Ultrasonic Detection of a Plastic Hinge in Bolted Timber Connections

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ABSTRACT

Connections between structural members are critical elements that typically govern the performance of structural systems; hence, techniques for monitoring the condition of connections are needed to provide early warning of structural damage. Plastic hinge formation in fasteners frequently occurs in timber connections when the yield capacity is exceeded. An innovative pulse echo testing technique was developed for detecting the formation of a plastic hinge in bolted timber connections and estimating the associated magnitude of connection displacement. A shift in overall signal centroid proved to be the best predictor of plastic hinge formation, with a coefficient of determination (R^2) of 0.9. As the plastic hinge angle increased, the signal centroid shifted to the right since a higher proportion of pulse energy was forced to undergo multiple transverse wave reflections caused by the deformed geometry of the bolt. Because the determination of a shift in signal centroid requires the availability of prior test information for the initially undeformed fastener, an alternate linear relationship between echo amplitude ratios and plastic hinge formation was also proposed with an adjusted R^2 of 0.87. This three parameter regression equation had the advantages of requiring no prior testing information and eliminating ambiguity in signal analysis associated with selection of echo start and end points. Plastic hinge formation was correlated with connection ductility, magnitude of connection overload and energy based measures of connection damage to assess residual connection capacity.

Keywords: bolt, connection, plastic hinge, waveguide, pulse echo.

INTRODUCTION

Ultrasonic testing is routinely used to measure thickness and detect internal discontinuities in metals and other structural materials. Ultrasonic testing is also employed to detect cracks and corrosion in metal components at inaccessible locations. With the advent of electronic sensors and real time analysis of data, the subject of structural health monitoring has become very important in recent years (see, for example, Chang, 1997). To date, no ultrasonic testing method exists for detecting damage in bolted timber connections. Plastic hinge formation in fasteners is a form of damage common to many structural wood connections, frequently preceding connection failure. Ultrasonic detection of plastic hinges in fasteners can serve as an indicator of internal connection damage and provide an early warning of impending structural collapse.

In wood structures, it is common for only one end of a fastener to be accessible for testing purposes. Therefore, a testing methodology is needed for propagating an ultrasonic pulse from one end of a fastener through its entire length and providing meaningful correlation between the resulting signal and internal connection damage. In the aftermath of extreme events causing failures in portions of some structures, this type of testing methodology can provide engineers and public officials with quantifiable estimates of damage and residual structural integrity. With this information, rational decisions can be made regarding which structures should be condemned, which are repairable and which require no structural renovation prior to being reoccupied.

OBJECTIVES

The goal of this study was to develop an ultrasonic testing methodology for detecting and quantifying internal connection damage caused by structural overload. Specific objectives were established to:

- select appropriate commercial ultrasonic equipment for pulse echo testing of 13 mm (0.5 in.) diameter ASTM A307, grade A bolts installed in double shear, wood to wood connections
- develop an ultrasonic signal analysis technique for detecting plastic hinge formation in 13 mm (0.5 in.) diameter bolts
- determine the statistical correlation between plastic hinge formation and the structural condition of connections subjected to overload.

BACKGROUND

Ultrasonic pulse echo testing of straight, cylindrical objects such as dowels and bolts can be accomplished by coupling an ultrasonic transducer (probe) to one end of the dowel for transmitting pulse energy into the specimen. According to Bray and Stanley (1997), the dowel diameter should be at least one order of magnitude greater than the wavelength of the ultrasonic pulse ($D \geq 10\lambda$) to ensure bulk longitudinal wave propagation in the dowel. As shown in Figures 1

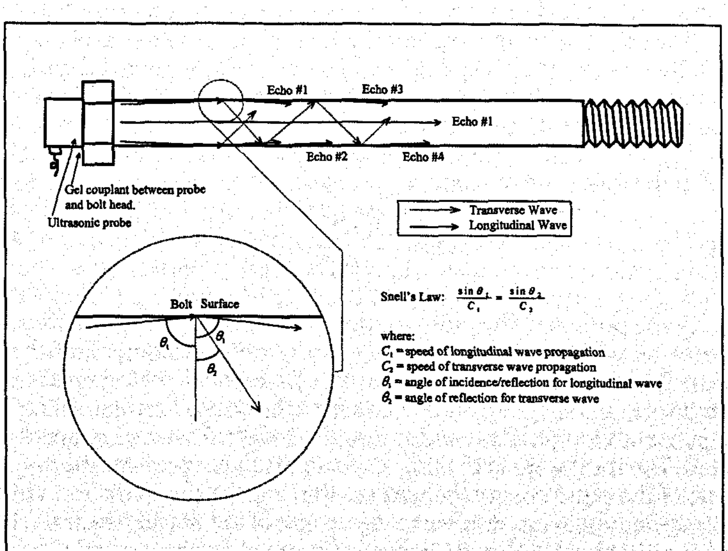

Figure 1 — Ultrasonic pulse propagation for pulse echo testing of bolts. Adapted from Redwood (1960) and Light and Joshi (1986).

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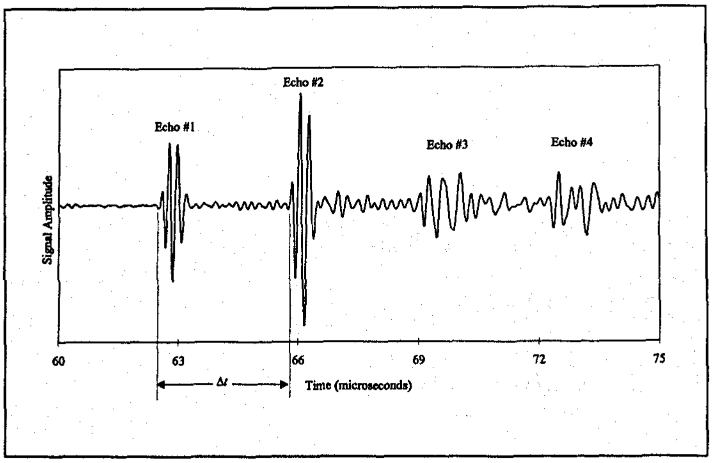

Figure 2 — Typical time domain signal for ultrasonic pulse echo testing of a straight bolt.

and 2, the ultrasonic signal received at the transducer after the pulse has reflected from the opposite end of the dowel will take the form of multiple echoes spaced a constant distance apart in the time domain (Redwood, 1960).

The initial (backwall) echo in the time domain display represents the pulse energy which traverses the length of the dowel as a longitudinal wave, reflects from the opposite end and returns to the transducer. For short dowels with relatively large diameters, much of the pulse energy propagates directly down the dowel without contacting sidewalls, resulting in a relatively large initial backwall echo amplitude. However, in long slender dowels a greater portion of the bulk wave energy comes into contact with the sidewalls of the cylinder due to beam spreading as the pulse propagates away from the ultrasonic transducer. When the longitudinal wave strikes a sidewall surface boundary, both longitudinal and transverse waves are reflected back into the dowel. The portion of the pulse energy which reflects from the sidewalls as a longitudinal wave continues traversing the length of the dowel at the bulk longitudinal wave speed of the material, thus merging with the pulse energy which takes a direct path down the center of the dowel to create the initial backwall echo in the time domain display.

Based on Snell's Law, the angle of reflection for mode converted transverse waves in steel dowels is $\theta_2 \cong 33$ degrees (Krautkramer and Krautkramer, 1990). The second echo in the time domain display represents the portion of the pulse energy which reflects from the sidewall as a transverse wave, crosses the dowel diagonally at a relatively steep angle ($\theta_2 \cong 33$ degrees) and experiences a second mode conversion back to a longitudinal wave when it reflects from the opposite sidewall of the dowel. Since transverse waves travel at approximately half the speed of longitudinal waves in steel, the delayed arrival of the second echo can be determined by calculating the additional time required for the transverse wave to travel diagonally across the dowel. Light and Joshi (1986) reported that the time interval (Δt) between successive trailing echoes is related to the dowel diameter (D), speed of longitudinal wave propagation (C_1) and speed of transverse wave propagation (C_2) in the dowel material in the following manner:

(1)
$$\Delta t = \frac{D\sqrt{C_1^2 - C_2^2}}{C_1 C_2}$$

Some portion of the pulse energy remains in the form of a transverse wave after the second reflection from the sidewall of the dowel. This reflected transverse wave crosses the dowel again at an angle of $\theta_2 \cong 33$ degrees and reflects from the opposite surface. Once again, both longitudinal and transverse reflected waves are generated. The third echo in the time domain display represents the portion of the pulse energy that crosses the dowel twice in the form of a transverse wave as it traverses the length of the dowel. The arrival of the third echo lags Δt behind the second echo arrival. This process continues, resulting in a series of trailing echoes which lag behind the initial backwall echo at increments of Δt.

Based on earlier studies by McSkimin (1956) and Varey (1976), Light and Joshi (1986) developed a cylindrically guided wave technique for detecting corrosion damage in straight bolts and studs in nuclear power plants. The cylindrically guided wave technique employs pulse echo testing principles by coupling an ultrasonic transducer to one end of a bolt, transmitting pulse energy into the bolt and evaluating the resulting ultrasonic signal characteristics. Stress corrosion cracks were observed to create an unusually early echo arrival due to the shorter travel path for the portion of the ultrasonic pulse that reflected directly back to the transducer from the surface of the crack. Simulated corrosion wastage (loss of fastener cross section) was observed to create additional trailing echoes at smaller magnitudes of Δt due to the reduced dowel diameter and associated reduction in transverse wave travel path (Light and Joshi, 1987).

A similar ultrasonic pulse echo testing technique has been developed for estimating the level of tensile stress in mine roof bolts (Rukavina, 1991) and pre-tensioned high strength bolts in steel structures (Notch, 1985). Longitudinal stress waves are initiated at the head of a bolt and the time required for the pulse to reflect from the far end of the bolt and return to the ultrasonic transducer is recorded. Increased travel time can be observed for higher levels of tensile stress in the fastener. This methodology exploits the correlation between material strain and characteristic longitudinal wave speed to estimate stress levels in straight bolts under an applied tensile load (Bray and Stanley, 1997). While this methodology demonstrates the use of ultrasonic pulse echo testing for straight bolts, ultrasonic testing techniques have not been developed for evaluating deformed fasteners. In particular, there are no ultrasonic testing techniques currently available for detecting plastic hinge formation in fasteners. Unlike mine roof bolts and pre-tensioned high strength bolts, which are primarily stressed in tension, fasteners in wood structures typically undergo plastic deformation in bending prior to connection failure. Thus, ultrasonic pulse characteristics in deformed fasteners are critical for assessing damage caused by structural overload in timber connections.

Bolts are frequently used in timber structures to connect structural members of wood, steel, concrete or composite products. Connection design formulas in the *National Design Specification for Wood Construction* (American Forest and Paper Association, 1997) predict when connection behavior will be dominated by: wood crushing (mode I); wood crushing combined with rigid bolt rotation at the shear plane (mode II); localized wood crushing combined with plastic hinge formation in the bolt at each shear plane (mode III); or localized wood crushing combined with two plastic hinges per shear plane (mode IV). See Figure 3 for a schematic model of these modes. Connections that exhibit modes I or II tend to fail in a relatively brittle manner at low levels of connection displacement under extreme load conditions. The brittle failure mechanism occurs as the fastener is forced through the wood members, causing one or more of them to split along the longitudinal axis of the member. Connections that exhibit modes III or IV demonstrate substantial ductile performance prior to fracture under extreme load conditions (Humphrey and Ostman, 1989). Although the ultimate fracture mechanism (splitting of wood members) is typically the same for all modes of bolted connection behavior, the ductile performance associated with plastic hinge formation in modes III and IV provides significantly greater connection ductility and energy dissipation than in modes I and II prior to fracture (Bracci et al., 1996; Dolan et al., 1995).

SIGNAL ANALYSIS TECHNIQUES

Over 25 ultrasonic signal parameters were investigated in this study based on analyses of time and frequency domain envelopes (Pollock, 1997). However, since time domain parameters provided the best overall correlations with plastic hinge formation in bolts, only time domain parameters of interest are described in the following paragraphs.

Ultrasonic signals are recorded as a series of points (t_i, a_i) in the time domain. Time coordinates (t_i) represent the elapsed time following pulse initiation from the ultrasonic transducer and amplitude coordinates (a_i) represent pulse pressure at the surface of the

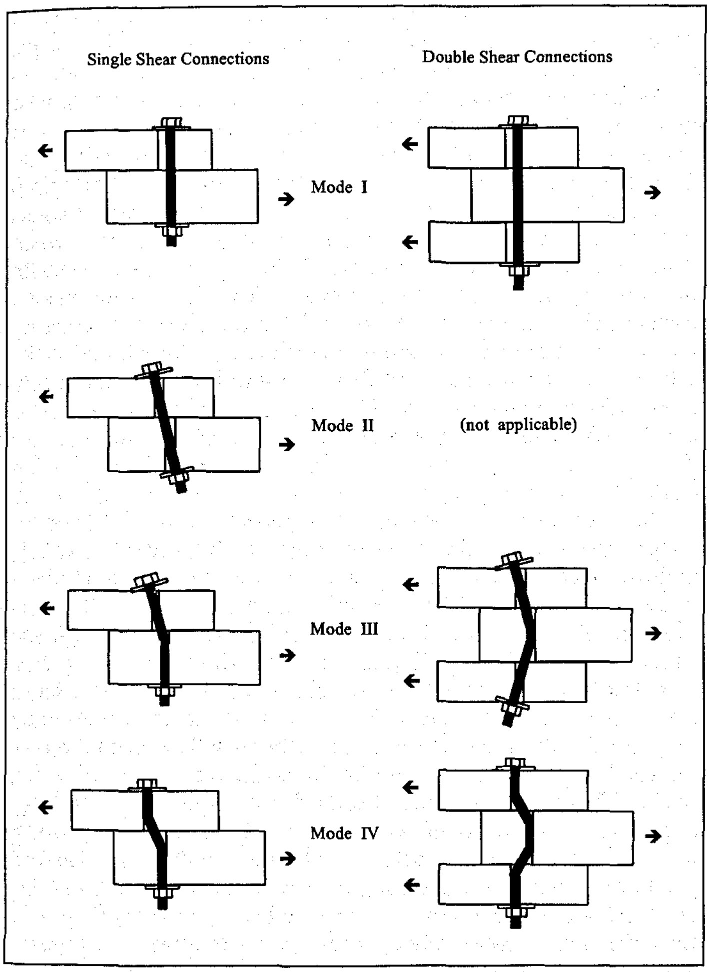

Figure 3 — Yield modes for laterally loaded bolted timber connections. Adapted from Johansen (1949) and the American Forest and Paper Association (1997).

transducer. In this study, key time domain parameters for each echo included peak amplitude (a_P), area under the rectified signal (A_T) and centroid (t_C). The peak amplitude (a_P) for each time domain echo was calculated as the average of the maximum positive and negative signal amplitudes for the echo. The rectified time domain signal was obtained by plotting the series of points (t_i, $|a_i|$). Since ultrasonic data were recorded at a constant rate of 100 MHz in this study, summing the absolute value of all signal amplitudes within the echo represented the area under the rectified signal for each echo:

(2) $$A_T = \Sigma|a_i|$$

Echo centroids were calculated as the first moment of the echo area with respect to the origin ($t = 0$ μs) in the rectified time domain signal:

(3) $$t_C = \frac{\Sigma t_i|a_i|}{A_T}$$

As reported by Varey (1976), concerns about consistent ultrasonic coupling and accurate and repeatable transducer placement render echo amplitudes somewhat meaningless for direct comparisons between independent ultrasonic tests of identical bolts and dowels. Therefore, ratios of echo peak amplitudes were determined for each ultrasonic signal in order to facilitate comparisons between signals. For example, with the peak amplitude of the second echo (a_{2P}) as a ratio basis, the following set of parameters was employed to describe the relative distribution of pulse energy among the first four time domain echoes:

- a_{1P}/a_{2P} = the ratio of the first to the second echo peak amplitude
- a_{3P}/a_{2P} = the ratio of the third to the second echo peak amplitude
- a_{4P}/a_{2P} = the ratio of the fourth to the second echo peak amplitude.

In addition to providing a relative measure for comparisons between independent test signals, amplitude ratios have the added advantage of repeatability. Since selection of peak amplitudes for each echo in a given time domain signal is not a subjective judgment, the calculated amplitude ratios are independent of the analyst assessing the signal.

Concerns about consistent ultrasonic coupling and transducer placement are equally applicable to comparisons of echo areas (A_T) from independent tests of dowels or bolts. Thus, a set of four area ratios (AR_{Tj}) was calculated as an alternate measure of the relative distribution of pulse energy among the first four echoes, in accordance with the following formula:

(4) $$AR_{Tj} = \frac{A_{Tj}}{\Sigma_{j=1}^{4} A_{Tj}}$$

where

$j = 1, 2, 3$ or 4 represents the echo number.

A potential advantage of using area ratios to detect differences in pulse energy distribution among trailing echoes is that echo area incorporates a consideration of amplitude distribution throughout the entire echo duration. However, the cost of this added sensitivity is the subjectivity involved in identification of the first and last "detectable" peaks for each echo, resulting in increased variability for comparison of signal parameters from independent tests.

An additional time domain parameter, the overall signal centroid (t_{CO}), was evaluated as an indicator of pulse energy distribution among trailing echoes. For the time domain envelope encompassing the first four echoes, the overall centroid was calculated as follows:

(5) $$t_{CO} = \Sigma_{j=1}^{4} t_{Cj} AR_{Tj}$$

Although an overall centroid can be determined for any number of echoes, the calculation was limited to four echoes since the majority of bolts tested in this study exhibited only four distinct echoes in the time domain signal display.

EXPERIMENTAL METHODS

An initial test of standard undeformed A307, grade A bolts and A36 steel dowels of various sizes was conducted to establish baseline ultrasonic signal characteristics and determine preferred ultrasonic transducer frequencies for subsequent fastener testing. The following observations were made from this initial investigation (Pollock, 1997):

- Each combination of transducer frequency and dowel or bolt geometry (length, diameter and threaded shank length) provides a unique ultrasonic pulse echo test signal.
- Trailing echoes exhibit larger relative amplitudes for long, slender dowels and bolts than for shorter, thicker specimens due to the greater proportion of ultrasonic pulse energy that undergoes transverse wave reflections from the sidewalls of the bolts.
- The presence of threads tends to clutter the ultrasonic signal, reducing the number of distinct trailing echoes for pulse echo testing of bolts. However, key ultrasonic signal parameters can still be extracted for bolts with standard threaded shank lengths.
- A transducer frequency of 5 MHz or higher should be used for pulse echo testing of bolts commonly used in timber structures 13 mm $\leq D \leq$ 25 mm (0.5 in. $\leq D \leq$ 1 in.) to maximize ultrasonic signal clarity and ensure bulk wave propagation in the bolt.

A sample of 113 ASTM A307, grade A bolts having unified standard (course series) threads and nominal dimensions of 13 mm (0.5 in.) diameter by 180 mm (7 in.) length was obtained from a single manufacturer. Each of the bolts had a threaded shank length of approximately 38 mm (1.5 in.) as specified in *ANSI/ASME Standard B18.2.1* (1981). Each bolt was tested ultrasonically using a 5 MHz transducer coupled to the bolt head to assess variability in signal parameters for a population of nominally identical bolts. Ultrasonic signal characteristics were very consistent for the entire sample of 13 mm (0.5 in.) diameter bolts, exhibiting coefficients of variation below 1 percent for time domain parameters such as Δt and t_{CO} and exhibiting coefficients of variation ranging between 5 and 20 percent for other signal parameters such as a_{jP}/a_{2P} and AR_{Tj} (Pollock, 1997). The relatively low variability for measures of energy content such as amplitude ratios and area ratios indicates that a particular bolt geometry exhibits a repeatable, characteristic distribution of pulse energy among trailing echoes. A typical time domain signal is shown in Figure 2 for a 13 mm (0.5 in.) diameter ASTM A307 bolt, illustrating four distinct time domain echoes (one backwall echo, followed by three equally spaced trailing echoes). Subsequent trailing echoes were typically indistinguishable from the noise caused by reflections from thread surfaces. Therefore, ultrasonic signal analysis for bolt testing was limited to the first four time domain echoes.

Double shear bolted connection tests were conducted using 52 bolts selected from the sample of 13 mm (0.5 in.) diameter ASTM A307, grade A bolts. Ultrasonic detection of plastic hinge formation was investigated by coupling a 5 MHz transducer to the bolt head and monitoring the ultrasonic signal during testing. The main member for each connection was approximately 70 mm (2.8 in.) thick with the side members being approximately 35 mm (1.4 in.) thick. Member dimensions were chosen to assure the formation of a single plastic hinge in yield mode III (Figure 3) prior to ultimate connection failure (American Forest and Paper Association, 1997).

A bolt extension fixture and a vertical plate fixture were fabricated for independent measurement of the internal bolt hinge angle using a digital protractor (inclinometer), accurate to ± 0.1 degree. The bolt hinge angle within the connection was determined by summing the changes in angle recorded at each fixture. A diagram of the bolted connection assembly, including placement of the spring loaded probe (transducer) holder, bolt extension fixture, vertical plate fixture and linear variable differential transformer is provided in Figure 4.

Bolted connection tests were conducted in tension in accordance with the provisions of *ASTM D5652* (1998) and tests were interrupted at predetermined levels of connection displacement to record ultrasonic signals and measure changes in bolt hinge angle. After each target displacement level was reached, the connection was unloaded until the load cell sensed zero force in the connection, at which time ultrasonic signals and inclinometer readings were recorded. Following ultrasonic and inclinometer data collection, testing was resumed by loading the connection to the next increment of displacement. The primary reason for unloading the connections at each displacement level was to simulate field inspection conditions where connections are typically in an unloaded or lightly loaded state following exposure to extreme load events. The detected permanent fastener deformation can then be correlated with connection damage that occurred under the extreme load. Following ultimate connection failure at maximum load and displacement levels, all connection main and side members were split apart to reveal the deformed fastener and facilitate measurement of the final plastic hinge angles.

RESULTS

The ultrasonic signals collected at intermediate levels of connection displacement provide a record of progressive increases in plastic hinge formation as connections experienced increasing magnitudes of load and displacement. As the bolt hinge angle increased, the initial echo was attenuated until it eventually became indistinguishable from the signal noise. The location of the maximum echo amplitude shifted from the second to the third echo and eventually to the fourth echo as bolt deformation increased within the connection. After the first echo disappeared in the noise, attenuation of the second echo was observed relative to subsequent trailing echo amplitudes. This was followed by attenuation of the third echo at very large plastic hinge angles prior to the ultimate connection failure. These changes in the time domain signal are associated with redistribution of pulse energy among trailing echoes due to an increasing number of transverse wave reflections caused by the deformed bolt geometry (Figure 5). Increasing noise levels were also observed throughout the time domain signal as bolt deformation increased in each connection.

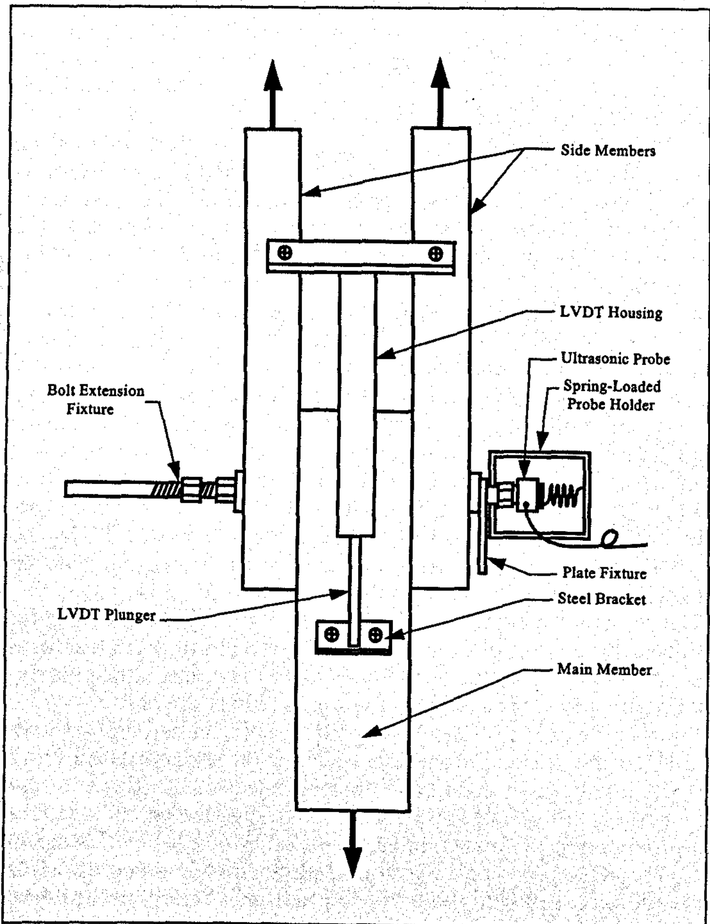

Figure 4 — Configuration for ultrasonic testing of bolts during connection tests.

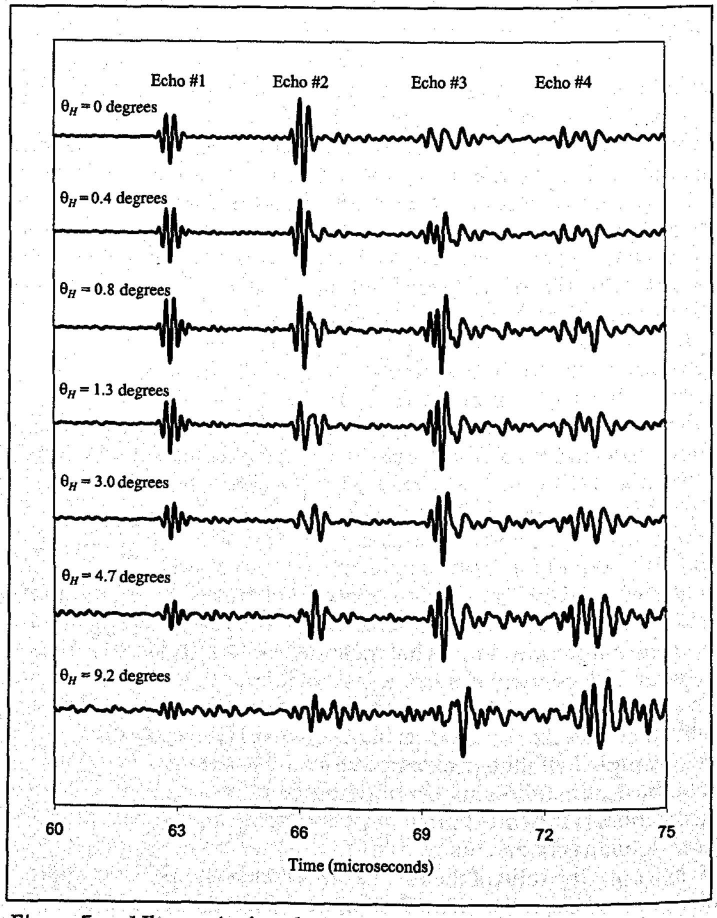

Figure 5 — Ultrasonic time domain signals for the testing of a 13 mm (0.5 in.) diameter bolt with a progressively increasing plastic hinge angle θ_H.

The observed trends in ultrasonic signals can be explained conceptually by noting that the deformed bolt shapes for various yield modes force greater amounts of propagating ultrasonic energy to reflect from the sidewalls of the bolt as the pulse traverses the length of the fastener. Since the first echo represents pulse energy that undergoes no transverse wave reflections, any change in bolt geometry that increases the number of sidewall reflections can be expected to divert energy from the first echo into trailing echoes. In a similar manner, some of the pulse energy originally in echo two is diverted to subsequent trailing echoes since the deformed bolt geometry causes more of the pulse energy to undergo additional sidewall reflections while traversing the length of the bolt.

The observed increase in signal noise is due to the presence of threads at the far end of the deformed fastener. As plastic hinges increase in magnitude, more of the threads at the far end of the bolt project into the path of the propagating pulse, creating additional reflections which tend to clutter the ultrasonic signal. Since the thread surfaces create a wide array of incidence angles, portions of the reflected pulse energy follow a variety of complex geometric paths in returning to the ultrasonic transducer.

Ultrasonic signals collected during connection tests were assessed to determine whether plastic hinge formation in bolted connections could be detected and measured ultrasonically. For connections tested to failure, the final hinge angle was observed to vary from 7.5 to 45 degrees. However, attention was focused on detecting plastic hinge angles between 0 and 10 degrees since angular deformations larger than 10 degrees were generally detectable by visual testing of either the bolt head or the threaded end protruding from one of the side members. Only two of the connections failed prior to reaching a plastic hinge angle of 10 degrees.

The best single parameter predictor of plastic hinge formation in bolts was the shift in overall signal centroid ($dt_{CO} = t_{CO\text{deformed}} - t_{CO\text{initial}}$), using the initial signal centroid from the undeformed bolt as a baseline, with an R^2 of 0.9. As the hinge angle increased due to applied connection load, the location of the overall centroid shifted to the right. This behavior reflects the greater amount of pulse energy shifted from initial echoes to subsequent trailing echoes. The linear relationship between plastic hinge angle θ_H and the shift in overall centroid dt_{CO} is illustrated in Figure 6. The regression equation in Figure 6 can be employed to estimate plastic hinge formation in the range of 0 degrees $\leq \theta_H \leq$ 10 degrees with an accuracy of $\pm$1.5 degrees at a 95 percent confidence level ($\alpha = 0.05$). The high R^2 associated with dt_{CO} illustrates the benefit of having baseline test records available for undeformed fasteners so that relative signal changes can be assessed.

In the absence of historic test records, a simple regression equation employing only echo amplitude ratios a_{jP}/a_{2P} or area ratios AR_{Tj} can provide adequate prediction capability with adjusted R^2 values of 0.87 and 0.89, respectively. It should be noted that from the standpoint of testing simplicity and repeatability, it may be desirable to use amplitude ratios rather than area ratios or shifts in centroid, despite the lower R^2 for the regression between amplitude ratios and hinge angle magnitude. The primary reason for this is that echo amplitude is an unambiguous quantity for any given ultrasonic signal, while echo centroid and area ratios require subjective decisions by the analyst regarding selection of the start and end points for each echo.

DISCUSSION

Detection of plastic hinge formation in bolted connections is not significant in and of itself, unless permanent deformations are correlated with some meaningful measure of internal connection damage. For this reason, the correlation between plastic hinge formation and connection performance parameters such as displacement, load beyond yield and energy dissipation (represented by the area under the load displacement curve) was investigated.

Hinge angle magnitudes were observed to vary linearly with connection displacement, as illustrated in Figure 7. Overall connection displacement in the linear region of the load/displacement curve is caused by deformation of wood fibers in bearing adjacent to the bolt, combined with elastic deflection of the bolt within the connection. In the inelastic region beyond the connection yield point, total connection displacement is due to crushing of wood fibers adjacent to the bolt combined with the plastically deformed bolt geometry. Visual testing of crushed fibers in wood members following connection failure indicated that total connection displacement was typically dominated by bolt deformation. The following functional relationship between plastic hinge angle θ_H and connection displacement Δ was developed assuming that displacement due to wood crushing is negligible (Figure 8):

(6)
$$\Delta = \left(t_s + \frac{t_m}{2}\right)\left(\tan\frac{\theta_H}{2}\right)$$

where
t_m = main member thickness
t_s = side member thickness

This functional relationship provides an R^2 of 0.95 and is illustrated in Figure 7.

As might be expected, based on the functional relationship between connection displacement and plastic hinge formation, energy dissipation (measured as the area underneath the connection

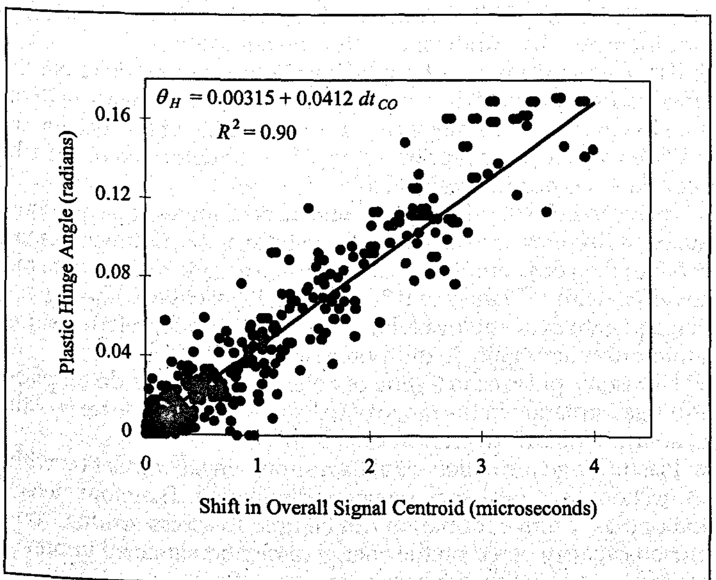

Figure 6 — Relationship between plastic hinge angle θ_H *and shift in ultrasonic signal centroid* dt_{CO}.

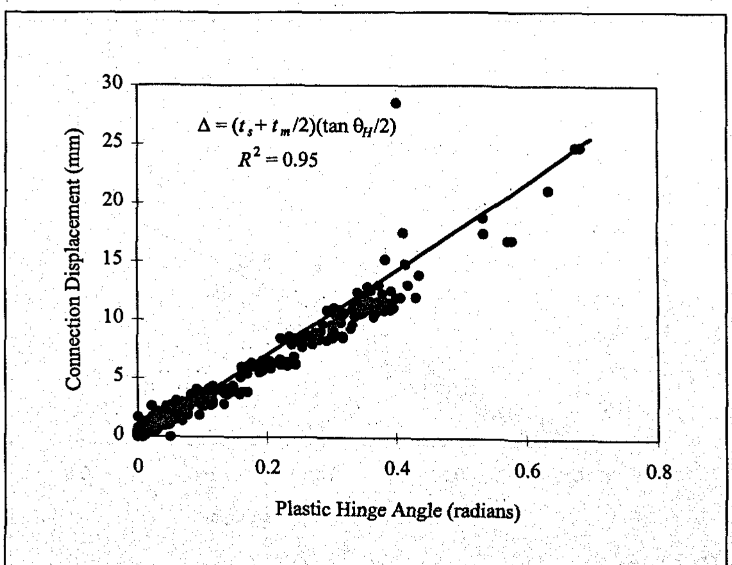

Figure 7 — Relationship between plastic hinge angle θ_H *and connection displacement* Δ.

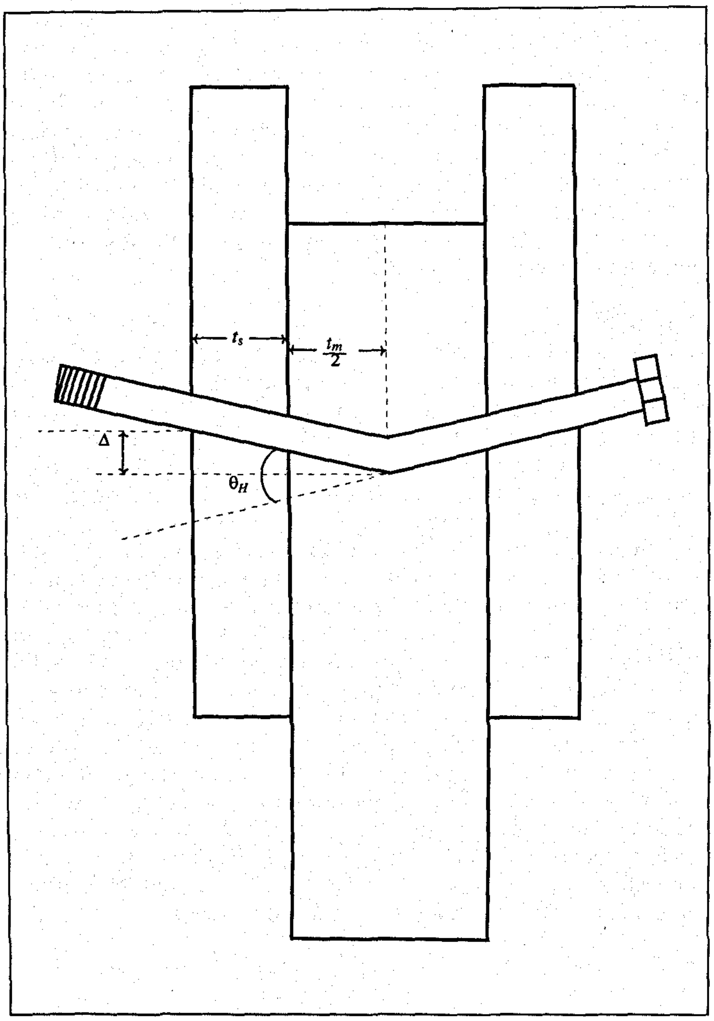

Figure 8 — Plastic hinge angle θ_H for a bolt in a mode III, double shear connection.

load/displacement curve) also exhibits a strong correlation with plastic hinge formation in bolts. This trend is illustrated in Figure 9. Thus, knowledge of the bolt plastic hinge angle within a connection facilitates estimates of the energy dissipation attained in previous loading events. This information can be utilized to estimate residual energy dissipation capacity and can therefore be employed in comprehensive structural reliability analyses.

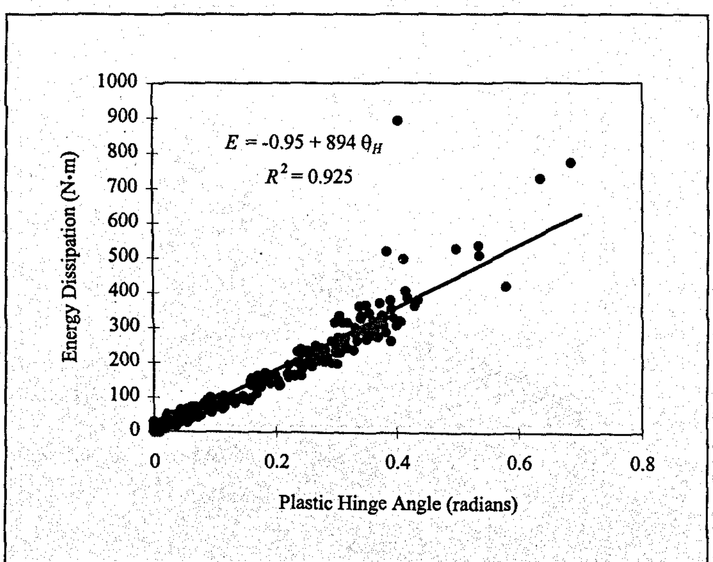

Figure 9 — Relationship between plastic hinge angle θ_H and connection energy dissipation E.

A scatterplot of plastic hinge formation versus connection load is provided in Figure 10. While a strong functional relationship between hinge angle and load is apparent, the steep slope of the curve for small magnitudes of angular deformation indicates that plastic hinge formation is not particularly effective for estimating connection loads prior to the yield point. Since much of the bolt deformation is elastic prior to the yield point, very small changes in angular deformation are associated with large variations in connection load. However, for connections loaded beyond the yield point a much flatter slope is observed, indicating that detection of permanent deformation could be employed to estimate load magnitudes which exceed the yield capacity of the connection. An empirical relationship between plastic hinge formation and load beyond the connection yield point is also provided in Figure 10. Although the coefficient of determination is only $R^2 = 0.8$, it is still sufficiently large to provide reasonable estimates of the connection overload (load beyond the yield point) associated with varying degrees of internal connection damage.

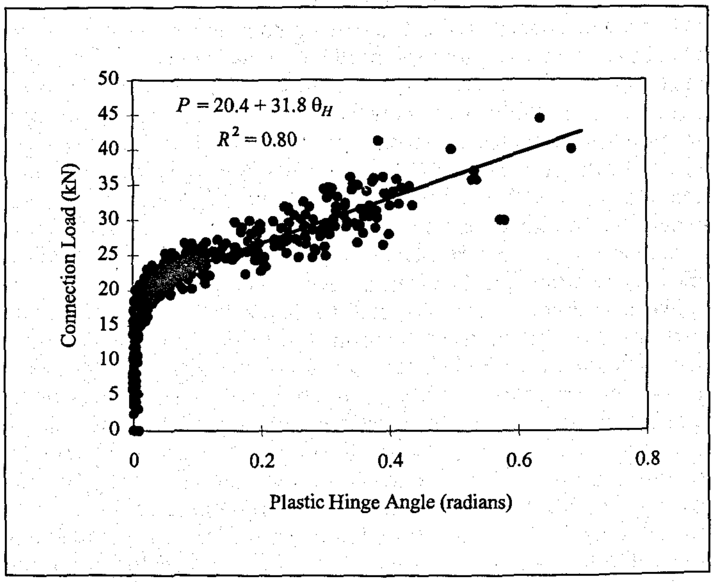

Figure 10 — Plastic hinge angle versus connection load; relationship between plastic hinge angle θ_H and load beyond the connection yield point P.

CONCLUSIONS

The following conclusions derive from this study for 13 mm (0.5 in.) diameter bolts in double shear connections of Southern pine members that exhibit mode III yield behavior:

- The best single parameter predictor of the magnitude of plastic hinge formation is shift in overall signal centroid dt_{CO}, with an R^2 of 0.9. However, this technique requires knowledge of the location of the signal centroid from prior testing of the undeformed bolt. Such information is not always available.
- In the absence of prior testing information, regression equations can be utilized for predicting the magnitude of plastic hinge formation based on echo amplitude ratios a_{jP}/a_{2P} or time domain area ratios AR_{Tj}, with R^2 values of 0.87 and 0.89 respectively. The regression equation that employs echo amplitude ratios is preferred since it minimizes ambiguity in ultrasonic signal analysis.
- Ultrasonic pulse echo testing of bolts can be used to detect plastic hinge formation in the range of 0 degrees $\leq \theta_H \leq$ 10 degrees with an accuracy of ± 1.5 degrees at 95 percent confidence.
- Plastic hinge formation exhibits a strong linear correlation with connection displacement and energy dissipation. Therefore, detection of plastic hinge formation can be used to assess residual connection capacity based on the energy dissipation attained in previous loadings of the timber connection.
- The magnitude of plastic hinge formation can be employed to estimate load levels that exceed the connection yield capacity.

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REFERENCES

American Forest and Paper Association, *National Design Specification for Wood Construction*, Washington, DC, AF&PA, 1997.

American National Standards Institute, *ANSI/ASME Standard B18.2.1, Square and Hex Bolts and Screws Inch Series*, New York, ANSI, 1981.

American Society for Testing and Materials, *ASTM D5652, Standard Test Methods for Bolted Connections in Wood and Wood-Base Products*, Philadelphia, ASTM, 1998.

Bracci, J.M., R.F. Stromatt and D.G. Pollock, "Seismic Performance of Confined Sill Plate Connections," *ASCE Journal of Structural Engineering*, Vol. 122, No. 11, 1996, pp. 1357-1363.

Bray, D.E. and R.K. Stanley, *Nondestructive Evaluation*, Boca Raton, Florida, CRC Press, 1997.

Chang, F.K., "Structural Health Monitoring: A Summary Report on the First Stanford Workshop on Structural Health Monitoring," September 18-20, 1997, available at <structure.stanford.edu/workshop/report.html>.

Dolan, J.D., S.T. Gutshall and T.E. McLain, "Monotonic and Cyclic Tests to Determine Short-Term Load Duration Performance of Nail and Bolt Connections — Volume I: Summary Report," Timber Engineering Report No. TE-1994-001, Blacksburg, Virginia, Virginia Polytechnic Institute and State University, 1995.

Humphrey, P.E. and L.J. Ostman, "Bolted Timber Connections: Part II — Bolt Bending and Associated Wood Deformation," *Wood and Fiber Science*, Vol. 21, No. 4, 1989, pp. 354-366.

Johansen, K.W., "Theory of Timber Connections," *Proceedings of the Division V Conference, International Union of Forestry Organizations (IUFRO)*, Vienna, Austria, 1949, pp. 646-655.

Krautkramer, J. and H. Krautkramer, *Ultrasonic Testing of Materials*, Berlin, Germany, Springer-Verlag, 1990.

Light, G.M. and N.R. Joshi, "Detection of Stress Corrosion Cracks in Reactor Pressure Vessel and Coolant System Anchor Studs," EPRI NP-4315-SR Special Report No. 28, Palo Alto, California, Electric Power Research Institute (EPRI), 1986, pp. 1-10.

Light, G.M. and N.R. Joshi, "Ultrasonic Waveguide Technique for Detection of Simulated Corrosion Wastages," *Nondestructive Testing Communications*, Vol. 3, 1987, pp. 13-27.

McSkimin, H.J., "Propagation of Longitudinal Waves and Shear Waves in Cylindrical Rods at High Frequencies," *Journal of the Acoustical Society of America*, Vol. 28, No. 3, 1956, pp. 484-494.

Notch, J.S., "Bolt Preload Measurements Using Ultrasonic Methods," *Engineering Journal*, Vol. 22, No. 2, 1985, pp. 98-103.

Pollock, D.G., "Reliability Assessment of Timber Connections Through Ultrasonic Inspection of Bolts," PhD Dissertation, Department of Civil Engineering, Texas A&M University, College Station, Texas, 1997.

Redwood, M., *Mechanical Waveguides*, New York, Pergamon Press, 1960.

Rukavina, M., "Ultrasonic Measurement is Bolt Load Determinant," *Rock Products*, Vol. 94, No. 7, 1991, p. 27.

Varey, R.H., "Ultrasonic Pulse Transmission in Cylindrical Waveguides," *Journal of Physics D: Applied Physics*, Vol. 9, 1976, pp. 1661-1669.