entire lamination up to the last foot. Yet, as mentioned in previous glulam discussions, one decayed lamination will not fail the member. The load can be transferred to the other surrounding laminations for support. The appearance of the normalized graph seems to have a large concentration of decay throughout the beam, indicated by the green areas, but this glulam only reaches travel times of 350- μ s, which is relatively low giving varying results from other glulams.



Figure 4.10.1: Field picture of Glulam 9.

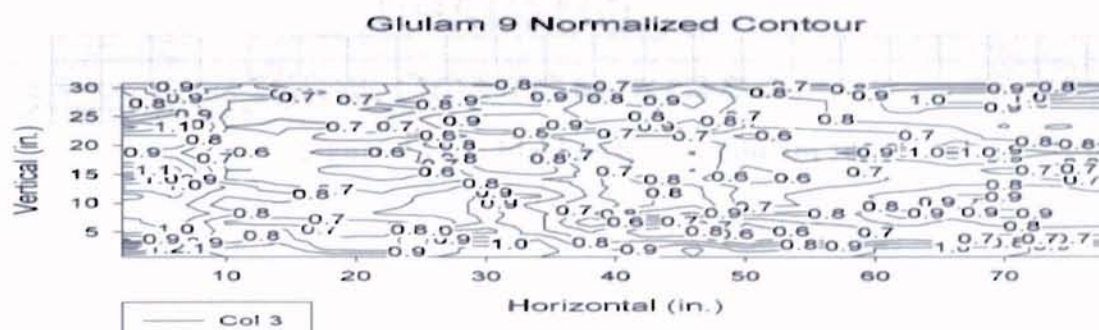
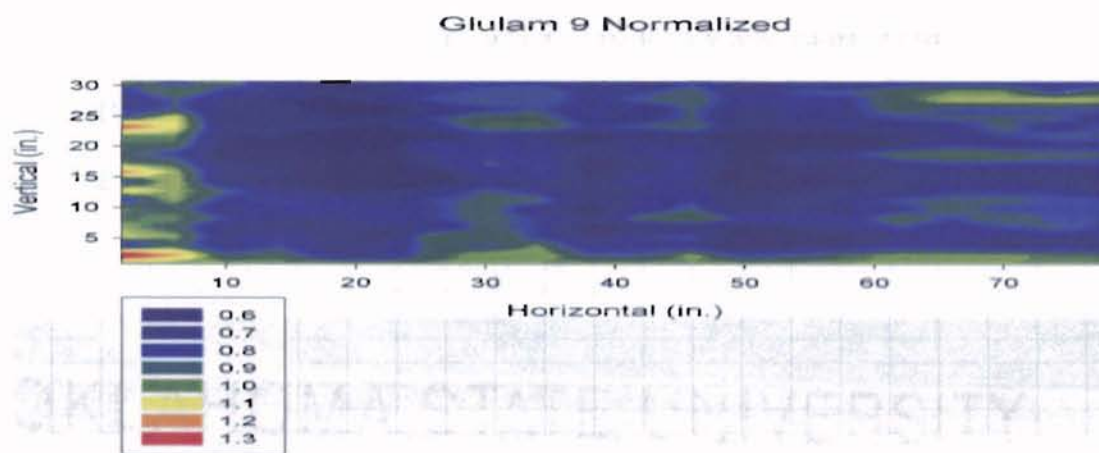
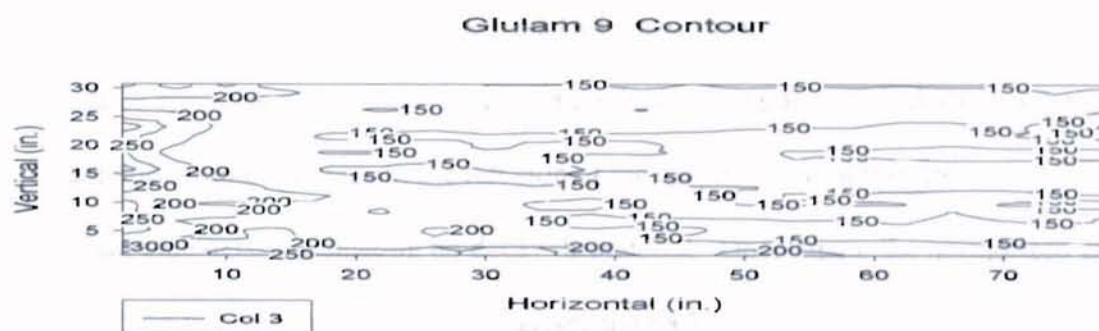
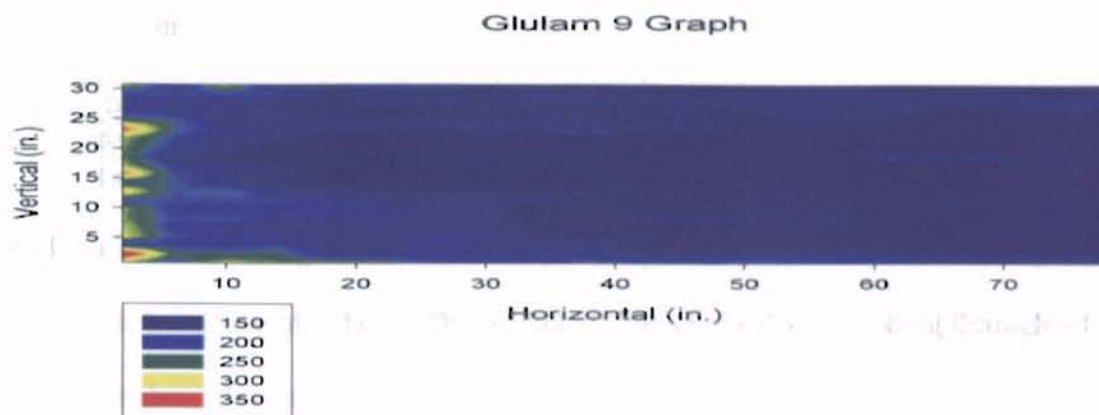


Figure 4.10.2: Glulam 9 Graphs

4.11 Glulam 10

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
10	09/06/00	89	none	16

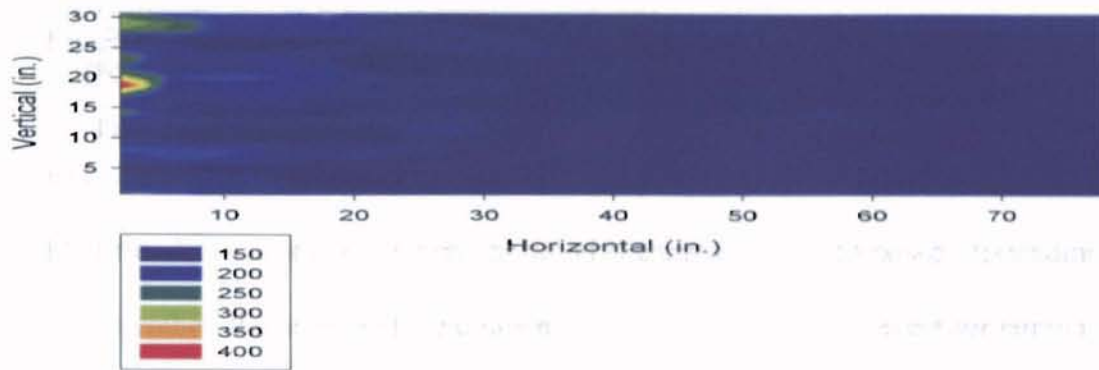
Table 4.11: Test conditions of Glulam 10.

As found in all others, glulam 10 also has a high concentration of moderate decay in the first 12-inches of the member, with no advanced or severe decay existing throughout the entire member. Beyond this region, a high concentration of early decay with interspersed moderate decay exists throughout the next 16-inches. From this point, only small amounts of early decay exist with no moderate decayed regions. This decay can be seen on the color contour diagram in the left side of the graph. Beyond this area, no coloration other than blue exists, indicating no decay throughout. Once again, the normalized graph is misleading because this graph shows green and dark areas throughout the entire beam, but the highest travel time is 400- μ s, which is relatively low, causing erroneous graph portrayals. Overall, this beam is in good condition, which is apparent in the field picture, Figure 4.11.1. Little paint has peeled off the beam, which is a good indication of little decay.

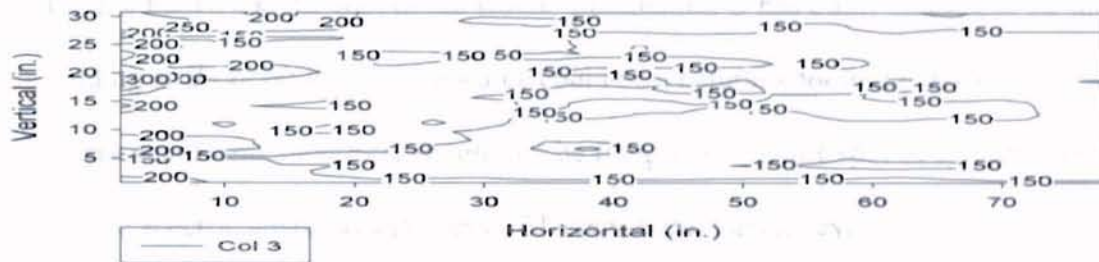


Figure 4.11.1: Field picture of Glulam 10.

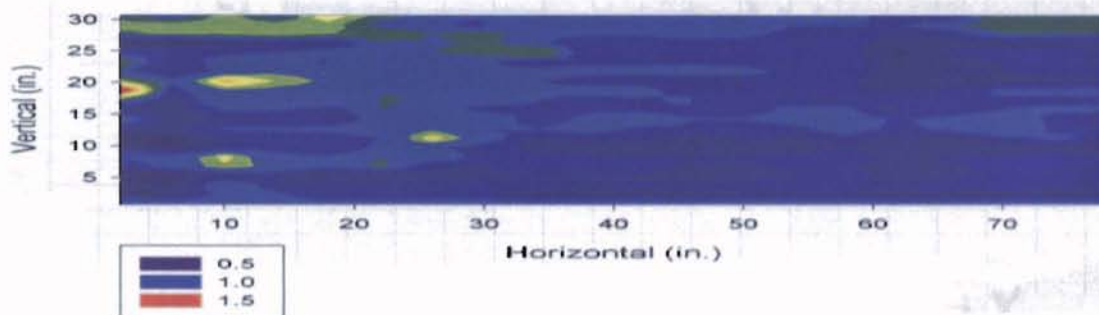
Glulam 10 Graph



Glulam 10 Contour



Glulam 10 Normalized



Glulam 10 Normalized Contour

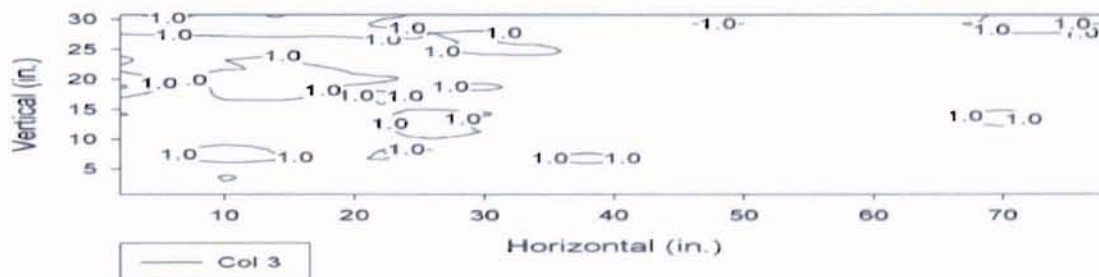


Figure 4.11.2: Glulam 10 Graphs

4.12 Glulam 11

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
11	09/13/00	95	none	11

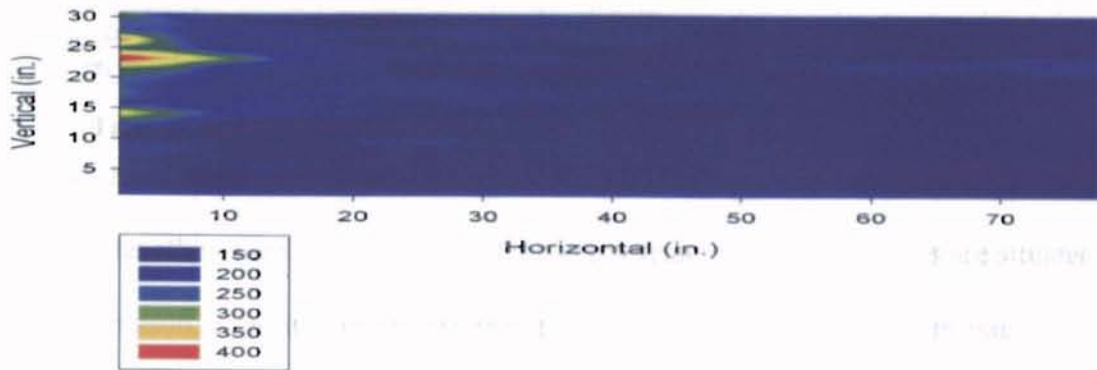
Table 4.12: Test conditions of Glulam 11.

A large concentration of moderate decay is limited to the first 12-inches of glulam 11. At grid location E1, a hole exists where the wood is completely decomposed. Extending on into the member, the usual early and low moderate decay subsists, except for laminations J and Q. Lamination J has moderate decay throughout the entire first 52-inches, which an area larger than a natural knot in the wood. Lamination Q has decay starting at 52-inches and ending at about 60-inches. This area could be a natural knot in the wood since it is relatively small, and, therefore, should not be flagged as a prime spot of concern. Other than these specific areas, no key areas of decomposition exist beyond the usual scattering of early decay.

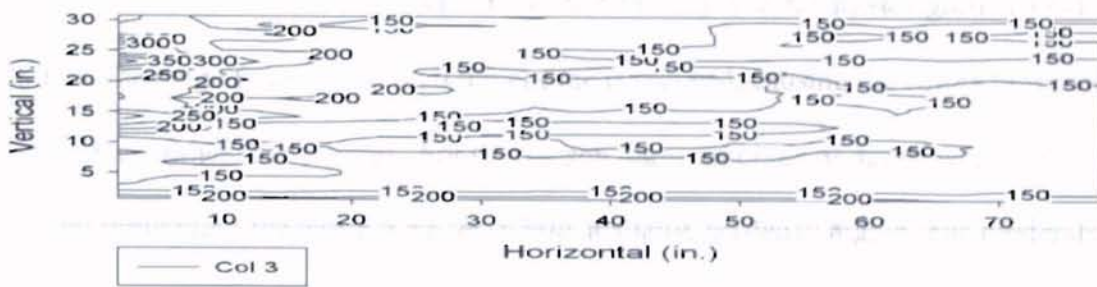


Figure 4.12.1: Field picture of Glulam 11.

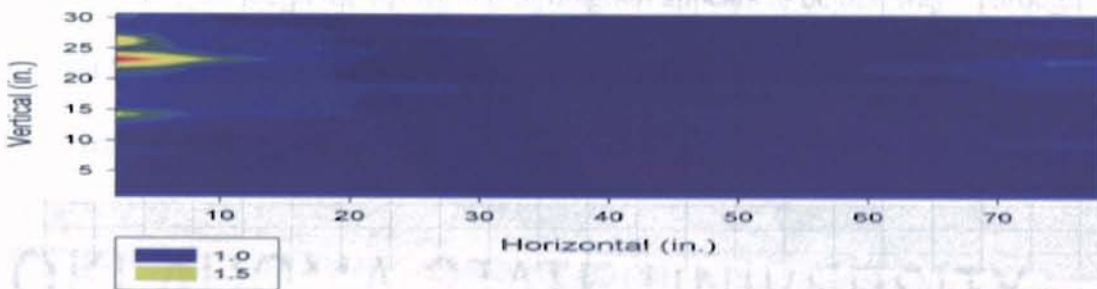
Glulam 11 Graph



Glulam 11 Contour



Glulam 11 Normalized



Glulam 11 Normalized Contour

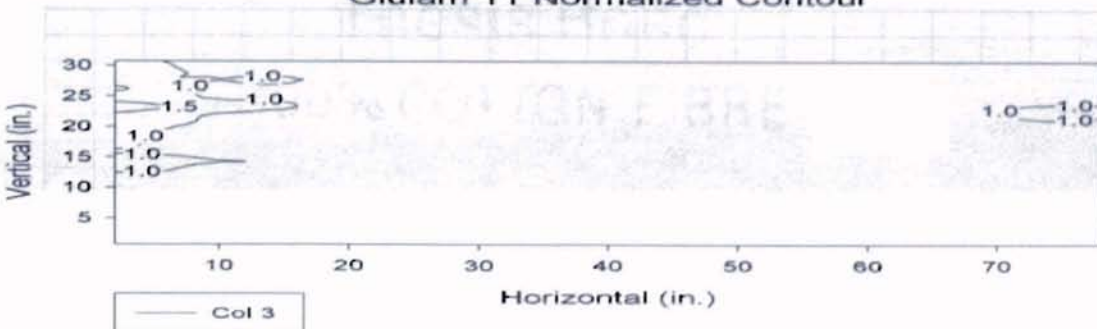


Figure 4.12.2: Glulam 11 Graphs

4.13 Glulam 12

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
12	09/18/11	93	none	20

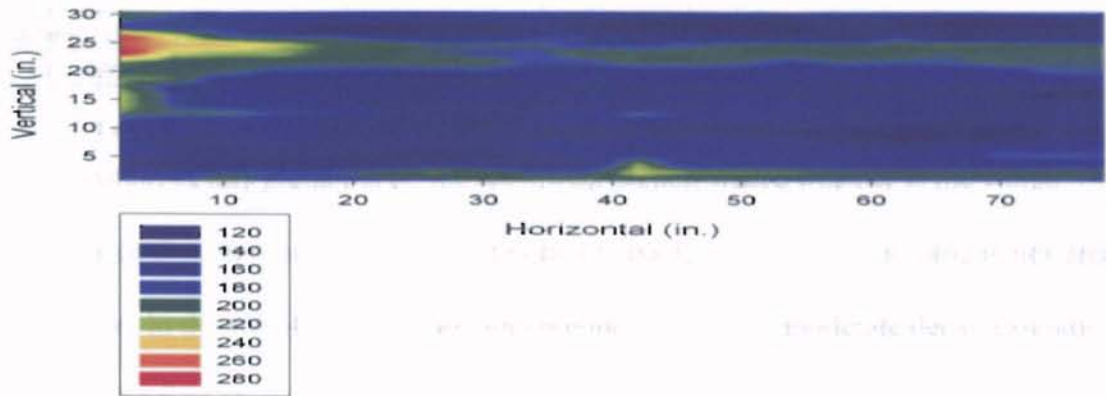
Table 4.13: Test conditions of Glulam 12.

Glulam 12 is protected on both sides from the environment. One side has a brick wall, and, on the other, the Oklahoma State University tennis courts' bleachers are situated. For this reason, very little decay exists in this member. The color contour diagram is misleading, because the green areas usually represent areas of large decay due to the high travel time. Yet, since all the travel times are relatively low, the most significant being 280- μ s, the range from low to high travel time is reduced, causing the colors to represent lower travel times than normal. For this reason, large amounts of decay seem to be present throughout the entire member, while, actually, no decay higher than moderate exists at all, and only early decay exists past the first 12-inches. This glulam is not one of major concern, although the color contour diagram appears to be that way. Throughout the member, some early decay is present, yet nothing to be concerned about due to the scattered nature of the decay.

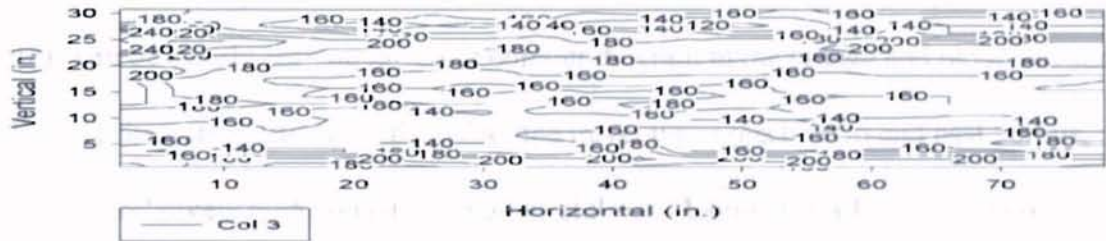


Figure 4.13.1: Field picture of Glulam 12.

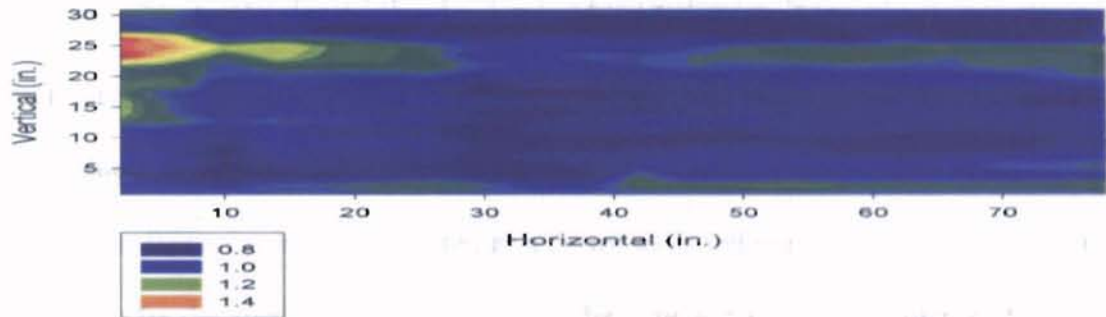
Glulam 12 Graph



Glulam 12 Contour



Glulam 12 Normalized



Glulam 12 Normalized Contour

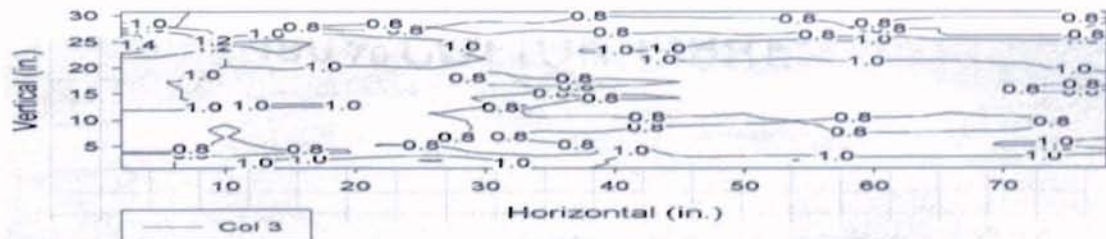


Figure 4.13.2: Glulams 12 Graphs

4.14 Glulam 13

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
13	09/22/00	89	none	17

Table 4.14: Test conditions of Glulam 13.

The location of this glulam is on the northwest corner, where weather is the worst.

Because of that, the condition of this member is poor. Glulam 13 has some major areas of concern in the first 4-inches, with a high concentration of moderate decay extending through the first 16-inches of the member. Severe decomposition is located in lamination F, with laminations E and G containing advanced decay, all in the first 4-inches. These areas can be clearly seen on the color contour diagram in the orange and red zones and in the field diagram on the left side. Also, the travel times reach up to and past 500- μ s, which is relatively high compared to other glulams. Laminations E, F, and G contain moderate decay throughout most of the glulam, with this region stopping at 52-inches. In lamination O, at about 50-inches, a small pocket of apparent decay exists, and due to the small nature of the area, this spot could be a natural knot in the wood, but may not be. A light blue area surrounds the green region, which is usually present when decay subsists. Therefore, this area should be treated as a decay spot, and precautions should be taken to treat or to fix the area. Other than these problem areas, nothing more than scattered early decay exists.



Figure 4.14.1: Field picture of Glulam 13.

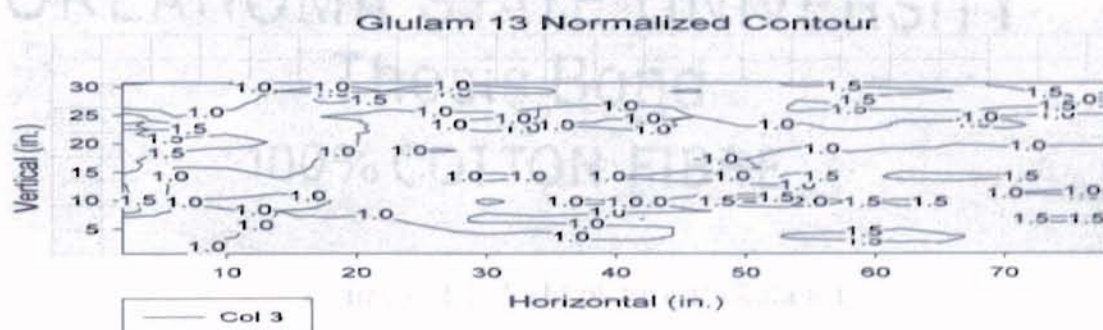
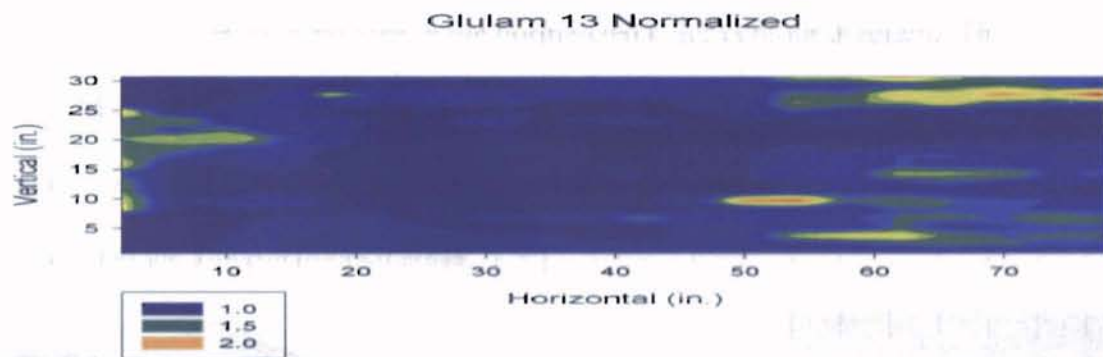
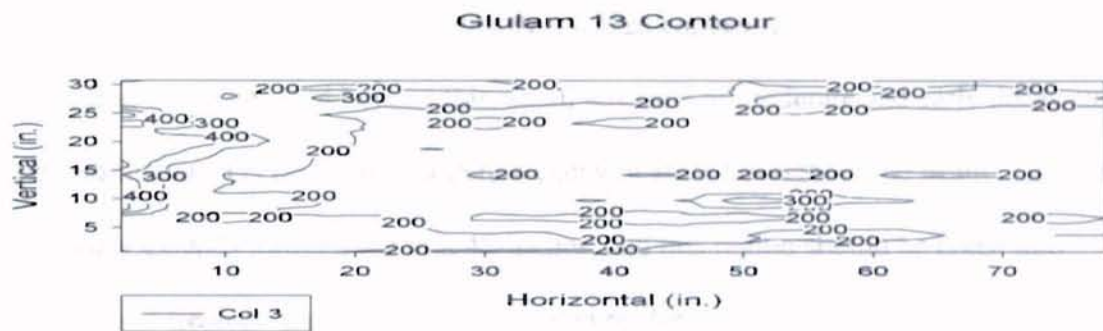
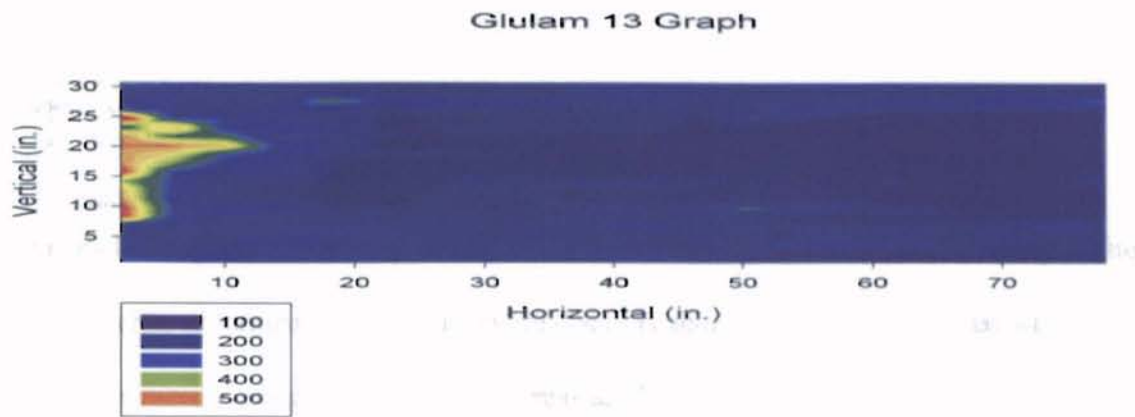


Figure 4.14.2: Glulam 13 Graphs

4.15 Glulam 14

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
14	10/01/00	61	none	21

Table 4.15: Test conditions of Glulam 14.

Glulam 14 contains 4-inches of severe decay in lamination G and advanced decay in the first 4-inches of lamination L. The severe decay is actually completely rotted wood, so a value was merely assigned to it. These areas are indicated with the orange and red hues on the color contour diagram. Besides this, a high concentration of moderate decay exists in the first 12-inches, and beyond this, small amounts of moderate and early decay exist. Yet, laminations G and S have moderate decay in areas throughout the beam. Lamination G's decay extends through the first 48-inches, and this region should be taken into account and treated. Lamination S only contains decay between 60- and 70-inches, which can be seen as a red area in the normalized color contour diagram. This area is most likely a natural knot in the wood, due to the small nature of the apparently decayed region. Past the first 12- or 16-inches, nothing more than scattered early decay exists, other than the aforementioned areas.



Figure 4.15.1: Field picture of Glulam 14.

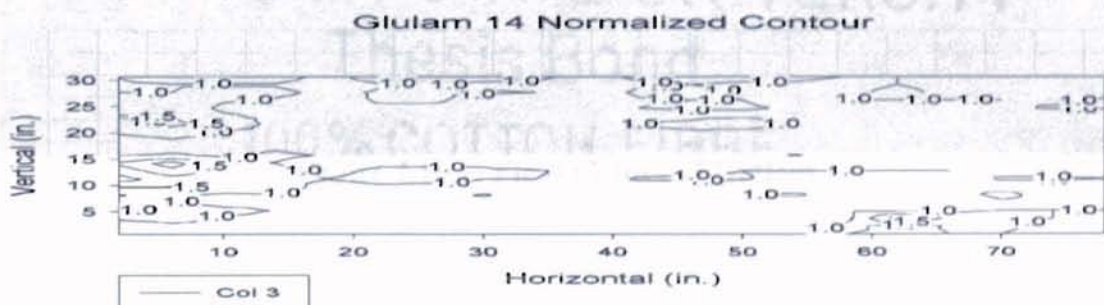
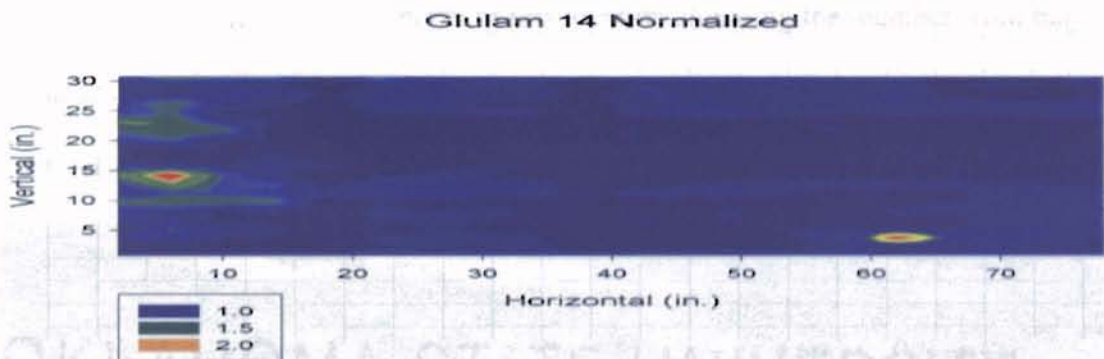
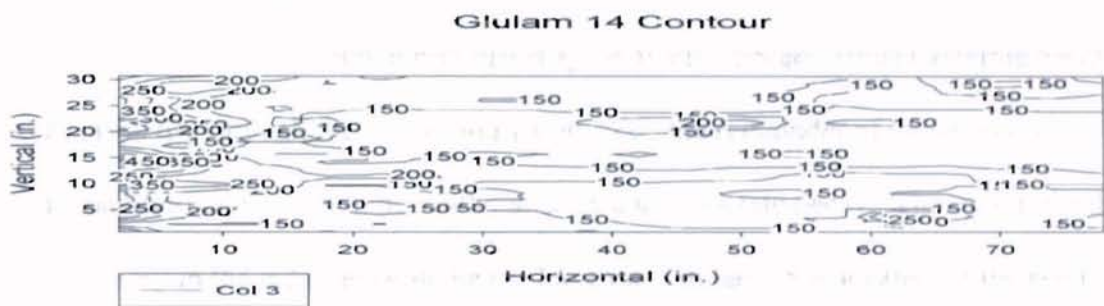
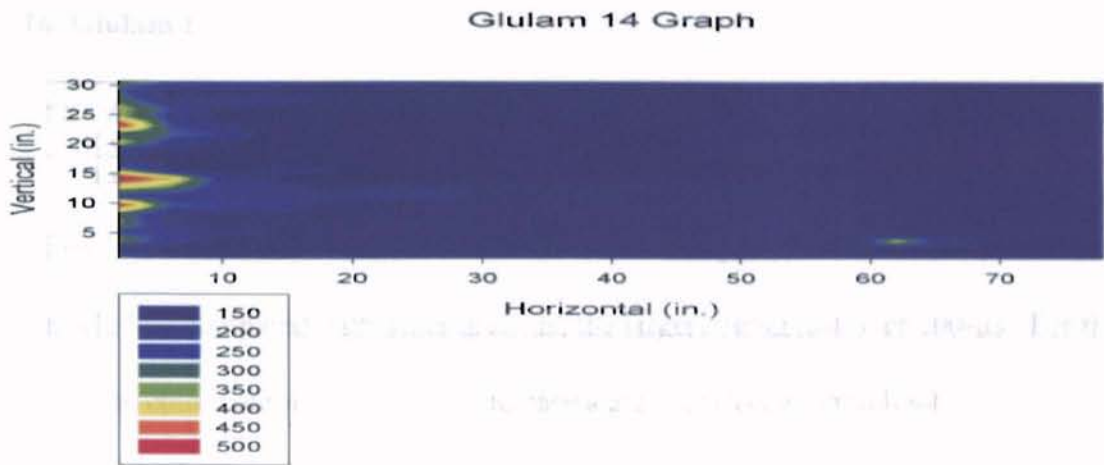


Figure 4.15.2: Glulam 14 Graphs

4.16 Glulam 15

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
15	10/09/00	68	none	14

Table 4.16: Test conditions of Glulam 15.

Glulam 15 contains no areas of severe or advanced decay. All of the travel times were relatively low compared with other glulams, the largest being just over 200- μ s. For this reason, the color contour diagram has apparent areas of decay throughout the entire member, but these green areas are merely caused by the minor changes in travel times. Lamination A is the only actual part that may be of any concern, since moderate decay exists primarily through the entire lamination. Yet, the remainder of the glulam is in great condition, only containing scattered early and moderate decay. The reason for the lack of decay in the member could be the location. Glulam 15 is located on the north side of the building, with a hill just north of this location shielding the member from major weather environments. As seen in the field picture, very little paint has peeled from this member, also providing protection and indicating little decay.



Figure 4.16.1: Field picture of Glulam 15.

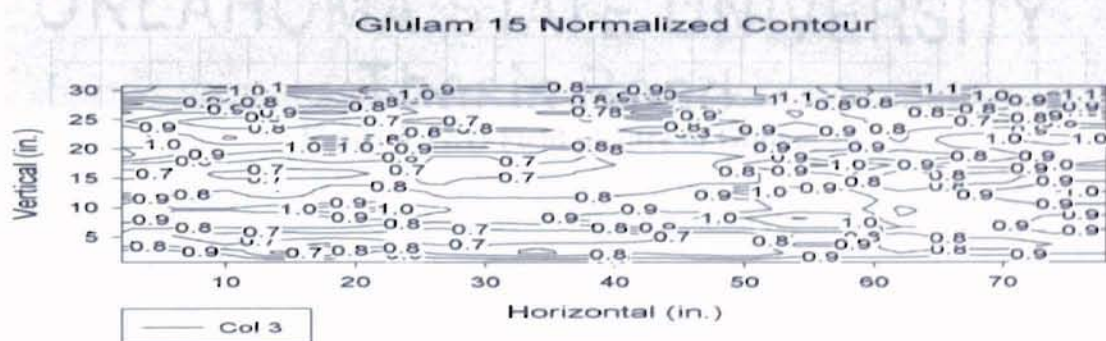
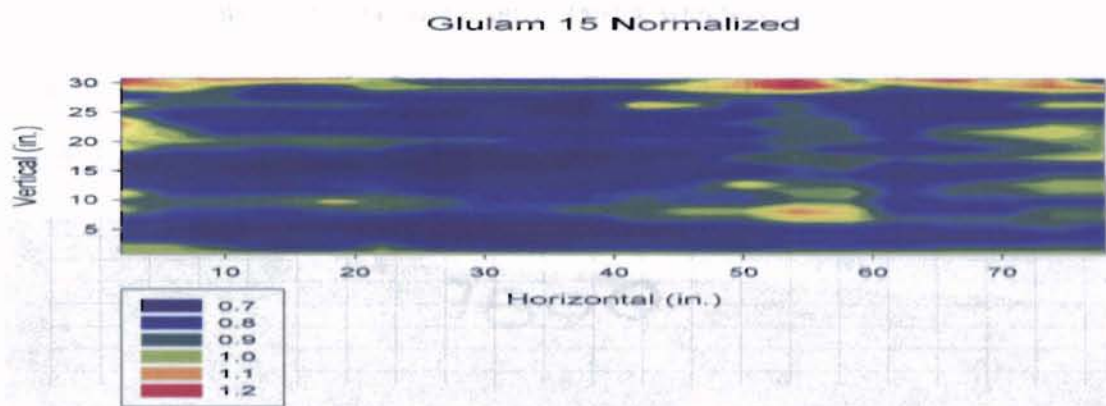
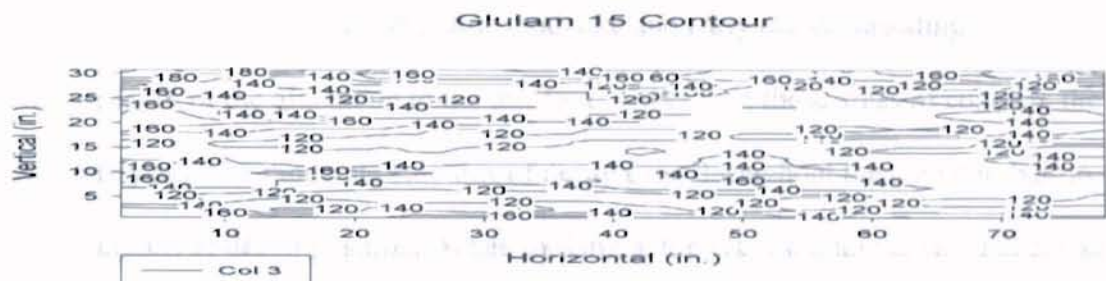
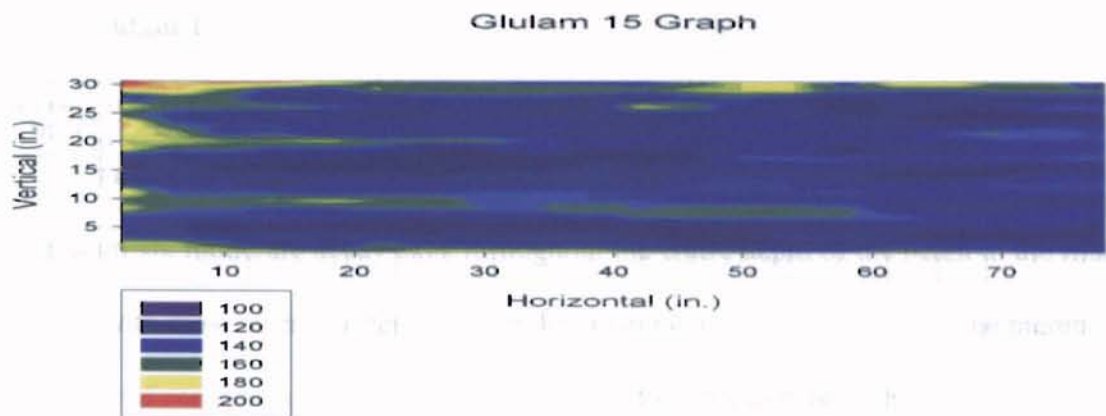


Figure 4.16.2: Glulam 15 Graphs

4.17 Glulam 16

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
16	10/10/00	83	none	17

Table 4.17: Test conditions of Glulam 16.

In glulam 16, moderate decay exist throughout the entire depth of the beam in the first 8-inches, with most of the moderate decay diminishing after the first foot of the member. One spot of concern is the moderate decay extending through 44-inches in lamination T, almost 3-feet of the member, with low moderate and early decay subsiding throughout the remainder of the glulam up to the last foot. Other than these areas of concern, the usual early and low moderate amounts of decay exist throughout the member, but no major regions of decomposition. When looking at the graphs, many areas of decay seem to exist, but the highest travel time is only 300- μ s, which is relatively small, so causes erroneous graph results. The field picture in Figure 4.17.1 seems to show a lot of decay, but this apparition is merely due to paint peeling.



Figure 4.17.1: Field picture of Glulam 16.

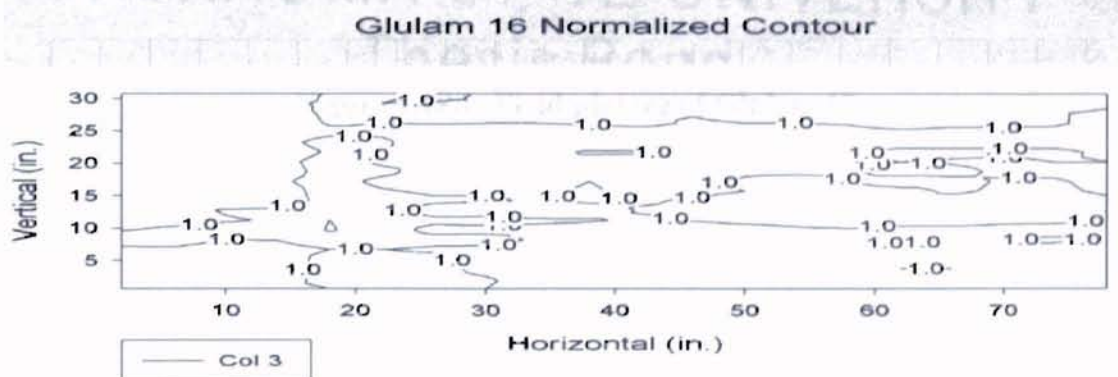
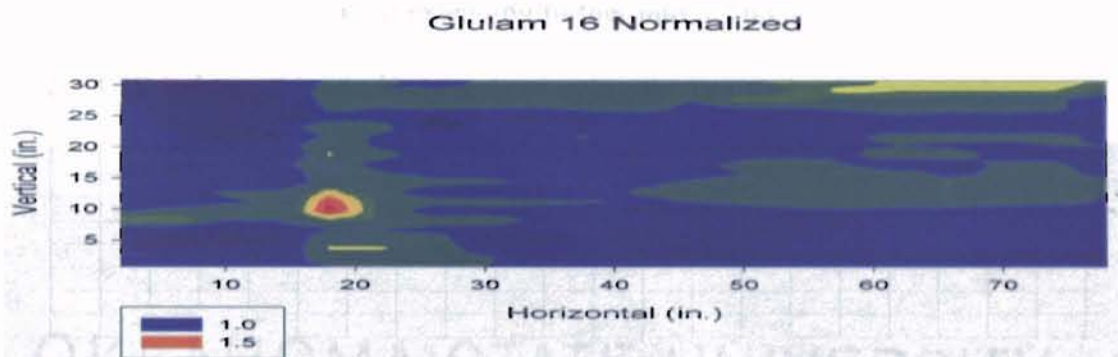
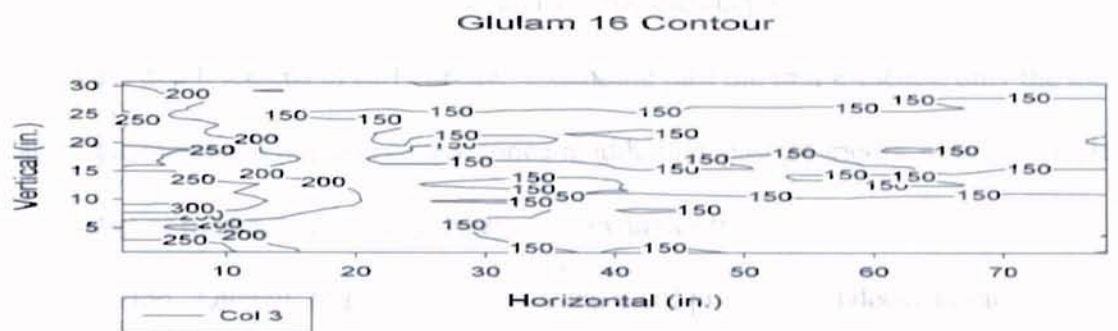
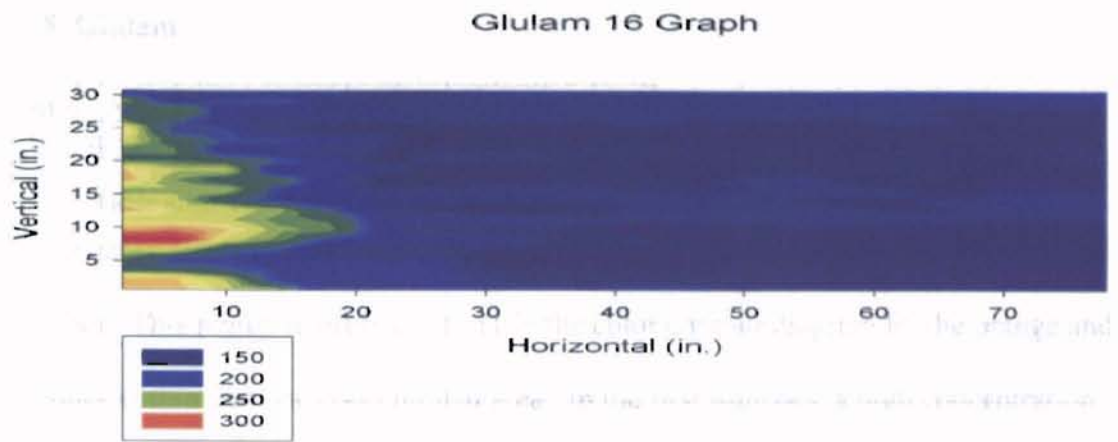


Figure 4.17.2: Glulam 16 Graphs

4.18 Glulam 17

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
17	10/13/00	81	none	16

Table 4.18: Test conditions of Glulam 17.

The primary area of decay in glulam 17 is in the top 10-inches of the first 2-feet of the member. This region is made apparent in the color contour diagram by the orange and red hues within that one concentrated area. In the first 8-inches, a high concentration of moderate decay exists throughout the depth of the member, but in this glulam, the bottom half of the depth lessens to early decay. Extending past the first 8-inches, only the top half of the member's depth is of any concern, although, past 24-inches, only miniscule scatterings of moderate and early decay exist in any of the member, both of little apprehension. Overall, this glulam follows the usual problems of decay in the first foot, with little or no decomposition extending further into the member. The field picture in Figure 4.18.1 shows this result.



Figure 4.18.1: Field picture of Glulam 17.

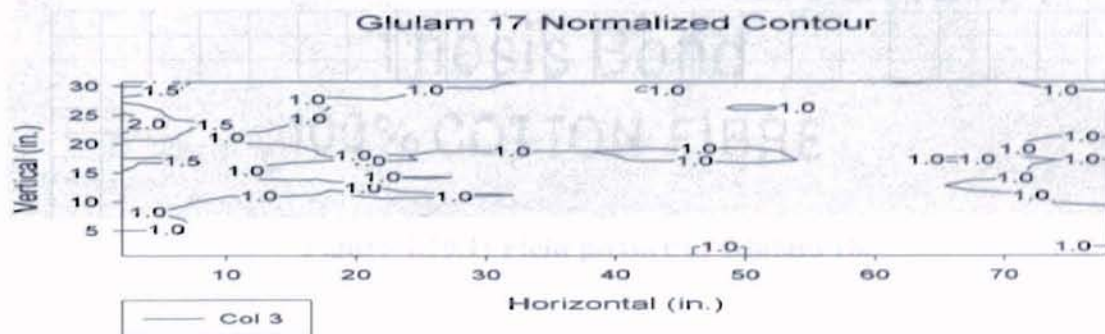
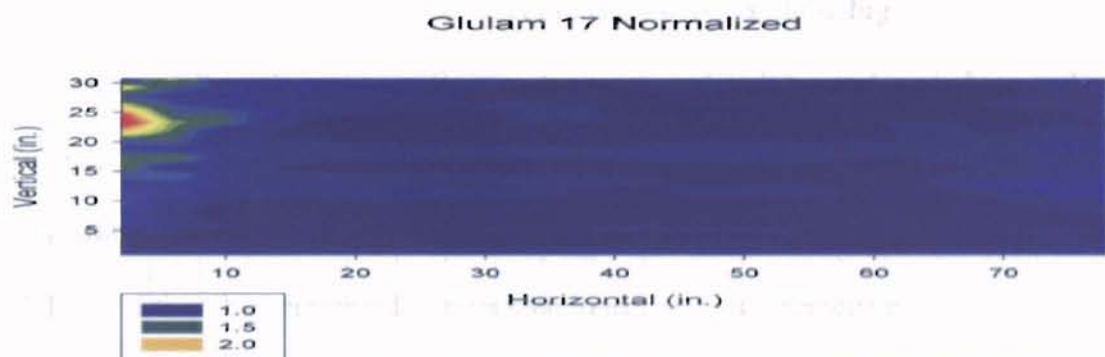
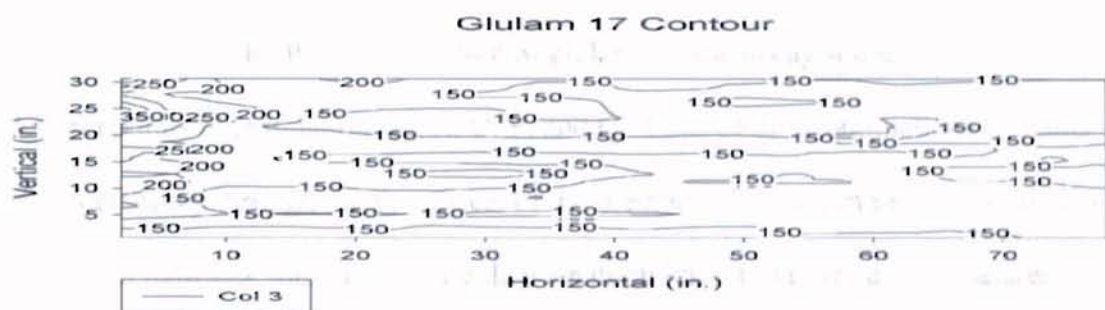
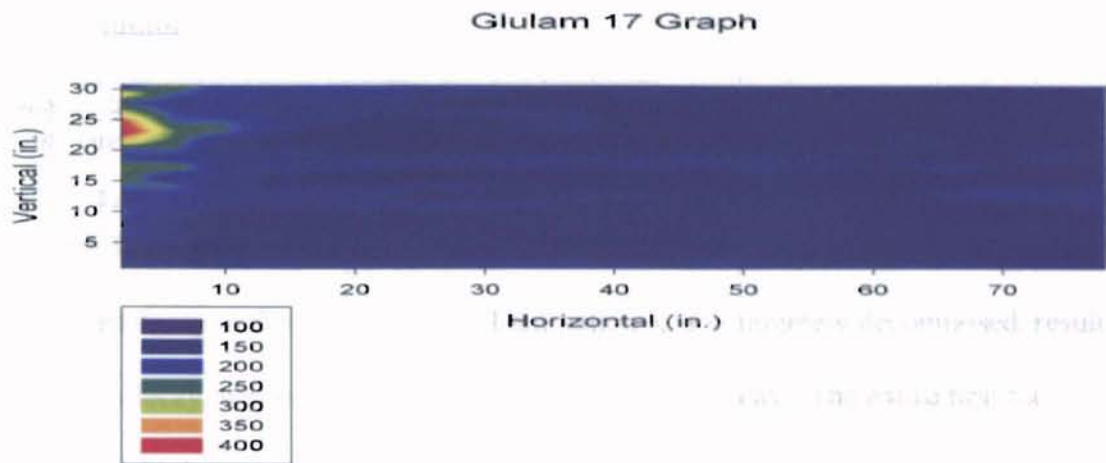


Figure 4.18.2: Glulam 17 Graphs

4.19 Glulam 18

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
18	10/14/00	76	none	20

Table 4.19: Test conditions of Glulam 18.

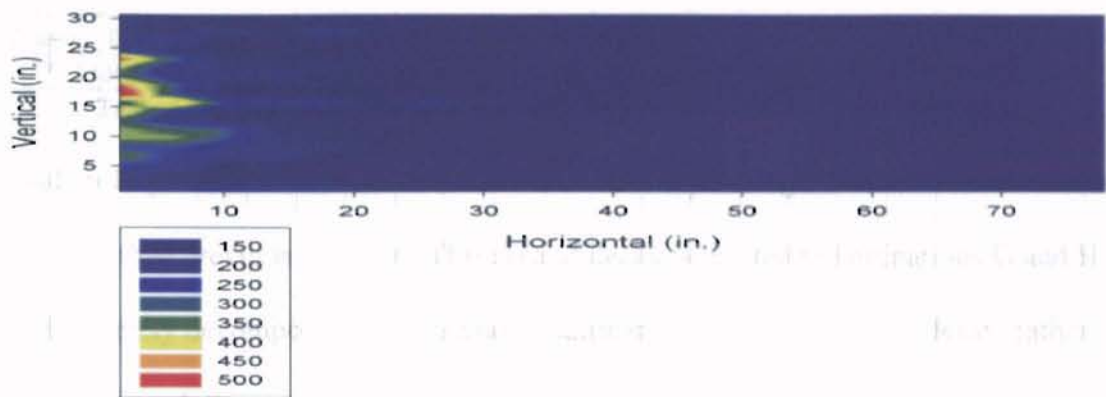
Glulam 18 contains a high concentration of moderate decay, with areas of severe and advanced decay in the first 4-inches. Lamination K is completely decomposed, resulting in severe decay, while lamination J contains advanced decay. The entire first foot contains a high concentration of moderate decay, with a few exceptions in the top half of the member's depth. Past the first foot of glulam 18, the decay somewhat subsides, with the exceptions of laminations K, N, O, P, and Q. Each of these laminations contains moderate decay through the first 2-feet of the member. The largeness, and continuity of the region indicates something more than a natural knot in the wood, so measures should be taken at this spot to avoid further decomposition. All of these high decay areas are easily seen on the color contour diagram in orange, red, yellow, and green hues and on the field picture in Figure 4.19.1. Primary emphasis should be placed on these laminations, especially since the decay is extending further than previously mentioned glulams. Other than the specific areas mentioned, no major regions of concern exist.



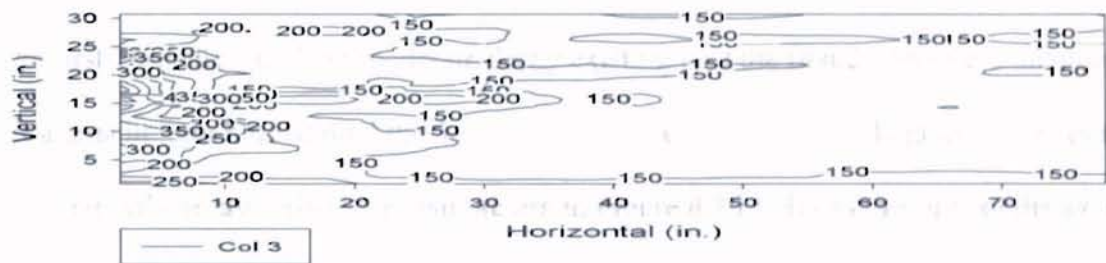
Figure 4.19.1: Field picture of Glulam 18.

4.19.2 Glulam 19

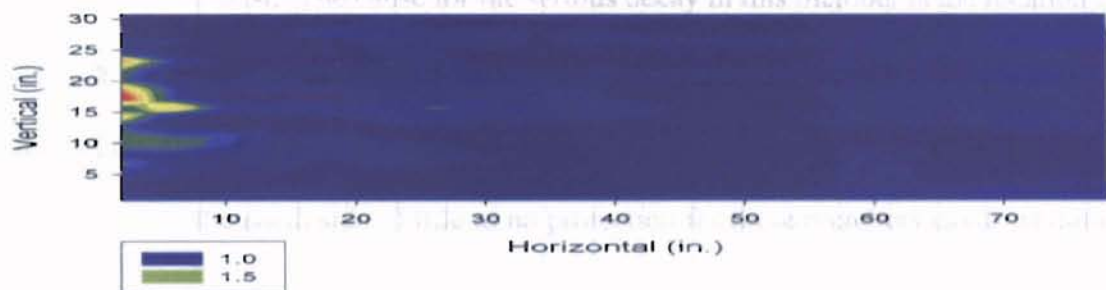
Glulam 18 Graph



Glulam 18 Contour



Glulam 18 Normalized



Glulam 18 Normalized Contour

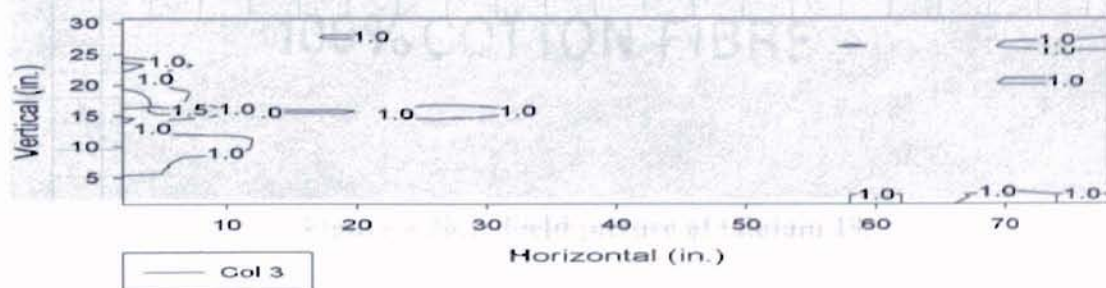


Figure 4.19.2: Glulam 18 Graphs

4.20 Glulam 19

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
19	10/17/00	69	none	14

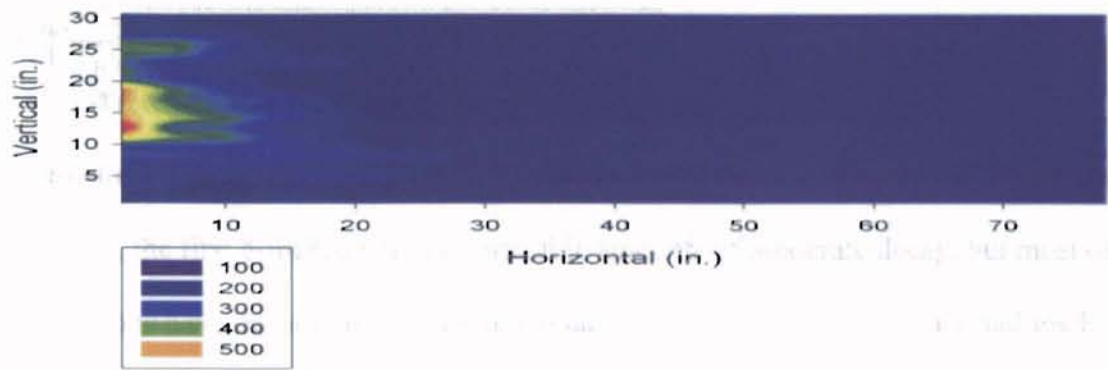
Table 4.20: Test conditions of Glulam 19.

Glulam 19 possesses more severe and advanced decay through the first 4-inches of the member than previous glulams. This area of decay is limited to laminations G and H with severely decomposed pockets and to lamination M with advanced decay, rather than spread through the entire depth of the member, with total decomposition occurring in spots G1 and H1. Past this region, a high concentration of moderate decay exists through the first 16-inches, with no moderate decay existing past the first 2-feet of the member. The area in light blue around the 5-inch mark on the color contour diagram indicates this lamination's decay. Also, the field picture in Figure 4.20.1 shows this area of decay as rotted wood on the left side of the picture. Other than the above-mentioned areas, no major concerns exist. The cause for the serious decay in this member is the location of the arch. A pattern has developed with the decay being more prevalent in the middle third of the glulams, such as glulams 4 through 8 on the south side and glulams 17 through 20 on the north side. Little to no protection for these members exists, resulting in more decay.

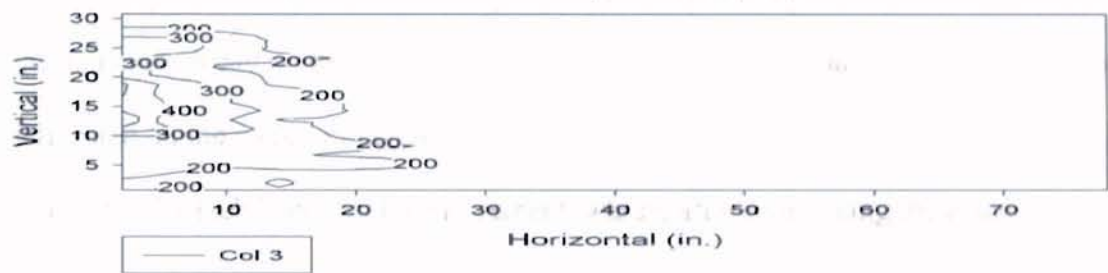


Figure 4.20.1: Field picture of Glulam 19.

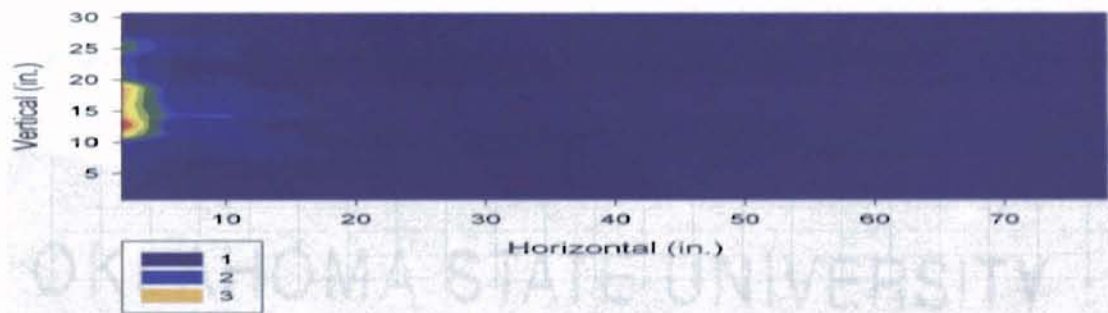
Glulam 19 Graph



Glulam 19 Contour



Glulam 19 Normalized



Glulam 19 Normalized Contour

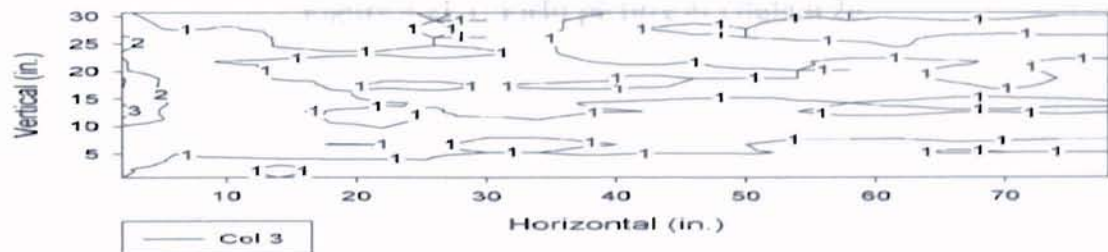


Figure 4.20.2: Glulam 19 Graphs

4.21 Glulam 20

Glulam 20 Graph

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
20	10/17/00	69	none	16

Table 4.21: Test conditions of Glulam 20.

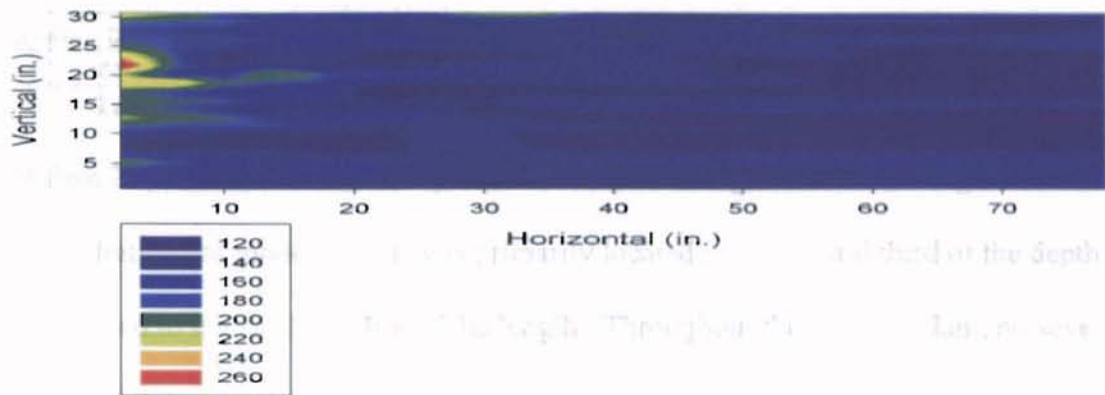
In glulam 20, decay does not persist through the entire depth of the member at any point. Actually, the first 8-inches have considerable amounts of moderate decay, but most of the laminations have decomposition limited to laminations F through M. Laminations F through I have moderate and early decay ranging from the ground connection up to 5-feet. This region is the largest amount of decay in the entire member. Lamination M also has moderate decay up to 3-feet of the member. These problematic areas are somewhat delineated on the contour diagram, but not fully. Also, lamination A has a green area around the 30-inch horizontal measurement, which, after referencing the excel worksheets, indicates moderate decay. The remainder of the member does not have any prime concern areas outside of the usual early decay, which can be seen in the field picture in Figure 4.21.1 in the good quality of the paint.



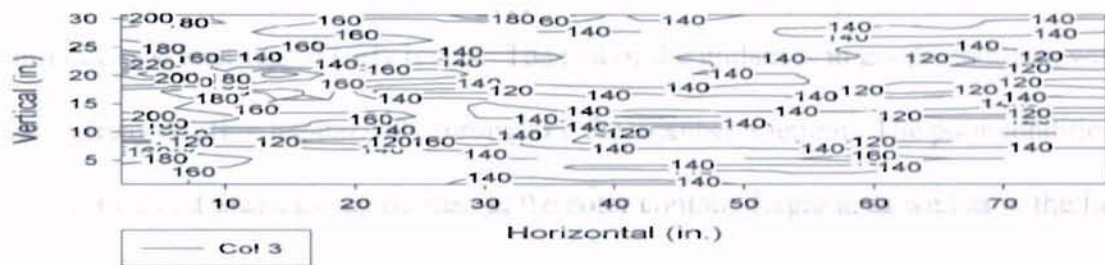
Figure 4.21.1: Field picture of Glulam 20.

4.21.2 Glulam 1

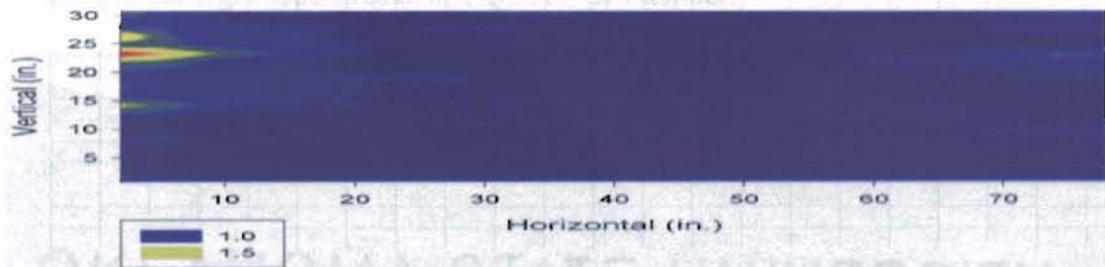
Glulam 20 Graph



Glulam 20 Contour



Glulam 20 Normalized



Glulam 20 Normalized Contour

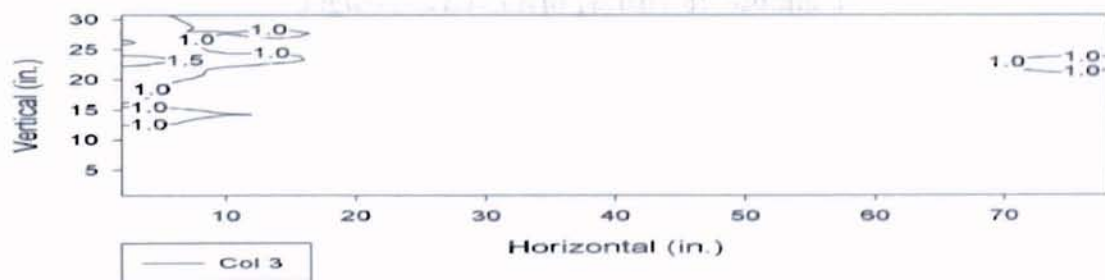


Figure 4.21.2: Glulam 20 Graphs

4.22 Glulam 21

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
21	10/22/01	64	none	22

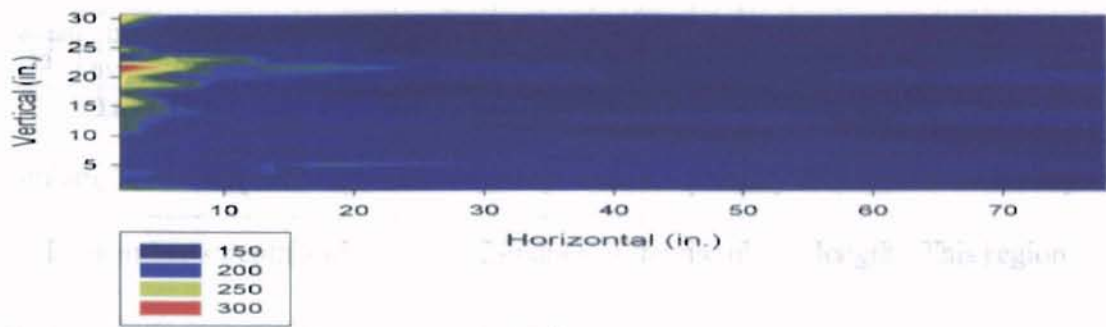
Table 4.22: Test conditions of Glulam 21.

Glulam 21 follows a similar decay structure as previous glulams in that high concentrations of moderate decay is primarily located in the central third of the depth, and limited to the first 8-inches of the length. Throughout the entire glulam, no severe or advanced decay exists, and the only crucial laminations are G and T. Moderate decay is present in this component through 3-feet of the member's length. From here, decay diminishes scatterings of early levels. The rest of the glulam is in good condition, with early decay existing haphazardly throughout the member's length. The poor condition of the beam's first 8-inches can be seen in the color contour diagram, as well as in the field picture in Figure 4.22.1. Also, the extended decay can be seen in the regular contour diagram in the light blue streaks throughout the member.

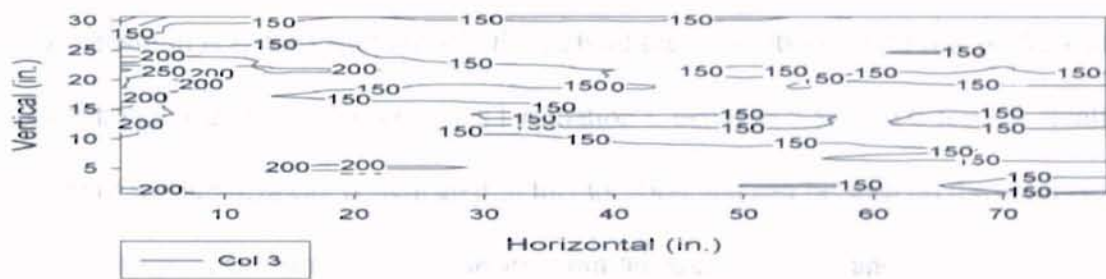


Figure 4.22.1: Field picture of Glulam 21.

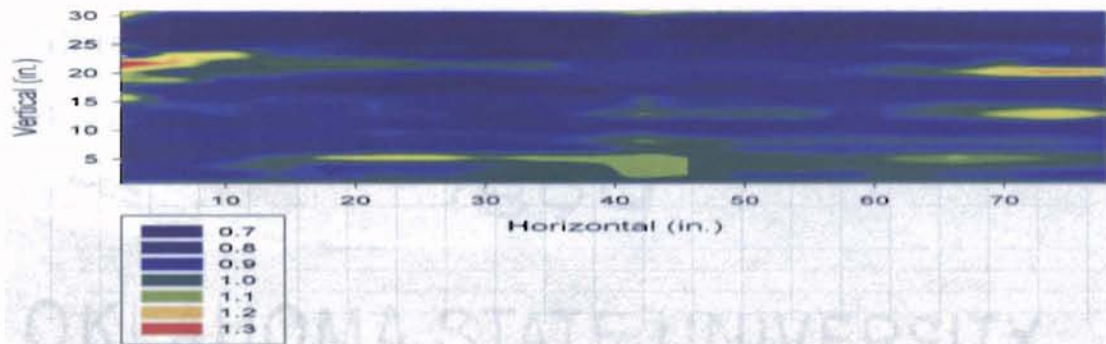
Glulam 21 Graph



Glulam 21 Contour



Glulam 21 Normalized



Glulam 21 Normalized Contour

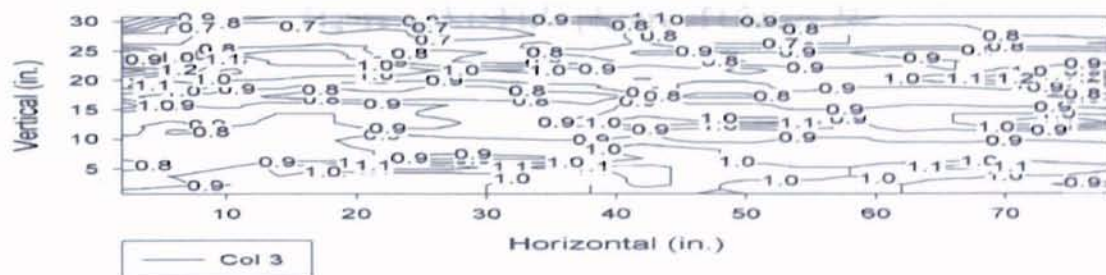


Figure 4.22.2: Glulam 21 Graphs

4.23 Glulam 22

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
22	10/26/00	62	none	18

Table 4.23: Test conditions of Glulam 22.

Glulam 22 has very little amounts of decay, with the primary area limited to the top third of the member's depth and the first 12-inches of the member's length. This region contains high concentrations of moderate decay, which is expected in trend with the other glulams. Yet, beyond this area, no decay exists above early, and most of that decomposition is spaced sporadically throughout the laminations, with few pockets of concentrated decay. One exception is lamination L between 5 ½- and 6-feet. A small pocket of moderate decay is indicated in this location and can be seen on the color contour diagram as a small, light blue area; but the area could be, and most likely is, a natural knot in the wood. Other than these limited regions of decay, glulam 22 is in excellent condition, despite what is indicated in the field picture in Figure 4.23.1. The peeling paint is misleading, since little decay actually occurs.



Figure 4.23.1: Field picture of Glulam 22.

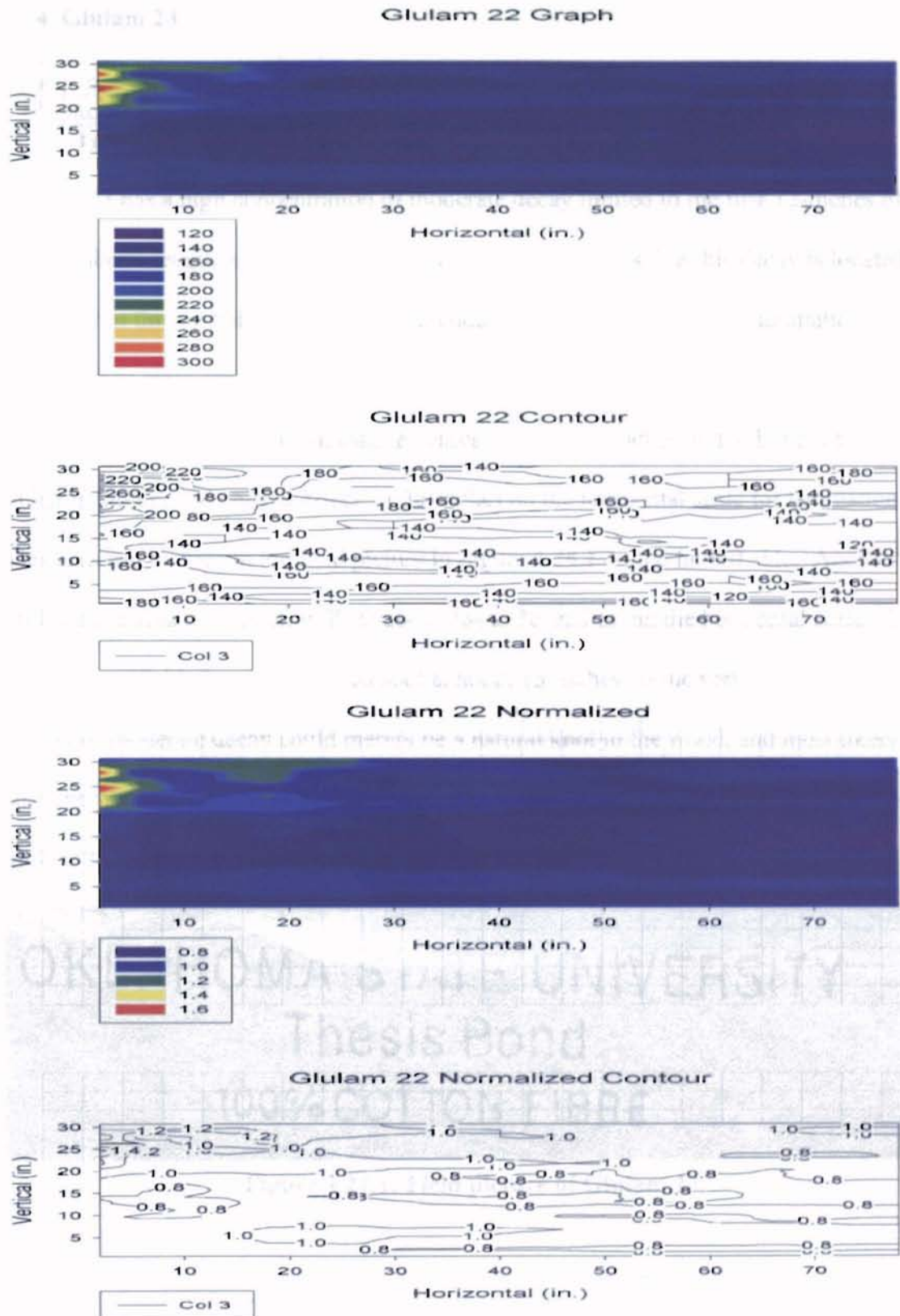


Figure 4.23.2: Glulam 22 Graphs

4.24 Glulam 23

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
23	10/28/00	52	none	22

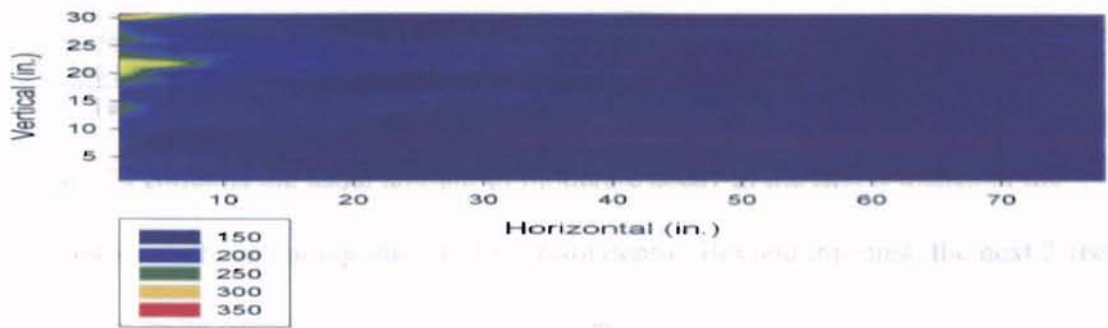
Table 4.24: Test conditions of Glulam 23.

Glulam 23 has a high concentration of moderate decay limited to the first 12-inches of the member's length, similar to previously discussed glulams, but this decay is located primarily in the top half of the beam. Extending further into individual laminations F and G, the decay areas can be seen as a light blue coloring, between 20- and 30-inches on the vertical scale. Yet, this decomposition ceases at about 20-inches on the horizontal scale in lamination F, and ends at 3-feet, or 36-inches on the horizontal scale for lamination G. This area can be seen in the field picture in Figure 4.24.1 on the far left side. Another problematic area is lamination K, at about 28- to 36-inches, on the horizontal scale. This area is identifiable by a small green spot at about 15-inches on the vertical scale. This pocket of moderate decay could merely be a natural knot in the wood, and most likely is since no major decay exists around the region. Other than these flawed areas mentioned, glulam 23 is in good condition and is easily treatable.

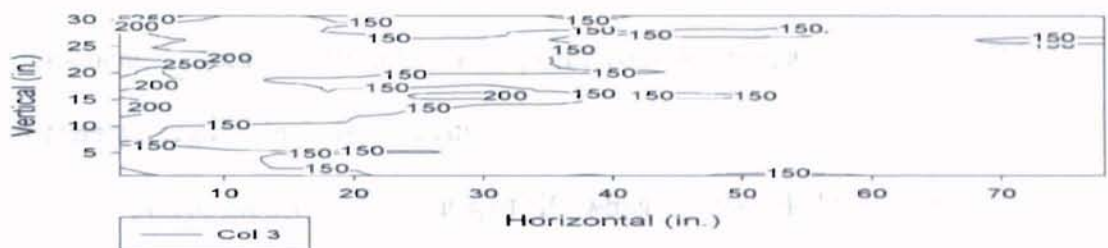


Figure 4.24.1: Field picture of Glulam 23.

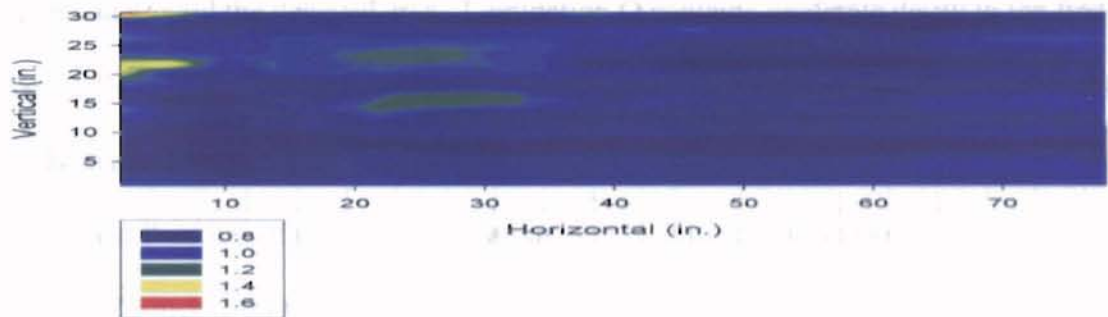
Glulam 23 Graph



Glulam 23 Contour



Glulam 23 Normalized



Glulam 23 Normalized Contour

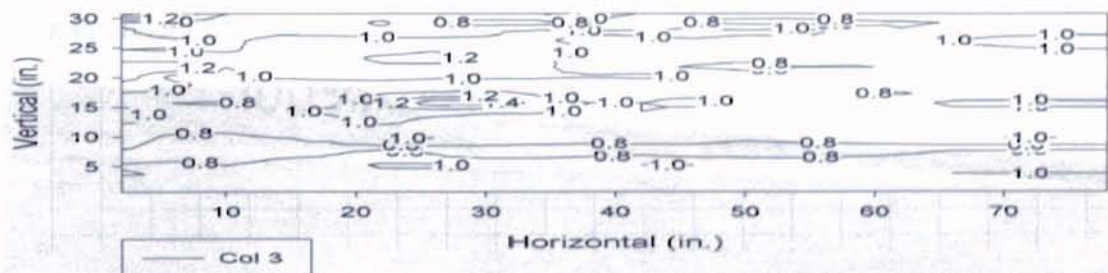


Figure 4.24.2: Glulam 23 Graphs

4.25 Glulam 24

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
24	10/28/00	52	none	23

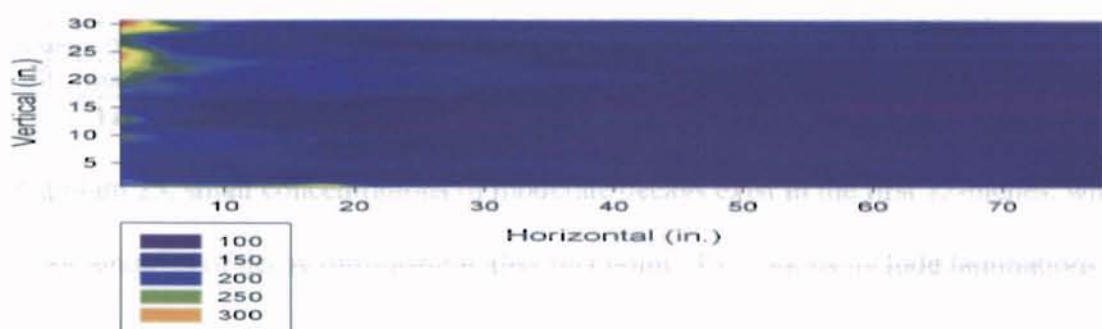
Table 4.25: Test conditions of Glulam 24.

Glulam 24 contains the usual amount of moderate decay in the first 8-inches of the member's length, extending through the entire depth. Beyond this area, the next 2-feet contain sporadic concentrations of moderate decay. Lamination U contains moderate decay in the first 2-feet of the member. This bottom lamination is a primary support component, so decay in this area needs special consideration and treatment. Other problematic regions include laminations K and O. Lamination K has an indication of randomly placed moderate decay at spot K9, which is most likely a natural knot in the wood due to the small nature of the area. Also, the decay does not slowly dissipate into the wood around the decayed area. Lamination O contains moderate decay in the first 3-feet of the member's length, which then diminishes to early decay for another foot. None of these areas can be seen well on the color contour diagram or the field picture outside of the first 8-inches of decay, except lamination U. Green and orange hues can be seen in the first 20-inches on the horizontal scale at the bottom of the member, which indicate the above-mentioned decay. Other than these problem areas, no major regions of concern exist in glulam 24.

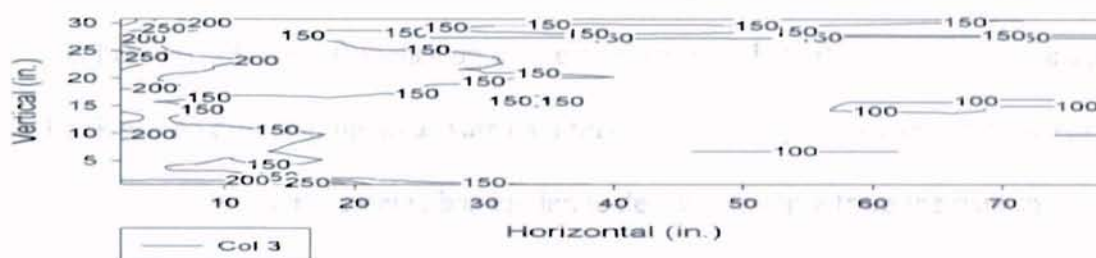


Figure 2.25.1: Field picture of glulam 24.

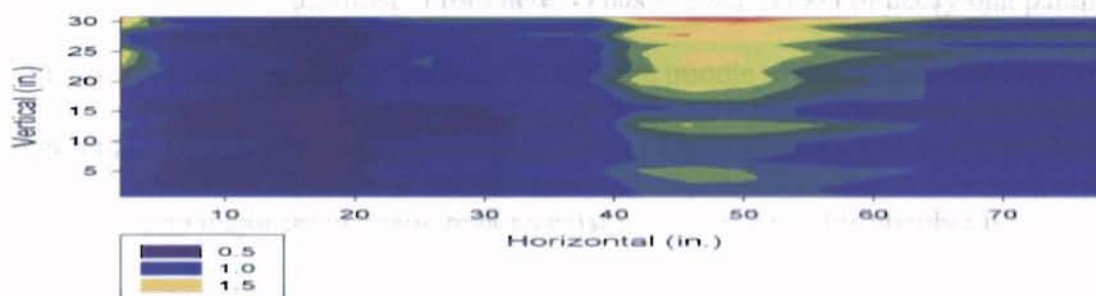
Glulam 24 Graph



Glulam 24 Contour



Glulam 24 Normalized



Glulam 24 Normalized Contour

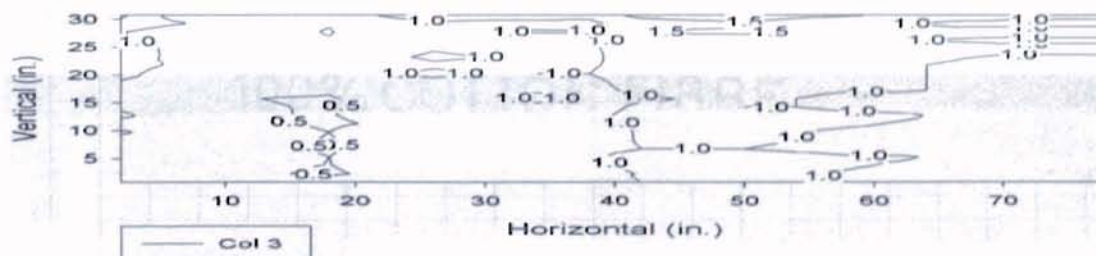


Figure 4.25.2: Glulam 24 Graphs

4.26 Glulam 25

Glulam	Date	Temperature (F)	Precipitation	Moisture Content
25	01/03/00	28	snow	22

Table 4.26: Test conditions of Glulam 25.

In glulam 25, small concentrations of moderate decays exist in the first 12-inches, with major amounts of decay diminishing after this point. Exceptions include laminations C, G, and H. In lamination C, a possible natural knot in the wood may be present between the first and second foot, as indicated in the color contour diagram by a small green pocket between 25- and 30-inches on the vertical scale and at 10-inches on the horizontal scale. Since no diminishing areas surround this region, decay is probably not the reason for the coloration. Lamination G has moderate decay extending from the base through the first 2-feet of the member. The red, orange, and green hues at about 20-inches on the vertical scale indicate this area. From here, G has another pocket of decay that parallels with decay in lamination H. This location is in the middle of the contour diagram, and represents high moderate decay from 3- to 4-feet of the member's length. Other than these areas, no major problematic regions exist in glulam 25. This member is in good condition because its location is between a brick wall and the OSU tennis courts. This coverage is the reason for the quality of the paint, showing little to no decay in the field picture.



Figure 4.26.1: Field picture of Glulam 25.

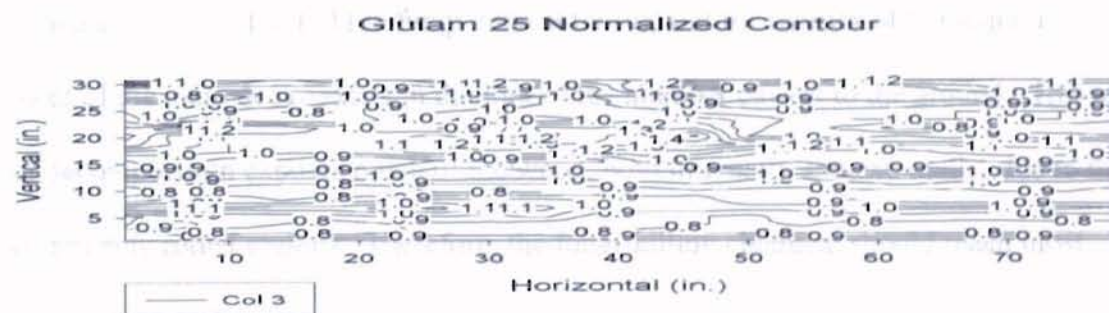
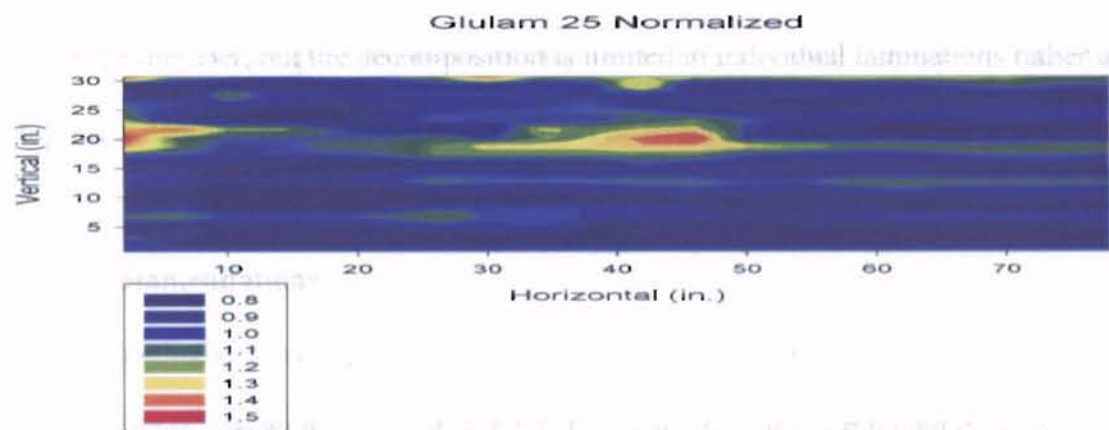
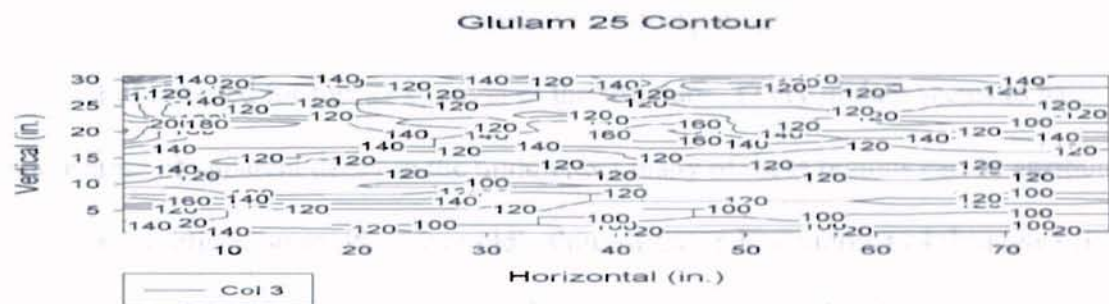
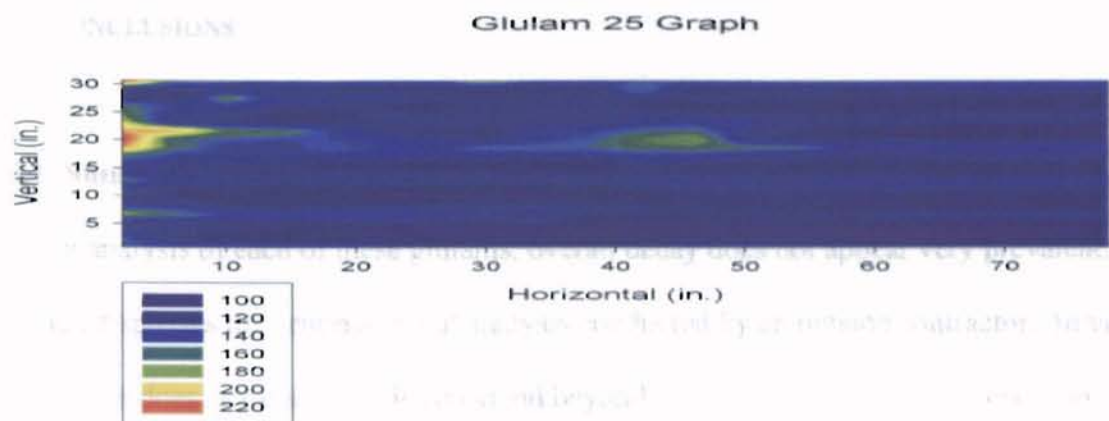


Figure 4.26.2: Glulam 25 Graphs

5. CONCLUSIONS

m. These first stems are the most

5.1 Summary

Upon analysis of each of these glulams, overall decay does not appear very prevalent, which disproves the original visual analysis conducted by an outside contractor. In very few cases does any decomposition extend beyond the first foot of the members. Yet, this area on each glulam is seriously diseased with a decay fungus, and treatment is imminently needed for further survival of the structure. Every glulam seems to have some areas of apparent decay in the middle, but many of these regions can be attributed to natural knots in the wood. The middle third of the arches, numbers 4 through 8 on the south side and 17 through 20 on the north, contain decay sporadically spaced throughout the entire member, but the decomposition is limited to individual laminations rather than the whole depth. This localized decay should be treatable since confined to a small area.

5.2 Recommendations

Several methods of curbing localized decay exist. All of these techniques begin with, first, killing the decay with an anti-fungal chemical. Yet, this compound may not penetrate the wood to kill the fungi present throughout the interior of the glulams, but most of the main decay exists in the foot of the member closest to the ground. This area of decomposition exposes much of the wood, both internally and externally, due to the completely rotted regions. Therefore, the fungi-killing chemical should reach most primary areas of decay or should penetrate far enough to exterminate a large portion of the fungi. After the decay fungi are killed, the rotted areas should be removed, and these

voids filled with an epoxy to add structural strength. These first steps are the most important to control the spread of further decay through the members.

Decay growth is affected by three primary factors including oxygen, temperature, and water. Most wood decay fungi are obligate aerobes requiring free oxygen for growth, but this atmospheric condition cannot be limited since oxygen is a naturally occurring element. Temperature affects crucial fungal metabolic activities that are controlled by enzymes, but, like oxygen, occurs out of the hands of mankind. Water is a critical component for fungal growth and must be present in appropriate quantities for fungi to digest the wood substrate, and this element can be controlled. The third recommendation for Annex survival is to add a localized roof covering over each glulam. This awning will divert direct precipitation from making contact with the wood, although air moisture content will still have some effect on the structure. Despite this, the adjusted path of the water should have a positive effect on the wood structure.

Final recommendations include structural additions to each glulam. A carbon retrofit could be employed, as has been used in other scenarios of this nature. This supplement would give more support to the individual members. Any other structural additions would be a good idea, yet financially, these supplements could be costly to the university. Therefore, killing the decay fungi, removing decayed areas, filling these regions with epoxy, and diverting the water flow from the members are the main recommendations for cost efficiency and further Annex survival.

voids filled with an epoxy to add structural strength. These first steps are the most important to control the spread of further decay through the members.

Decay growth is affected by three primary factors including oxygen, temperature, and water. Most wood decay fungi are obligate aerobes requiring free oxygen for growth, but this atmospheric condition cannot be limited since oxygen is a naturally occurring element. Temperature affects crucial fungal metabolic activities that are controlled by enzymes, but, like oxygen, occurs out of the hands of mankind. Water is a critical component for fungal growth and must be present in appropriate quantities for fungi to digest the wood substrate, and this element can be controlled. The third recommendation for Annex survival is to add a localized roof covering over each glulam. This awning will divert direct precipitation from making contact with the wood, although air moisture content will still have some effect on the structure. Despite this, the adjusted path of the water should have a positive effect on the wood structure.

Final recommendations include structural additions to each glulam. A carbon retrofit could be employed, as has been used in other scenarios of this nature. This supplement would give more support to the individual members. Any other structural additions would be a good idea, yet financially, these supplements could be costly to the university. Therefore, killing the decay fungi, removing decayed areas, filling these regions with epoxy, and diverting the water flow from the members are the main recommendations for cost efficiency and further Annex survival.

5.3 Conclusion

Upon completion of analysis of the Oklahoma State University Colvin Center Annex glulam arches, failure does not seem to be imminent. Upon completion of the structural analysis of the members, the previous suggestion that decay existed throughout the members has been proven incorrect. Although, the structural stability is rapidly decreasing with the degradation of the wood arches. Decay primarily exists in the bottom third of the exposed glulams presently but will continue to spread if the fungi are not killed. By adopting the above-mentioned recommendations, the future of the existing Annex is optimistic. Not only will the university be saved a costly expenditure, but also some of OSU's heritage will be preserved.

SELECTED BIBLIOGRAPHY

- Beall, Frank C., Tiitta, Markku, and Biernacki, Jacek M.** (1997). "The use of acousto-ultrasonics to detect biodeterioration in structural wooden members." *Proceedings of the Nondestructive Testing and Evaluation for the Aging Infrastructure*. American Society for Nondestructive Testing.
- Biernacki, J.M. and Beall, F.C.** (1993). "Development of an acousto-ultrasonic scanning system for nondestructive evaluation of wood and wood laminates." *Wood and Fiber Science*, 25(3), pp. 289-297.
- Bray, D.E. and Stanley, R.K.** (1997). *Nondestructive Evaluation*. McGraw-Hill, New York, NY.
- Emerson, R.N.** (1999). "Nondestructive Evaluation of Timber Bridges." Doctor of Philosophy Dissertation. Washington State University, pp. 180-181
- Forest Products Laboratory.** (1987). *Wood Handbook: Wood as an Engineering Material*. Agriculture Handbook 72. Washington DC: United States Department of Agriculture, pp. 4-2 to 4-44.
- Halabe, U.B., Chen, R.H.L., Allu, M., and Pei, L.** (1996). "Assessment of defects and mechanical properties of wood members using ultrasonic frequency analysis." *Materials Evaluation*, 54(2), pp. 314-322.
- Highley, T.L.** (1977). Requirements for cellulose degradation by a brown-rot fungus. *Material and Organism*. 12, pp. 25-36
- Lamble, J.H.** (1963). *Principles and Practice of Non-destructive Testing*. John Wiley and Sons, Inc. New York, NY, p. 238.
- McGonnagle, Warren J.** (1961). *Nondestructive Testing*. Gordon and Breach. New York, NY, p. 455.
- Microsoft Corporation** (2001). *Microsoft Excel Software*. Redmond, WA.
- Pellerin, Roy F., DeGroot, Rodney C., Esenther, Glenn R.** (1985). "Nondestructive Stress Wave Measurements of Decay and Termite Attack in Experimental Wood Units." *Proceedings of the Fifth Nondestructive Testing of Wood Symposium*. Washington State University. Pullman, WA, pp. 319-352.

- Ross, Robert J.** (1985). *Nondestructive Evaluation of Wood Products with Longitudinal Stress Waves*. Pullman, WA: Metriguard, Inc.
- Ross, Robert J., DeGroot, Rodney C., Nelson, William J., and Lebow, Patricia K.** (1997). "The Relationship Between Stress Wave Transmission Characteristics and the Compressive Strength of Biologically Degraded Wood." *Forest Products Journal*. Vol. 47, No. 5. pp. 89-93.
- SPSS Inc.** (2000). *SigmaPlot 2000 Software*. Chicago, IL.
- Thomas, Graham.** (1995). "Overview of Nondestructive Evaluation Technologies." *Proceedings of Nondestructive Evaluation of Aging Bridges and Highways*. The International Society for Optical Engineering (SPIE). Bellingham, WA. Vol. 2456, pp. 5-9.
- Wilcox, W.W.** (1978). "Review of literature on the effects of early stages of decay on wood strength." *Wood and Fiber*, 9(4), pp. 252-257.

VITA²

Sarah Rebecca Markes

Candidate for the Degree of

Master of Science

Thesis: NONDESTRUCTIVE EVALUATION OF OKLAHOMA STATE
UNIVERSITY COLVIN CENTER ANNEX DECAYED TIMBER ARCHES

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Enid, Oklahoma, on September 19, 1976, the daughter of David and Joyce Markes.

Education: Graduated from Enid High School, Enid, Oklahoma in May 1995; received Bachelor of Science degree in Civil Engineering from Oklahoma State University, Stillwater, Oklahoma in December 1999. Completed the Requirements for the Master of Science degree with a major in Civil Engineering at Oklahoma State University in December 2001.

Experience: Raised on a farm near Enid, Oklahoma; employed by Environtech Engineering, Inc. and Oklahoma Department of Transportation as a summer intern, 1996 and 1998, respectively; employed by Oklahoma State University, Engineering Department as an undergraduate and graduate teaching assistant, Fall 1999 to Spring 2001.

Professional Memberships: American Society of Civil Engineers, Chi Epsilon