In-Place Detection of Decay in Timber Bridges-An Application of Stress Wave Technology

Roy F. Pellerin and Jeff A. Lavinder (Authors), Washington State University
Robert J. Ross and Robert H. Falk, USDA Forest Products Laboratory
Norbert Volny, Volny Engineering

Abstract

A study was recently conducted to assess the technical feasibility of using stress wave nondestructive evalualion methods to locate decayed members in timber bridges.

Stress wave nondestructive evaluation techniques were used to locate decayed components in several timber bridges in eastern Oregon. Various stress wave techniques were used to conduct an in-situ evaluation of stringers, decking, and compression members Components suspected as having decay were identified and evaluated in a laboratory after dismantling. Both visual evaluation of the members and subsequent laboratory testing indicated that the stress wave techniques were able to locate decayed components with a high degree of accuracy.

Keywords: NDE, stress wave, residual strength, timber bridge, MOE, compression, decay, properties

Introduction

Evaluation and upgrading of timber structures is an important area of professional practice for a structural consultant. Design strength parameters for timber are known at the time of construction. The National Design Supplement tabulates various strength parameters for different types of wood (NDS 1991). Size, grade, and species are addressed in various tables in the supplement. Once the structure is built, there is no guarantee on its life span. If properly maintained and monitored, wood structures can last a long time. With the introduction of nondestructive evaluation (NDE), problem areas can be identified and removed, increasing the life of the structure.

There are many methods of determiniug the strength characteristics of the timber components, which are categorized into two classes, destructive testing and nondestructive testing. Destructive testing can only be performed in a laboratory. Nondestructive materials evaluation is the science of identifying the mechanical properties of a piece of material without altering its end-use capabilities (Pellerin 1994). Many wood structures, such as buildings and bridges, rely on the strength properties of the timber from which they are constructed. Testing procedures used in NDE can be utilized to recognize potential problem areas in all structures. Due to the natural origins of wood, the potential is there for decay. With the introduction of NDE, it is possible to locate problem areas and fix them before they become hazardous. Through the use of stress wave technology, the progression of decay can be identified and the component evaluated for removal. Replacing components, rather than the structure, is time and cost efficient (Hoyle and Rutherford 1987).

Wood structures, generally, are subject to degradation of their structural integrity due to decay. Periodic inspection of wood structures is necessary to insure continued performance. Stress wave technology has proven to be a successful method of inspecting wood structures (Ross and Pellerin 1991). If decay is present in the member being tested, the attenuation and propagation time passing through the member is increased. Several techniques that utilize stress wave propagation time have been developed for the in-situ evaluation of wood structures. The need for NDE is expanding due to the increasing amount of resources that are being devoted to repair and rehabilitation of existing structures rather than to new construction (Ross and Pellerin 1991). Raising costs of new construction have been attributed to the increase in prices for wood. These increases had engineers looking for ways to cut their costs. The answer is to repair existing problem areas instead of replacing the entire structure. As more resources are devoted to repair, the need for in-situ assessment of structures is evident. Stress wave technology is a cost efficient solution to the problem of in-situ evaluation.

There are three main goals in this project. The main goal in this research was to be able to validate an in-situ NDE stress wave evaluation with actual destructive and nondestructive laboratory results. The NDE is to show where decay is in the bridge and the extent of the damage caused.

The second goal of this research is to verify in-situ data with laboratory data. The goal was to correlate the two sets of data and prove that an in-situ evaluation gives accurate results. These results, in turn, would show that a timber bridge can be assessed in-situ and the results would not be subject to question.

The third goal of this research is to establish the feasibility of accurately predicting residual strength from stress wave evaluation. Correlating the stress wave evaluation with column capacity is a major part of the third goal. Using destructive compression testing, the capacity of each column can be determined. By comparing the capacity to the tabulated National Design Specifications value for sound wood, the residual capacity can be determined.

Case Studies

Two timber bridge inspection case studies are presented. Both bridges are rural bridges found in Umatilla County, Oregon. Inspection methods and procedures include sounding, stress wave velocity, and moisture measurement. These two bridges were classified by the Umatilla County Bridge Department as being deficient and in need of repair. The opportunity arose for a research team from WSU to perform a nondestructive evaluation (NDE) on these bridges to detemined their deficient components. A complete analysis was to be performed on the bridges before and after removal. After removal, the components of the bridge were taken to the Wood Materials and Engineering Laboratory (WMEL) at WSU for verification of results.

There were two main goals in this project. The first goal was to perform stress wave NDE on a bridge in place. The NDE was to show where decay was in the bridge and the extent of the damage that it had caused. NDE is more thorough and scientific than the visual inspection that most timber bridges get for evaluation. Where visual inspection will spot a good portion of the decayed material, it can also miss possible decayed sections and condemn sound sections. Eliminating the guesswork involved in a simple visual analysis is the first step in proceeding to a more scientific approach to bridge analysis. Avoiding condemnation of a structure with limited amouts of decay can minimize the extent and cost of unnecessary replacement.

The second goal of this research was to verify in-situ data with laboratory data. The goal was to correlate the two sets of data and prove that an in-situ evaluation gives accurate results. These results, in turn would show that a timber bridge can be assessed in-situ and the results would not be subject to question.

The list of deficient bridges presented by the Umatilla County Bridge Department contained two bridges that were scheduled for immediate removal. These two bridges were ideal for the proposed research, since there immediate removal would allow the laboratory evaluation to be performed soon after the in-situ evaluation.

Bridge 529

Bridge 529 was not found on the County's original list of deficient bridges. It was placed on their list and scheduled for immediate removal when, on a routine inspection, the stringers were found to be decayed on the ends.

Bridge 529 consisted of steel side trusses, concrete abutment wall, and wood decking and stringers. The stringers were untreated and sat on the abutment wall (Figure 1).

Bridge 529 spanned a creek that flowed only in the spring. During high water, it was not uncommon for water to be splashed up onto the abutment wall ledge. Having no way of draining, the water was absorbed by the untreated stringers. This additional moisture created

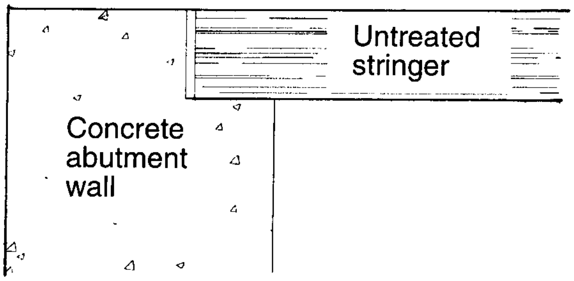

Figure 1—Drawing of wall and stringer.

an environment where decay could flourish in every one of the stringers. The stringers' ends decayed at approximately a 45° angle and were starting to slip off of the wall.

Inspection of Bridge 529

The inspection of Bridge 529 started with a visual inspection and evaluation. By picking out the obvious decayed material, the damage done by the high water could be determined. Through NDE, the evaluation could be taken further to determine the extent of decay.

The visual inspection yielded that the stringers had extensive decay in the ends that sat on the abutment wall. This determination matched Umatilla County's bridge inspectors evaluation. The condition of the tops of the stringers, where the decking was nailed to them, was uncertain. The decking appeared to be in good shape. Since the decking had no wearing course, water was free to fall between the deck planks onto the tops of the stringers below. The potential for decay existed in the tops of the stringers since water was able to penetrate to the them through the spaces between the deck pkanks.

The second phase of NDE was to start testing the components. The stringers were marked at two foot intervals lengthwise, two inches from each edge, and on centerline transverse. The stringers were measured to be 3.75 inches by 11.75 inches by 20 feet long. Transverse stress wave evaluation was completed on the stringers at the above intervals. Longitudinal stress wave times were taken for a few select stringers. The stop accelerometer was clamped to the decayed end due to that end being inaccessible. The accelerometer was clamped as close to the decayed end as possible.

The inspection of Bridge 529 was completed using a Nicolet 410 oscilloscope and Metriguard 239A stress wave timer. Longitudinal analysis of the decking was completed using the oscilloscope. Each deck member was evaluated twice for accuracy. The stringers were evaluated by means of transverse stress wave evaluation.

Analysis of Field Data— The stringer's modulus of elasticity (MOE) was calculated from the longitudinal stress wave velocity and mass density, which was derived from the weight and dimensions of the member. Using a template, stress wave times were recorded and probable decay areas marked out.

Testing at the Wood Materials Engineering Laboratory— Six stringers and five deck planks were brought back to the WMEL at WSU and reanalyzed. All of the stringers were again visually inspected for decay. The ends of the stringers had excessive decay where they sat on the abutment wall. It was observed that a couple of the stringers had decay pockets along the top where the deck planks were secured. The stringers were sketched and the visual decay marked on the drawings (Figure 2).

The stringers were evaluated in the laboratory the same way they were tested in the field. The stringers underwent longitudinal and transverse stress wave evaluation. In addition to the longitudinal stress wave evaluation with the oscilloscope, additional procedures were used to evaluate the stringers. Using the Dolch PC, pulse-echo times were recorded and their corresponding MOE calculated. The Metriguard stress wave timer was also used to record stress wave times.

The deck members of Bridge 529 were evaluated using longitudinal stress wave evaluation and compared to the results that we obtained in the field. The stress wave times were converted to MOE values and then graphed against each other.

A regression coefficient (R^2) value of 0.79 was obtained from the in-situ versus laboratory longitudinal stress wave times. The regression coefficient predicts the variability in the data, with an R^2 of 1 being perfect. Figure 3 shows the data of in-situ longitudinal stress wave time graphed versus laboratory longitudinal stress wave time.

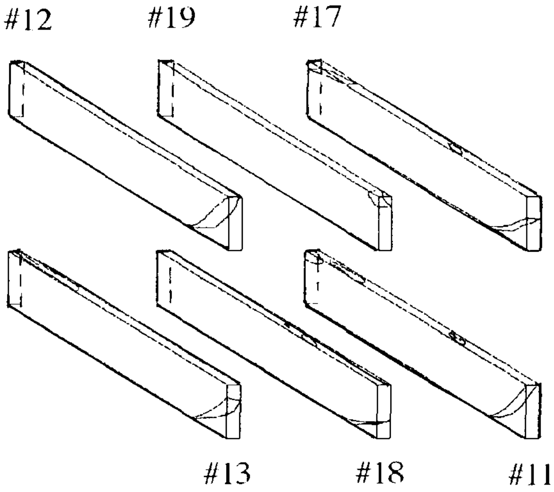

Figure 2—Sketchs of Bridge 529 stringers and decayed areas.

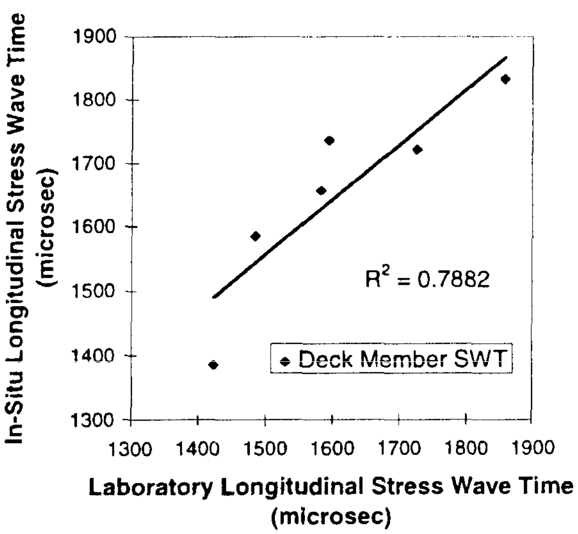

Figure 3--Laboratory stress wave time versus in-situ stress wave time for Bridge 529.

In summary the results for Bridge 529 showed that there was severe decay damage to the ends of the stringers and no decay damage to the decking. Longitudinal stress wave times are often analyzed as microseconds per foot (ps/ft) rather than inches per millisecond. Values for sound wood, moderate decay, and severe decay can all be derived from the values given in Table 1. Generally, longitudinal stress waves in sound wood travel at a rate of approximately 60 µs/ft and transverse waves travel at a rate of approximately 200 µs/ft in untreated sound wood.

The stress wave travel rates in the stringers varied from 56 µs/ft to 64 µs/ft using a Nicolet 410 oscilloscope. In-situ evaluation of the stringers was used with a clamped accelerometer due an end being restricted. Having the end that was decayed bypassed, the longitudinal stress wave times were not representative of the entire length of the stringer. There is obvious decay in all of the stringer ends. However, looking at the members stress wave transit rate, no decay would be assumed. If the Dolch PC pulse-echo technique were used, an analysis could be done from end to end. The Dolch analysis produced travel rates between 56 µs/ft to 74 µs/ft. The variation is small between the Dolch and Nicolet, but noticeable. The difference in times is attributed to the decayed end.

The decking yielded results that the members were structurally sound without any noticeable decay.

The NDE of Bridge 529 produced similar results for the in-situ evaluation and the laboratory evaluation. The variability between the tests that were performed was small. The evaluation of the deck members yielded a 0.79 R^2 regression coefficient. The quality of the deck members was high. There was no visible or detectable decay in any of the deck members. The treated decking had held up to the weather and abuse sustained by traffic. However, the stringers did not fair as well as the decking. The untreated stringers were very susceptible to decay. They were exposed to excessive moisture caused by overspray from the creek at high water. Improper drainage capacity on the abutment allowed the water to sit on the sill until the stringers absorbed it. The combination of being untreated and sitting in water led to the excessive decay encountered in the NDE of the stringers.

Bridge 117

Bridge 117 was on the Bridge Department's list for immediate replacement. The inspector for the county had assessed the bridge and determined that the columns that supported the bridge were deficient.

Inspection of Bridge 117— The NDE of Bridge 117 started with a visual inspection. Overall, the bridge was in good shape except for the columns and wings. The columns (Figures 4 and 5) had a few visual signs of decay. Water had leaked through the deck and had introduced moisture to the stringers, caps, and columns. Bridge 117 spans a runoff creek bed that was dry at the time of our evaluation. The bridge was on a rural road that was subjected to loaded grain trucks and combines.

A complete NDE of Bridge 117 was accomplished in four hours time. Longitudinal stress wave evaluation was performed on all of the deck members using the Nicolet 410 Oscilloscope. The transverse evaluation of the caps, columns and stringers was performed with the Metriguard 239A stress wave timer. No signs of decay

Figure 4—Columns 1-5

Figure 5—Columns 7-11

were evident in the visual inspection of the stringers. Two stringers were marked and evaluated with transverse times at every two feet intervals at two inches from the top and bottom, and at the centerline. The outside two stringers were picked for laboratory for evaluation since they were the most susceptible to weathering and decay. The columns were marked every two feet and transverse stress wave times were taken at the centerline of each column. Column 11 showed advance signs of decay due to high stress wave times and the transverse stress wave spacing was reduced to six inches. The caps were tested at the location where every column was connected.

Analysis of Field Data— The field analysis was broke down into three groups: decking, caps and stringer, and columns. The first group of data that was analyzed was the decking. The longitudinal stress wave evaluation did not show any deficient members. All 19 members were tested twice for accuracy. From the NDE results, it was determined that the decking was in good shape and was not in need of replacement.

The NDE of the bridge proved that the caps and stringers were in excellent shape. Questionable areas on the stringers were marked to be verified by the laboratory testing, but generally the analysis proved the stringers to be in excellent condition. The caps had very consistent times throughout the respective lengths of each member. The end of the south cap did have a higher stress wave time than the rest of the timber and, therefore, was marked for laboratory verification.

The main reason the bridge was on the deficient list was due to the columns. Visual inspection revealed that only a couple of the columns had obvious areas of decay. The stress wave evaluation was conducted by inking readings at the bottom, top, and middle of the columns along the centerline. Through NDE, all of the columns were determined to have some decay.

Laboratory Evaluation of Bridge 117— The laboratory evaluation at the WMEL began with a visual inspection of all the components. The stringers, decking and caps appeared to be structurally sound. Column inspection revealed excessive decay to most of the bottoms and a few of the tops. Figure 6 shows the tops of the columns and the decay damage; Figure 7 shows the bottoms of the columns.

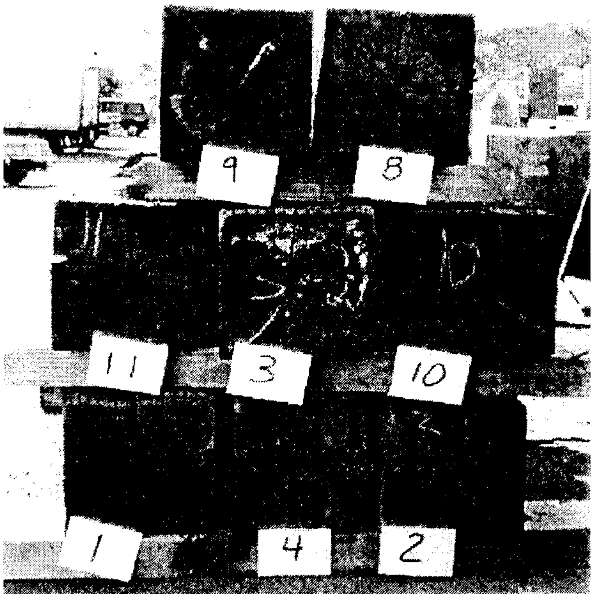

Figure 6—Tops of Columns

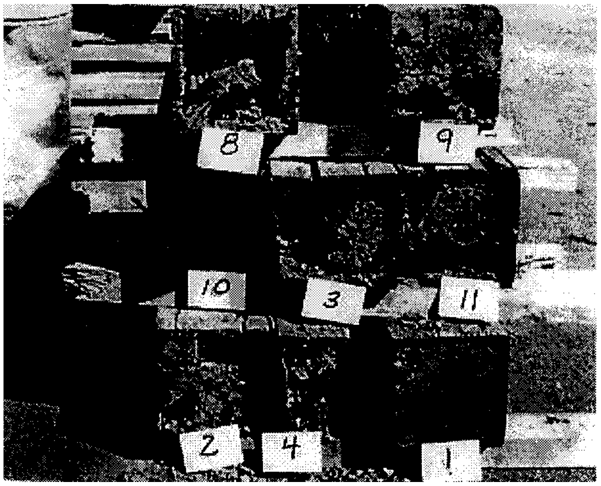

Figure 7—Bottoms of Columns

The second phase of the evaluation in the laboratory was to verify the results we tabulated with our in-situ assessment. The testing methods in the laboratory would follow, as closely as possible, to the in-situ testing that took place. Further laboratory testing would expand the testing done in the field in order to map out the decayed sections in the components of the bridge.

Caps And Stringers— The caps and stringers were the first to undergo the stress wave evaluation. The stringers were determined to be structurally sound with no decay. Due the good quality of the timbers, only two stringers were tested in the field. Both outside stringers were tested since they would be the most probable of being deficient due to being the only two exposed to weather. Field results and conclusions were verified by the laboratory results.

In-situ, the caps had been tested immediately next to where the columns came into them at the centerline of the cap. Stress wave times at the WMEL were taken on the centerline as well as three inches off centerline each way. Field results were again verified by the laboratory results. The questionable end of the south cap that raised concern in the analysis of the field data was verified by the laboratory results showing high stress wave times. Visual inspection of the end showed a split that caused the high stress wave times. Overall, the caps were in excellent shape except for a few splits. Rebar had been driven into the cups where the columns were connected to the caps. This rebar had initiated and amplified some of these splits.

Columns— The columns underwent an extensive stress wave evaluation to determine the extent of decay in each one. Values for sound wood, moderate decay, and severe decay for this project were configured and tabulated in Table 1.

Table 1—Laboratory conclusions for decay detection.

Column Condition	Stress wave time (μs/ft)
Sound wood	250-300
Incipient decay	300-500
Moderate decay	500-800
Severe decay	800-2000
Extreme decay (shell only)	2000+

In the laboratory the columns were evaluated from side to side and front to back. The field times were side to side transmission. Front to back times were taken to help map out possible decay areas. Many of the bottom ends of the columns were so badly degraded that it was not possible to get stress wave times.

The field evaluation correlated well to the laboratory results, both identifying decayed areas. The direct correlation of times between the laboratory and in-situ testing was not a goal of this research. The interest was more in the fact that both procedures were uble to spot problem areas.

All but four of the columns were loaded to failure in compression. The setup for the compression test can be seen in Figure 8. Figures 9 and 10 show the top and bottom, respectively, of column 5 before testing. Before the compression test was performed, the ends were squared. The top of the column can be seen to have extreme rot in the center and only a shell of good wood holding the column together. Creosote penetration of the column top was minimal. The bottom of the column did not show any visual signs of severe decay. However, the stress wave analysis showed that the entire column was decayed.

Column 12 was a corner column, as was column 5, that did not have a large amount of decay, compared to column 5. After the ends were squared the column was visually inspected for internal decay. The visual inspection showed that there was no decay present. However, the stress wave analysis showed that there was a pocket of decay in the bottom end of the column. Figures 11 and 12 show the top and bottom of column 12.

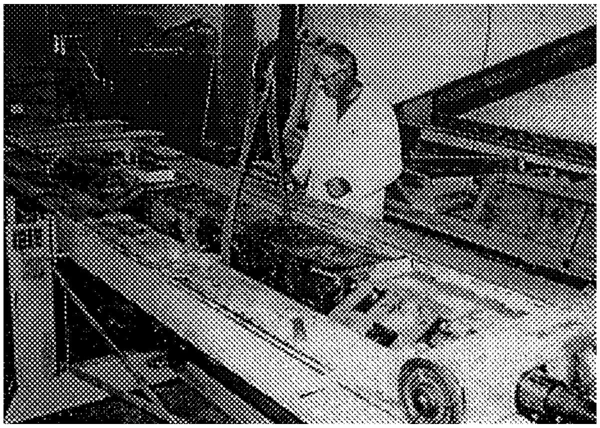

Figure 8—Column compression test

Figure 9—Top of column five

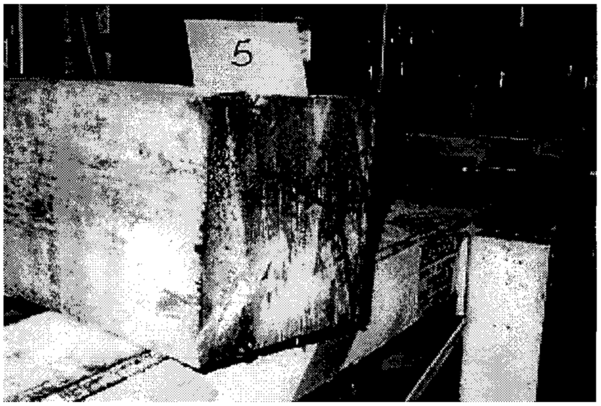

Figure 10—Bottom of column five

The columns were loaded until failure. Column 5 failed abruptly (Figure 13) at an ultimate load of 37.5 kips. The National Design Specifications (NDS 1991) Supplement tabulates compression parallel-to-grain values for Douglas-fir Larch as 700 psi for No. 2 grade in Table 4D. Adjusting for loading rate and changing the tabulated fifth percentile to the median value, the capacity should be 258 kips. The load duration factor can be calculated from Figure 14 (National Design Specifications 1991). The columns' low capacity is a direct result of the extensive decay in the column. Decay had completely deteriorated the interior of the column. Figure 15 shows column 5 after the compression test.

Column 12 was loaded to an ultimate load of 172.0 kips. The column failed by a compression failure where the end was decayed (Figure 16). The visual inspection failed to identify the decayed area. However, the stress wave evaluation of column 12 showed a high stress wave time at the point that it failed in compression. The decay pocket can be seen in Figure 16 on the upper left corner of the picture.

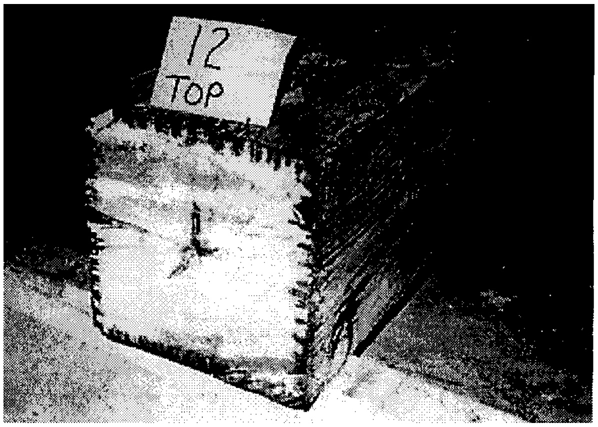

Figure 11—Top of column 12

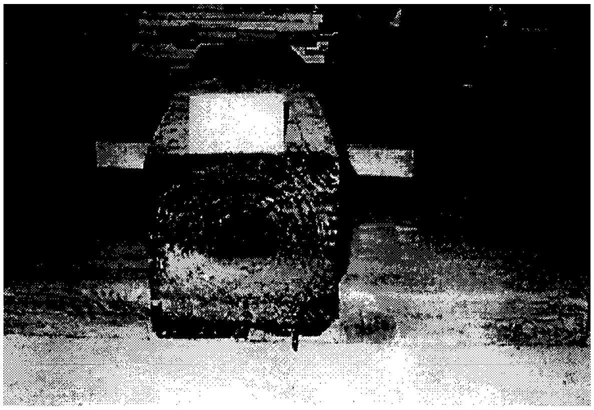

Figure 12—Bottom of column 12

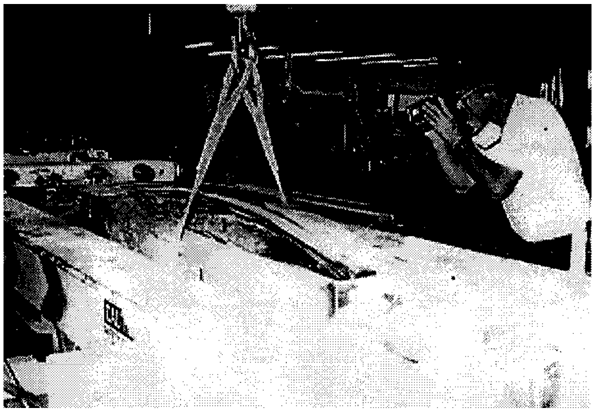

Figure 13—Column #5 at failure in the compression test

The rest of the columns, except three which exceeded the machine capacity and one that fell apart before testing, were tested and their capacities compared to the NDS (1991) value for sound wood. Figure 17 is a graph of the columns' capacity divided by the NDS (1991) value for sound wood versus stress wave time. The capacity is in terms of percentages of the NDS

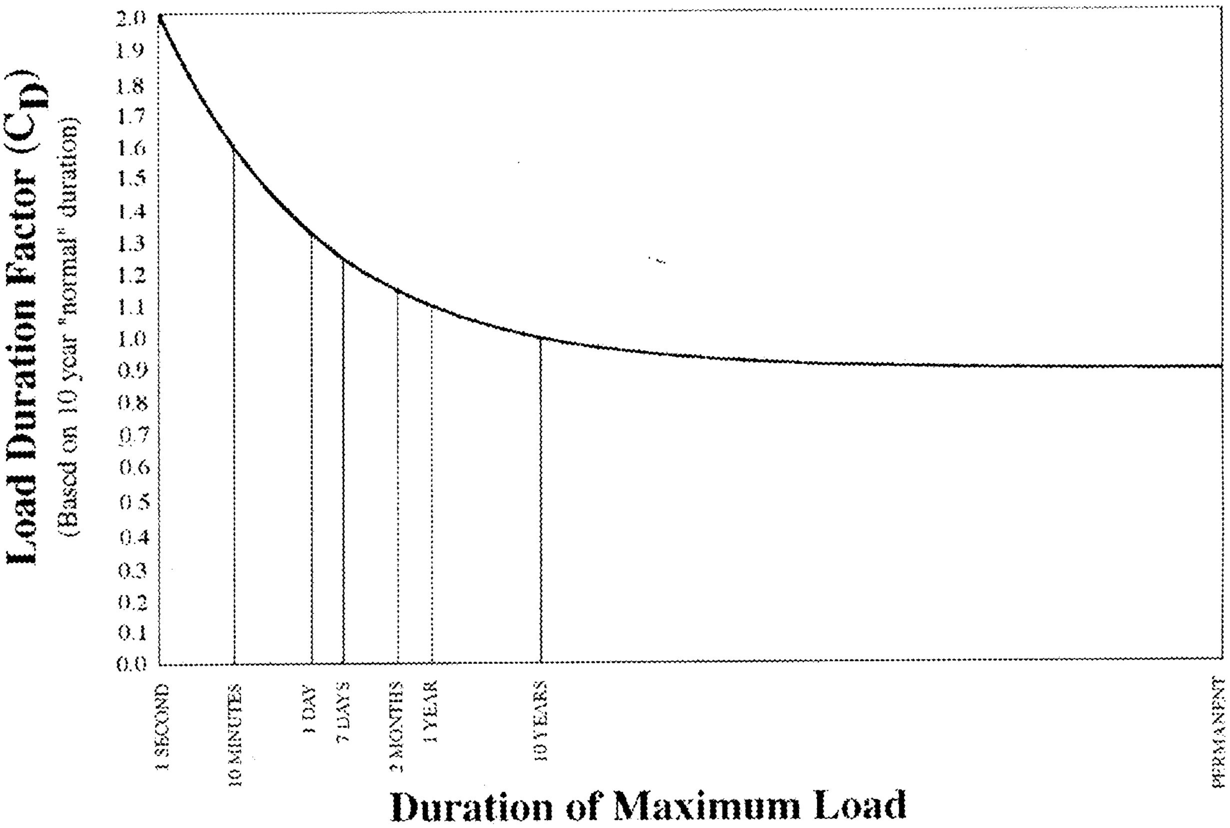

Figure 14—Load duration factors for various load duration (NDS 1991)

(1991) value. The worst cross section of the column from the transverse stress wave evaluation was used in the graph. It was assumed that failure would occur at the weakest cross section of the column. An R^2 regression coefficient of 0.91 was determined through least squares linear regression. The high regression coefficient shows that the variability in the data is low and that using stress wave evaluation to predict residual compressive strength is a strong possibility.

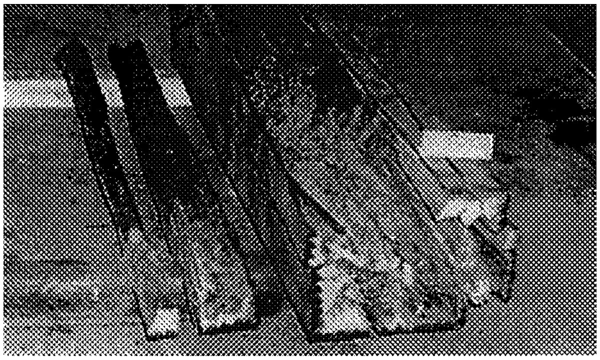

Figure 15—Column #5 after failure

Decking— Longitudinal stress wave evaluation of the decking produced results that showed no decay throughout the members. The Nicolet 410 Oscilloscope was used to obtain the longitudinal stress wave transit times in the laboratory. Two readings were taken in the field for accuracy. Five readings were taken at the WMEL for increased accuracy. The

Figure 16—Column #12 after failure

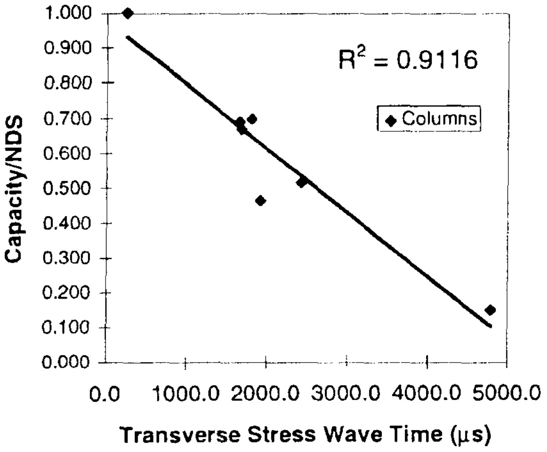

Figure 17—Graph of column capacity/NDS median capacity versus transverse stress wave time

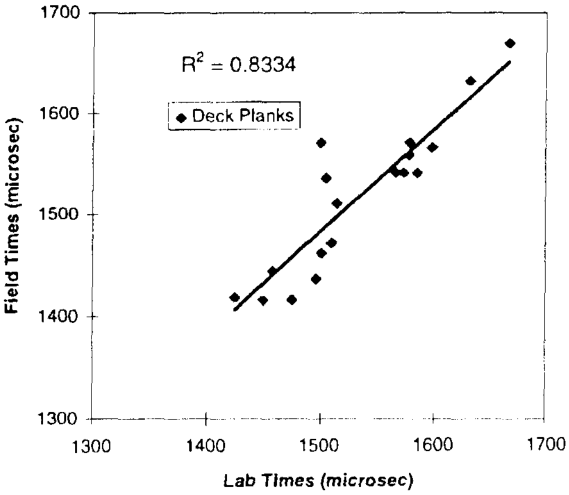

Figure 18—Graph of field longitudinal stress wave times versus laboratory longitudinal stress wave times

averages of each were plotted against each other and can be seen in Figure 18.

In summary, Bridge 117 turned out to be a perfect case study. The in-situ NDE of Bridge 117 was verified by the laboratory NDE. The bridge was placed in 1965, giving it a 30 year life span at the time of removal. The bridge, given the life span, was in remarkable shape, except for a few components. Deterioration due to decay in the columns and backwalls had made the replacement of the bridge necessary.

The decking was in excellent shape with no visible or detectable decay. Longitudinal transit rates for the stress waves averaged 64 µs/ft for the laboratory evaluation and 63 µs/ft for in-situ evaluation. The regression coefficient between in-situ stress wave times and laboratory times produced an R^2 value of 0.83. The high regression coefficient, and almost exact transit rate average, lead to the conclusion that results obtained in the field could be reproduced easily in the laboratory for longitudinal stress wave evaluation.

The caps and stringers were evaluated at the same locations as those in the field. Longitudinal stress wave evaluation was not performed on either component. Instead, a more detailed transverse stress wave evaluation was performed on the members to determine the presence of decay. Initial in-situ evaluation of the stringers and caps yielded results of showing no decay in the members. The caps were evaluated where the columns were attached. The cap ends were the only places that higher stress wave times were recorded. The south cap had one particular place on the end that produced a high stress wave time. Decay was not a factor in the high time obtained in the field. This was verified by the laboratory results in that the high stress wave time was caused by a split. In general, the stringers all looked to be in excellent shape. Two were brought back to the WMEL for verification of results. The NDE of the stringers in the laboratory verified the in-situ analysis. The stringers were in excellent shape and the results for both tests verified this.

Reasons for the deterioration of the columns were obvious when the laboratory evaluation was completed. As can be seen in Figures 9 and 11, the penetration of the creosote was poor in the tops of the columns when compared to the penetration in the bottoms (Figures 10 and 12). All of the columns had both ends squared for the compression test. After squaring the ends, it was hypothesized that the columns had been 'cut to fit' when they were being placed. The tops were cut so they would fit the bridge at the time of construction. Additional treatment had been applied to the tops after they were cut, but the penetration was poor. Essentially, this created a treated column with the top being penetrated more easily by moisture. The treated shell helped keep the moisture in, accelerating the decay process. The hypothesis is backed by the fact that all of the bottoms were decayed in the columns (Figure 7) where the moisture was locked in. With the exception of column 5, the tops of the columns showed little visible decay. Both the stress wave evaluation in the field and in the laboratory spotted excessive decay in all of the columns.

All of the columns except four were loaded in compression until failure. Three of the columns exceeded the capability of the testing machine, and one fell apart before it could be tested. For a 12 inch x 12 inch Douglasfir timber post, The capacity is 258 kips when adjusted for load duration and median value. The values obtained in the compression test are considerably lower than the median value specified by the NDS (1991), The high regression coefficient (0.91) showed that the variability in the data was low. Using the stress wave times to predict the column capacity can be performed by using the graph.

Conclusions

Through the use of stress wave technology, researchers and engineers have been able to evaluate structures for deterioration without harming the structure. Testing procedures used in NDE can be utilized to recognize potential problem areas in structures. Rather than removing the structure itself, these problem areas can be removed, saving time and money.

The two bridge case studies showed the application of nondestructive testing on in-situ structures. The field data can be reduced and the structure evaluated for decay. By being able to reproduce the field results with destructive and nondestructive laboratory results, confidence in future field evaluations without laboratory verification grew. In-situ assessment is relatively easy when applying the nondestructive stress wave evaluation techniques.

Stress wave velocity technology is valuable in determining the soundness of timber structures. It has been shown to be a valid and accurate method for mapping the extent of unsoundness due to decay in timber structures. Considerable effort has been devoted to developing NDE techniques for assessing the performance of timber structures.

The use of stress wave velocity to detect rot, other defects, and their extent in timber structures is practical. It is time and cost efficient to identify and remove individual components, rather then the entire structure. Stress wave techniques have proven to be reproducible and an accurate way of mapping decay.

In years past, researchers have been unable to predict residual strength of various components. In part, this is attributed to the lack of a correlation between residual capacity and stress wave times. With the additional destructive compression testing of the columns, a correlation between residual capacity and stress wave time has been established. Initial results from the tests that were ran show that it is feasible to use stress wave evaluation to predict residual capacity.

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