NONDESTRUCTIVE TESTING OF WOODEN VESSELS

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ABSTRACT: The Coast Guard is responsible for the safety of over 2000 wooden boats which are used as passenger vessels throughout the U.S. There is limited direction given to the Coast Guard inspectors within the Code of Federal Regulations and other documents so they must rely on their experience to assess the safety of the vessels. On December 5, 1993, the small passenger vessel El Toro II sank in the Chesapeake Bay with the loss of three people. As a result of the casualties, the National Transportation Safety Board made several recommendations to the Coast Guard and small passenger industry. One of these was that nondestructive inspection techniques for inspecting fasteners on wooden vessels should be investigated. This paper reports the results of a project at the Coast Guard R&D Center which has tested and identified some methods which may be utilized to improve the inspection of wooden vessels. In this project, previous work performed for inspection of wooden structures was reviewed and those which held the most promise were evaluated on a donated vessel. The test hull was then taken apart and the actual conditions compared to the test results. It appears that conventional and real-time x-rays can help inspectors determine the condition of vessels without causing damage. With some further development, two other techniques, SMARTHAMMER and CAPICIFLECTOR, have the potential of helping inspectors identify questionable areas.

I. BACKGROUND

The Coast Guard is responsible for the safety of over 2000 wooden boats which are used as passenger vessels throughout the United States. The types of vessels included in this group are ferries, charter fishing vessels, and any other wooden boat which can carry more than 6 persons for hire. The vessels are visited on a yearly basis for general inspections. A major dry-dock inspection of the hull is required every two years (5 years in fresh water). The Coast Guard inspector must also review and approve major modifications or repairs.

Work was initiated by the Coast Guard as a result of the sinking of a wooden-hulled vessel, the EL TORO II, in the Chesapeake Bay with the loss of three lives. The investigation by the Coast Guard and the National Transportation Safety Board (NTSB) determined the probable cause was flooding resulting from several sprung planks near the keel. Upon examination, the nail fasteners from the end of the plank adjacent to the keel were found to be severely corroded, although the fasteners at the other end of the plank were not.

The Coast Guard convened a Joint Industry/Coast Guard Wooden Boat Inspection Working Group which reviewed Coast Guard Navigation and Vessel Inspection Circular (NVIC) 1-63 and the results were published as a new document, NVIC 7-95 in November, 1995[1]. This document provides guidance for pulling fasteners "for cause" as well as periodic random sampling of "a minimum of eight fastenings per side below the waterline."

Even with the guidance provided, it still may be possible for an inspector or surveyor to miss corroded fasteners. For this reason, and because of the recommendations of the NTSB, the Coast Guard's Office of Operating and Environmental Standards (G-MSO) requested that the Research and Development Center initiate a project to identify some nondestructive inspection techniques for wooden hulls. The intent is for these methods to replace pulling the fasteners or at least have the capability of evaluating potential problem areas. The best alternative would be to find a technique which could easily examine all of the fasteners and the local wood to determine their holding capability. This paper is a condensed version of the main report, reference [2].

II NONDESTRUCTIVE TESTING FOR VESSELS

There have been uses of nondestructive testing in vessels. The most well-known has been the efforts on the U.S.S. CONSTITUTION [3]. It was noted that the vessel seemed to be "hogging" at the bow and stern. A complete evaluation of the wood and fasteners was performed. The fasteners used in the CONSTITUTION are copper alloy drifts on the order of 3/4-inch diameter and as long as five feet. An ultrasonic flaw detector was used with an "A" scan presentation. The signals can indicate if the pin is sound or wasted. The major structural wood components of the Constitution also were measured by stress wave velocity measurements. This method has been used successfully on large structures to locate decay or to estimate the remaining strength of a member.

A general review of the use of nondestructive inspection methods for small vessels is given in Reference 4.

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This describes the use of a fiberscope in examining areas within a hull box-section which was inaccessible. The use of thermography and ultrasonic flaw-detection equipment is also discussed. These advanced techniques are usually used for unique situations when the only alternative is to take the vessel apart or cause damage in some other way such as taking a core sample.

The only reference to x-rays being taken on plank fasteners was by the Anvil Corporation of Bellingham, Washington, The occasion was that a vessel that had never been inspected previously was being transferred from a private owner into a passenger-carrying vessel. Rather than pulling a large number of fasteners needed to ensure that the vessel was sound, x-rays were taken of over 400 fasteners. The local Coast Guard office accepted these shots as proof of the vessel's condition. For these shots, the film was placed on the inside of the vessel and the source is located outside of the hull. The major issues were the accessibility inside of the hull and the angle at which the shot is taken. Not all of the fasteners were accessible, especially some of those which are near the keel and considered to be crucial. For the documenting of this vessel with a length of 86 feet, 100 images were taken and the materials and labor were approximately $3500.00.

III NONDESTRUCTIVE EVALUATION OF WOOD STRUCTURES

Extensive research has been performed in the area of wood evaluation. Several organizations, including the U.S. Department of Agriculture Forest Service, at the Forest Products Laboratory, have done extensive work for the lumber and utility industries [5]. This work has included issues with sorting and grading structural products, but has evaluated large structures starting about 20 years ago. Among the most useful techniques for evaluating in-place structures is stress wave analysis. The time that it takes for sound to travel through an object is dependent upon the material properties and conditions. Decayed wood greatly reduces the speed at which the sound travels. Mechanisms which generate a pulse in the wood and measure the speed to get to a second sensor have been used on a football stadium, a school gymnasium, bridges, water-cooling towers and utility poles [5]. This method was also used to assess the condition and length of unknown timber piles [6]. Other techniques used in the past but not useful for vessels include static bending, transverse vibration, screw withdrawal and the Pilodyn test which measures how far a pin is driven into the wood.

There have been attempts to utilize computerized tomography, commonly known as CAT scans, to locate nails and voids in wooden poles. A portable unit was designed in 1986 [7], but was deemed to be too costly and it could not evaluate that portion of the pole below ground level. The Navy also performed a feasibility study for an underwater CAT system in 1985 for use at docking facilities, but it was thought to be too large and costly.

IV EVALUATION OF METHODS

A two-part approach was taken to obtain parts of vessels which could be used to evaluate potential technologies. A test fixture using standard boatbuilding techniques and included known defects was constructed to serve as a control piece. The second was to find an existing vessel which could be dissected upon completion to determine the actual conditions.

A. TEST FIXTURE

A wood hull test fixture was fabricated which is two feet by three feet and constructed of southern pine and white oak. Galvanized bolts, screws, and nails were included as well as two butts. A portion of the planks were thinned from behind with a sander and a portion of one of the frames was dug out and a polyurethane foam adhesive/sawdust mixture put in place to simulate deterioration. The scantlings used are the approximate size for a 40-50 foot party fishing vessel.

B. TEST HULL

One of the main objectives of this project is to evaluate potentially useful technologies on an actual vessel. The vessel would be dismantled at the conclusion of the tests so boats still in use could not be utilized. A derelict hull was eventually found in the town of Short Beach in East Haven, Connecticut. The vessel, the VOLSUNGA III, was a 39-foot ferry vessel which has been stored on land since 1994. It was built in 1969 with oak frames, cedar planking and clinched galvanized nails. It is a carvel planked over bent frame "Novi" (as in Nova Scotia) style lobster boat hull. The original 1-inch by 3 1/8-inch frames were spaced approximately eight inches apart. It was originally used to provide ferry service to islands in Long Island Sound. Steam-bent sister ribs and gussets were installed in 1986 and various sections have been refastened with stainless wood screws.

Among the general comments was that these types of boats are considered "throwaway vessels," being used for 8-10 years and then discarded. In theory, the light structural members permit the vessel to flex in a seaway but maintain relatively watertight integrity although the surveyors indicated that the structure is still deficient. Some of these types of vessels are sold to locations south of Maine at the end of their useful life and deserve added attention when encountered.

Areas that were identified to be used for testing and discussed in this paper are:

Area	Description
1.	A five-foot-long area just below the rub rail. The condition of the area ranges from good to a hole which has been created due to rot.
3.	The port stern area includes cracks and a wire which can be utilized for reference. The plank ends are exposed.
5.	A generally good area above the water line but below the middle rub rail. Area is about 3 feet by 3 feet.
6.	The entire stem area appears to have some problem areas. Some of the underwater section appears to be soft and the top of the stem head had large amounts of putty under the paint.

C. TECHNOLOGY EVALUATION

1) SOUND TECHNIQUES

The first product demonstrated was SMART HAMMER (Patent Pending) which is a tool being developed by Bruce Pfund/Special Projects. The control component of this device includes some air actuators which can control the vibration of several impact devices. The other major part of the SMART HAMMER is a microphone connected to a recorder by which data can be fed to the computer for processing. The computer analysis basically performs the function of an experienced surveyor's ear, tracking the frequency response to determine the good sections versus the questionable areas. The difference in the good and loose areas can be easily seen in Figure 1 where individual graphs at two specific times are shown. A sharp-tipped probe was also attached to the vibration piece and used on individual fasteners in an attempt to see if the response was different for good and questionable fasteners. No differential sound was noted for any of the clinched fasteners but showed promise previously when tested on very loose fasteners.

This technique has a patent pending on it and is still in the developmental stage and is primarily designed for use on fiberglass and composites. The general feeling is that the large vibrator tool may increase the speed at which a vessel is sounded, but that the ear of an experienced inspector is still required. A set of curves, such as those shown, may be useful in determining very good versus very bad areas, but additional information, such as visual clues, would still be required.

2) SPECIALIZED DRILLS

One of the techniques demonstrated was the use of specialized drills which can be used to detect decay and voids below the surface of the wood. These are normally used for large members such as bridge structures. There are systems on the market which drill holes smaller than 1 mm and can penetrate up to 16 inches into wood. The model demonstrated was the RESISTOGRAPH, manufactured in Germany . The RESISTOGRAPH measures the drilling resistance by measuring the electrical current needed to penetrate the wood. The results are printed out on a paper inside the machine which displays the resistance along a 1:1 scale of depth in centimeters. Figure 2 shows the lower resistance of the one-inch cedar plank, the higher resistance of the one-inch oak frame, and a small gap before the drill penetrates the plywood ceiling on the inside of the hull. Even though the hole drilled is very small, this technique would be considered a destructive test if used on the outer hull. If used on structure members on the inside of a vessel which are not responsible for watertight integrity, the hole would not be expected to cause sufficient damage to cause problems. Structural members, such as the oak frames and floors could be evaluated using this model.

The use of this method is most highly suited for larger and lower density woods although knots should be avoided in any type of wood. The variability of soft woods, due to knots, etc., such as cedar, make it more difficult to detect the kind of density changes caused by questionable wood. Voids in members could easily be detected although the probability of selecting the right location may be minimal. The cost of these units starts at about $4000 so their purchase may be prohibitive for all inspection offices.

3) STRESS WAVE TECHNIQUES

One of the pieces of equipment demonstrated by the Forest Product Laboratory utilized stress wave techniques which is one of the most widely used methods used for evaluating wooden members, especially those which are in place. The method records the amount of time that a wave generated by an impact travels over a particular length of a structure. Areas with decay will slow down the sound increasing the time of travel.

The measurement device demonstrated had a digital readout of the time in micro-seconds that it took for the sound to travel between the probes. These probes were hand held approximately one foot apart so that some of the variability is dependent upon the non-steady distance between the probes. The numbers ranged between 30 and 60 with the higher numbers recorded in suspect areas. The signal was lost at some discontinuities such as putty, but was not consistent. The signal was also lost at some seams and across one of the butts indicating a questionable area. It was thought that the sound may sometimes have found alternative paths such as through the paint, or down, over and up through an adjacent plank. This also appeared to be the case for some butt inspections which were performed.

Overall this method appeared to point out degraded areas but the level of resolution is far beyond that required by marine inspectors. The amount of loss in structural integrity found by this method is not sufficient to cause problems in a planked wooden vessel. In addition, the paint and fasteners seem to cause problems in data interpretation just as knots would over relatively small areas.

4) ULTRASONICS

Ultrasonics has been used for many years as a nondestructive tool for metals and composites. The major problem with wood is its lack of homogeneity which results in variable mechanical properties such as changes in density within the material. As a result, an ultrasonic gauge cannot be calibrated for sound speed so other methods for wood have been found. On the other hand, ultrasonics can be used on the metal fasteners.

The major use of ultrasonics in fasteners was demonstrated on the large pins (3/4 inch) of the USS CONSTITUTION as described previously. The unit used for the CONSTITUTION and this test was the Krautkramer-Branson Model USD 10 digital flaw detector. The sound created by the probe is transmitted into one end of the fastener. Since the standard ultrasonic probe is 1/4-inch in diameter, it is difficult to measure any fasteners that are smaller than 3/8-inch. Smaller probes are available, but these are special order and may not work with all machines. Only the rudder stock and rudderpost bolts were large enough to be tested and the test confirmed the visual inspection of dezincification. In addition, nails and wood screws do not provide a good backwall. The sharp points and threads distort the return signal, rendering it unreadable.

5) CAPACIFLECTOR

One of the more interesting techniques evaluated was the CAPACIFLECTOR developed for the National Aeronautics and Space Administration (NASA). This system is a capacitance-based, non-contact sensor that detects the presence and position of high dielectric materials. This is the same principle behind many of the moisture meters use for the inspection of fiberglass and composite boats, but the processing of the resultant changes in the electric field is much more sophisticated. There have been many applications which have ranged from monitoring film thicknesses of less than 1/1000 of an inch to measuring fluid levels up to 30 inches away. The unit demonstrated for this effort is in the developmental stage. It currently has the capability of changing the frequency of the output signal and can detect changes in the amplitude and phase of the resulting field as influenced by the surrounding material.

The probe selected for this demonstration was designed to permit the deep penetration of wood and had a three-inch diameter footprint. Differential readings were taken by subtracting a baseline reading taken in air, away from an object, from a reading taken at the surface. As expected, the readings taken at a known wet area, where water was dripping, provided four times the response than on most of the remaining parts of the hull. This indicated that most of the hull had dried out and the wood was no longer saturated.

Locations above the waterline were tested in Areas 1 and 5. In Area 1, dips in the readings were seen at two areas where the marine surveyors had indicated problems. (See Figure 3) In fact, it was marked right on the wood. But the dip at the 12 inch area is not consistent, especially since it is at a frame where the oak and fasteners should increase the readings. Area 5 was expected to be good and the data generally agreed except for a couple of areas on the left and top of the area (see Figure 4). Again, the data did not match the vessel frames as expected.

Overall, this technique did appear to detect changes in the wood structure of the hull although a rigorous analysis was not done to determine the actual conditions which were in place for both the wood density and moisture content. This technique currently requires processing back at the laboratory so development is still needed. It is still unclear if changes in fastener properties or even fastener locations are masked by changes in wood density or moisture content. Additional development work is needed to calibrate a system such as this and make it useful for field work.

6) X-RAY EVALUATION

For x-rays there are multiple parameters which could influence the results. The test fixture fabricated served as a known structure to verify the x-ray equipment's capability and be utilized for comparison. The conventional x-ray images were processed in about 15-20 minutes in a portable darkroom contained on a truck specially configured for this. The real-time system was supplied by Ultra Image International, a division of Science Applications International Corporation was a Digital Radioscopy System (DRT). The source is a low level, pulsed unit to ensure safe operation. The system is designed for special problems such as detecting plastic explosives in luggage, identifying damage in composite and aluminum aircraft structures, and inspection of printed circuit boards so the energy levels are insufficient for thick pieces of wood. As a result, the images are not as sharp as other portable, real-time systems with a higher source level. This system currently sells for about $30K and a stronger source would be another $10-15K.

a) TEST FIXTURE EVALUATION

The first shots for both systems were taken of the test fixture built for this experiment. These shots were taken of the upper right-hand portion of the test fixture. The conventional x-ray results (Figure 5) shows the first problem encountered; the angle at which the shot is taken makes fasteners at different locations overlap and even appear not to be in the location thought. The shanks of the fasteners which were filed are easily seen. In the real-time shot (see Figure 6), a more limited area is covered. The results are a positive picture so that this shot is a mirror image of the conventional x-ray. The defects are easily seen.

Both systems detect the known defects within the test fixture. The resolution of the conventional x-rays is better than what is shown in this report due to the conversion from an 11-inch x 17-inch x-ray to a smaller picture required for this paper. The wood grain lines are seen much clearer in the actual film. On the other hand, the real-time results took only about five minutes for each shot (as compared to the conventional time of 15-20) and the sharpness and resolution can be enhanced by moving the image (stored in a .TIF configuration) to a variety of software image processing packages. The resulting images were still not as clear as the conventional ones.

b) TEST HULL

Based on the success of the shots on the test fixture, it was decided to move to examine the test hull. The areas where the location can be determined and the exact fasteners identified for both techniques are at the stern (Area 3) and at the bow (Area 6). After the completion of the tests, the hull was cut up and the test areas were saved. Several other pieces have been sent to participants and the remainder of the vessel was scrapped. The saved sections were split open and the fasteners identified with respect to the x-rays. The results of the dissection is described along with the corresponding x-ray in the sections below. The fasteners were extracted by spitting away the surrounding wood, disrupting the fastener as little as possible. The wood surrounding the fastener was also examined carefully. Many of the clinch-nail fasteners in the lower section of the hull were so badly damaged that only the heads and the part of the shank in the planking remained.

Stern

The stern area was a unique area because it was very accessible from the inside and outside. The conventional x-ray was taken with two overlapping pieces of film attached to the outside of the hull and the source inside on the deck and is seen in Figure 7. This shot was taken with the source approximately 36 inches away from the film. A 2½-minute exposure was used using 120 KV with 2½ milliamps. Note that in the x-ray, the outlines of the good fasteners are distinct. The lighter color near the head is the bung placed over the fasteners. Closer to the waterline, the fasteners in the x-ray begin to have less distinct shapes and almost seem to have a halo-type ring around them. In this case, the oxide created by the corrosion process has a different density. The real-time x-rays of this area are not as clear. Figure 8 shows an angled shot taken at the same location as the conventional one.

Bow

The stem (Area 6) is typically a difficult area to inspect. Interior structures can limit access and some fasteners are completely inaccessible due to the construction techniques required for the knee area. The inspection can be concentrated on the exterior fasteners as long as the outer planks keep moisture away from the interior sections. .

The conventional x-ray of the bow utilized a 17-inch by 13-inch film (see Figure 9). The resolution of this is reduced when compared to viewing the full-size film on an x-ray viewer so that not all of the 42 fasteners identified by the x-ray technician can be seen here. The stem has a one-inch-wide brass cover, seen down the center of the x-ray, with two pieces butting together just below fastener #27. The x-ray was taken with the source inside of the hull. Note the inside structure and ceilings with fasteners in various directions. As was the case for the stern, the fasteners above the waterline (above the brass butt) appear to generally be in good condition. There are a few ceiling nails, going from the inside out on both sides of the x-ray.

Just below the center of the x-ray in Figure 9, the washer (near the center of the figure) and the head of a bolt can be seen (nearer the bottom). This was a major attachment of the stem to the knee and is in generally good condition although the x-ray does not provide any information. Near the bolt, there are several partially corroded fasteners just to the right of the brass. The center of the fastener which still has good metal is surrounded by a slightly lighter layer of oxide. The difference can be seen in the actual amount remaining in the fasteners in Figure 10. The upper fasteners (15, 22,23,32) are all in good condition. While the ones located below the waterline show extensive wastage as predicted by the X-ray. It is important to note that all fasteners started off the same size: large (15,18,22,32,38,40) and small (19,23,37,40) so using these type of references can help provide a relative wastage rate.

The real-time x-rays were also taken with the source inside of the vessel. The butt-in brass can be seen just above the center in Figure 11. The lower energy real-time system had some difficulty penetrating the large amount of structure.

C. LABORATORY SHOTS

A set of x-rays were taken of saved pieces of the hull in a controlled laboratory setting. The first set of x-rays were taken of a 6-inch square section of the keel which contains two through-bolts. The necking of the fasteners can be seen in the conventional (Figure 12) and the real-time shots (Figure 13) taken at zero degrees. The effect can be seen in the other shots as well (Figure 14) taken at a 30 degree angle. This shot also shows how fasteners can hide behind other ones so that orientation of the source is important. Finally, the size of the bolts on the X-ray varies with the distance that the film is from the fastener. Thus, rod "B", which is closer to the film, has truer dimensions which can be measured right off of the film, especially for the 30 degree film. Larger distances increase the angles and therefore increase distortion.

A series of shots utilizing both conventional and real-time techniques were also taken of a section of the hull dissected from near the keel. The objective of this group of shots is to provide some standard types of arrangements which will help film interpretation. It is also important to note that these shots were not taken through the entire so the result is a clearer picture. The shots were taken at 30 (Figures 15 and 16) and 45 degrees (not shown here) from the side and cover sections of two frames. Both techniques indicate questionable fasteners, but the conventional x-rays provide more detail. A real-time shot was taken at a 60-degree angle (see Figure 17). Although the condition of the fasteners can be determined, the distortion is very severe and this amount of angle should only be used for extreme cases.

V. CONCLUSIONS

There are two general groups of conclusions which can be drawn from this evaluation. The first group of issues concerns the inspection process for wooden vessels, especially for Coast Guard inspectors and will not be discussed here. The second group is concerned with the evaluation of the nondestructive inspection techniques, the primary objective of this project. These issues are mainly the applicability and effectiveness of the methods. The conclusions are drawn from marine surveyors reports, a report on the dissection of the hull and personnel communications.

A variety of techniques were demonstrated during this project. Several may be useful in the initial phases of an inspection when locating questionable areas. Additional development would be required for SMART HAMMER and CAPACIFLECTOR to be utilized in this phase. Extensive testing would be required to develop a repeatable calibrated method which would be capable of handling all of the variables. These variables may include, but not be limited to, all material properties (wood, fasteners, coatings, caulking materials, etc.) as well as various wooden vessel fabrication and repair techniques. The specialized drills and ultrasonics would be useful for unique situations, mostly for larger vessels with large structural members and fasteners.

The stress-wave technique may be useful for larger vessels as well. It would still need extensive calibration and development of test procedures. The level of defect detection may still be too fine for most vessel requirements although the calibration effort could resolve this issue. The Forest Products Laboratory has also expressed interest in trying this technique across connections.

Only the two x-ray techniques directly measured the condition of the fasteners themselves. Conventional x-rays were effective at identifying the fasteners and their condition. They are well suited for use in the field. The real-time x-ray system used in this study did not perform as well but it shows potential due to its size and process speed. Other real-time systems with stronger sources, currently on the market, are expected to perform as well as the conventional x-rays. Neither technique can evaluate the condition of the wood immediately adjacent to the fasteners although deteriorated wood is not usually found next to a good fastener unless the vessel has been refastened. The orientation of the wood grain can be seen in the x-rays. This may be useful information in some cases where paint does not allow the determination of the type of planking used. The results of the x-rays should not be the only piece of information used to assess the condition of the fasteners. Other information such as the vessel's history, and visual clues should be combined for a total assessment.

The x-ray firms utilized in this study require a minimum charge for 4 hours of work of about $400-500.00 for either the conventional or real-time methods. This is expected as an average throughout the industry. Four hours should be more than sufficient to examine the "eight fastenings per side below the waterline" as recommended in NVIC 7-95. The real-time technique could be completed in less than 2 hours which reduces the total time spent on site.

Comparing the conventional and real-time x-ray costs to the current methods results in a wide range of time and costs. Screw type fasteners are relatively easy to remove and examine. The coatings and wooden plug are removed and the screw is backed out. There are three options at this point which is generally left up to the inspector:

1) if the fastener and wood both appear good, the screw is reinserted.
2) if the fastener is generally good but some minor wood deterioration is found, the next larger size screw is inserted.
3) if moderate wood deterioration is found but most of the adjacent wood is good, fasteners can be inserted in the good areas and the old hole plugged up

4) if the wood and fastener are deteriorated, then a plank and/or frame may have to be replaced.

The action taken by an inspector depends upon the severity and location of the problem area. The first three options are generally low- cost (maybe $50.-100. per fastener) and minimal time (1-2 hours per fastener at the most). If complications arise such as breaking a fastener or stripping the screw head the costs and time can go much higher. A plank removal can take several days and cost over $1000.00 depending upon the location of the plank being removed. One surveyor in Maine routinely pulls one-half inch diameter fasteners out of schooners by welding a rod to the end. Several other marine surveyors have mentioned performing this type of pull as well. Minimal damage is caused so the plank usually does not have to be replaced.

In general, it is much more difficult to remove and examine a nail. On most occasions, the plank is damaged locally and some rework is required as sufficient wood must be removed to get a cats paw or equivalent tool to reach the nail head. Ring nails are extremely difficult to pull and caution should be taken. If the ring nail does not pull out with a reasonable effort, then it is likely holding adequately and a major removal effort should not be performed. Some nail removals may be extensive. The effort required becomes equivalent to the final option for removing screws as described above. Thus it can involve several days if the required material is not readily available and cost over $1000.00.

There are some problems with the inspection of wooden boat fasteners which this project did not address but were raised in discussions with the commercial surveyors. These include counterfeit fasteners, mixing fasteners in the same area and the use of bonded GRP joints where fasteners do not really supply support. All of these types of situations should be approached carefully.

VI. RECOMMENDATIONS

It is recommended that the use of both the conventional and real-time x-ray techniques be encouraged, especially for unique situations such as critical areas and special or antique vessels if the owner refuses to remove and examine fasteners. It is expected that the effort would be at the owner's expense to show that the area in question is sound. The results of the x-ray should not be the only information used to make a decision. All aspects of the vessel's condition and history should be taken into consideration. As the use of this technique increases, it will be improved and knowledge of it will grow throughout the industry. Advances should be taken into consideration such as other sizes of film and new and smaller sources. The location on the vessel that the x-ray was taken must be recorded with sufficient detail so that the individual fasteners can be identified and found later.

Future research should focus on advancing the methods currently used to identify problem areas. An experienced inspector can utilize visual clues and the hammer technique to good effect to identify questionable areas. An inexperienced inspector does not always possess sufficient knowledge which can only be gained through experience. Further development of methods such as SMART HAMMER and CAPCIFLECTOR have the potential of providing quantifiable results which could supplement the training and knowledge of an inspector.

The opinions or assertions contained herein are the private ones of the writer and are not to be construed as official or reflecting the views of the Commandant or the Coast Guard at large.

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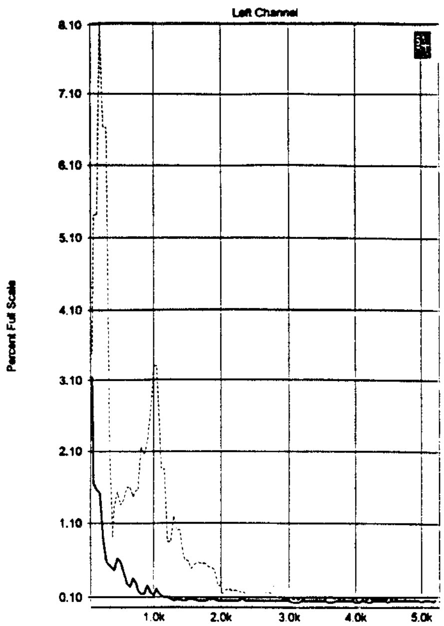

FIGURE 1. Results from SMARTHAMMER (Dotted line = good plank, solid = rotten)

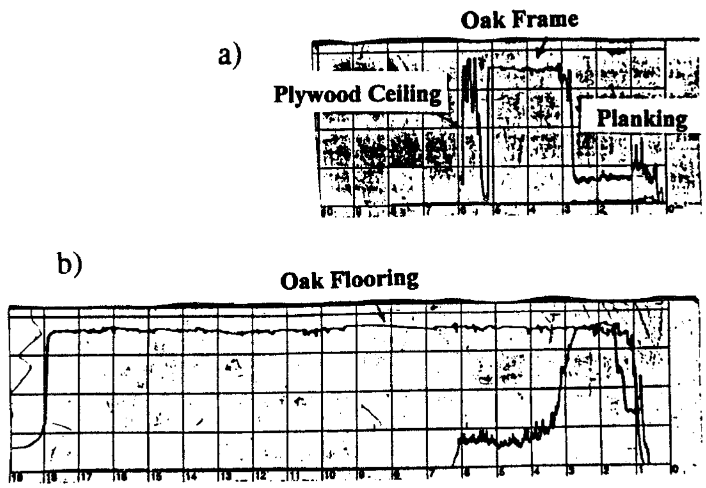

FIGURE 2. Results from RESISTOGRAPH.

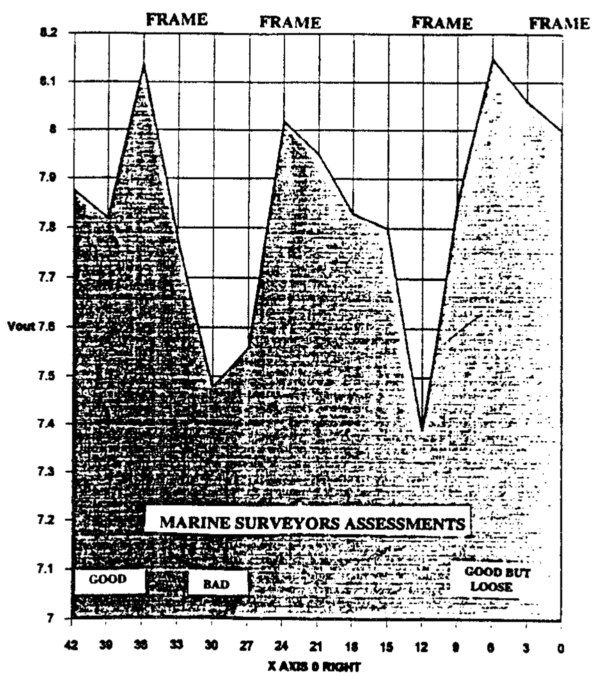

FIGURE 3. Results of CAPACIFLECTOR of Area 1.

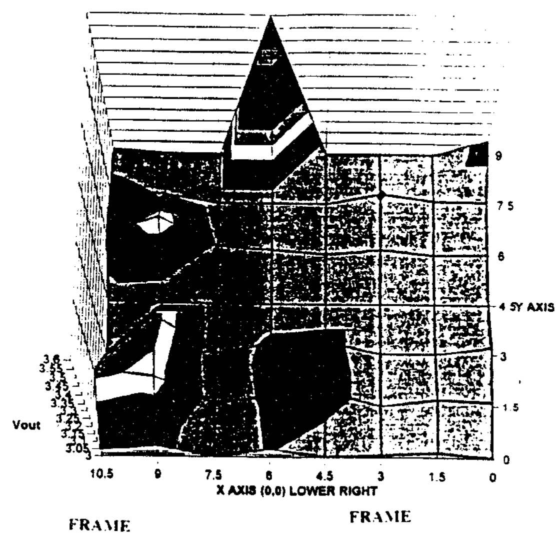

FIGURE 4. Results from CAPCIFLECTOR of Area 5.

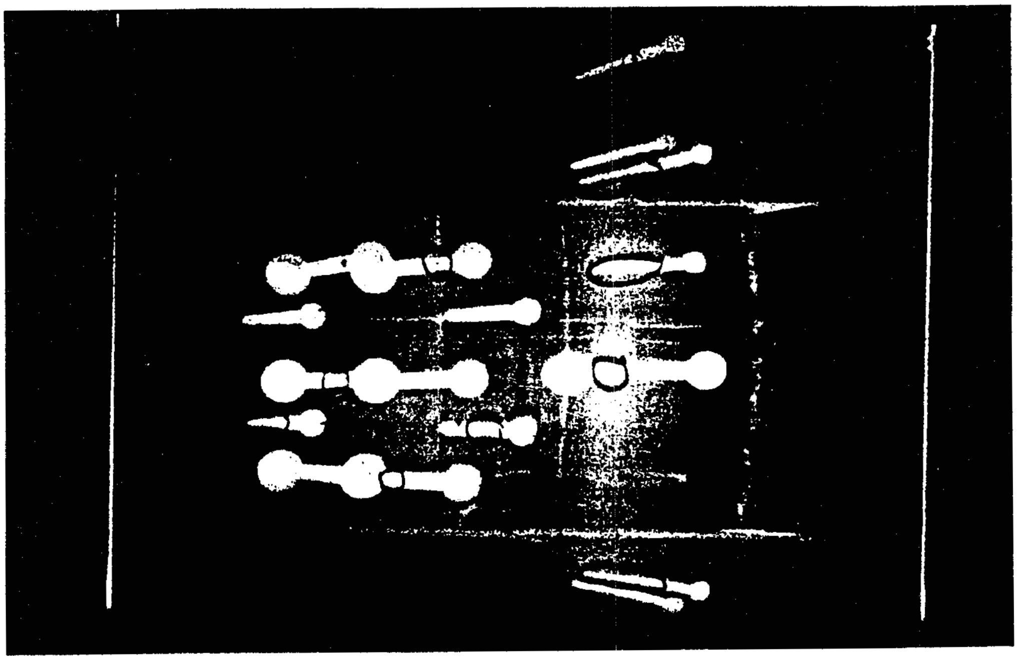

FIGURE 5. Conventional x-ray of test fixture

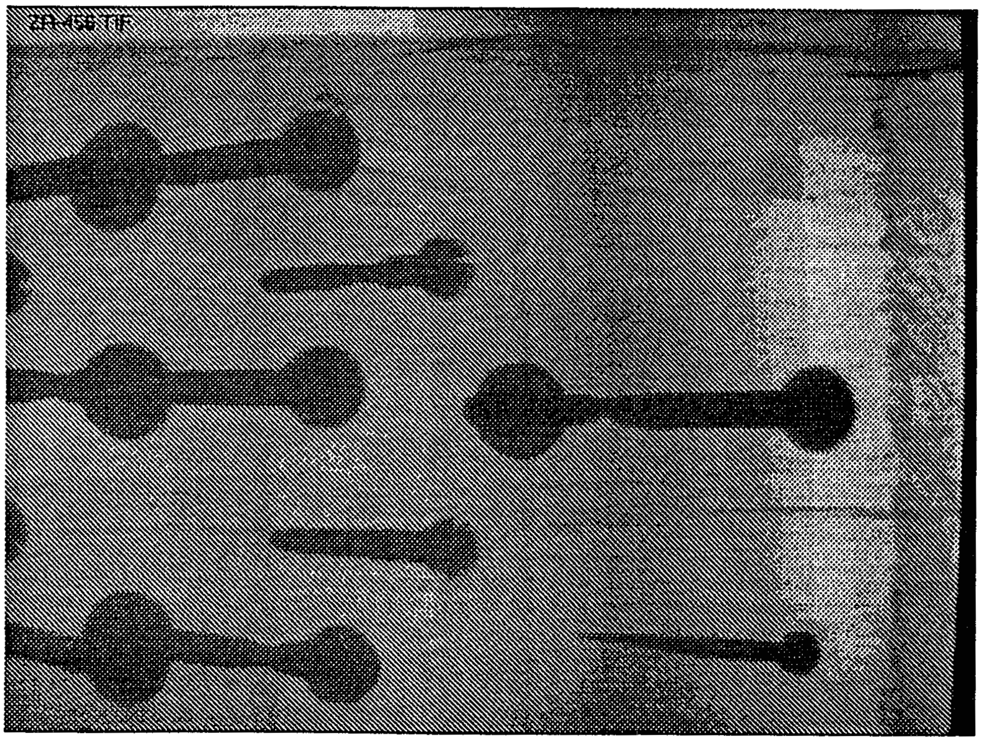

FIGURE 6. Real-time x-ray of test fixture

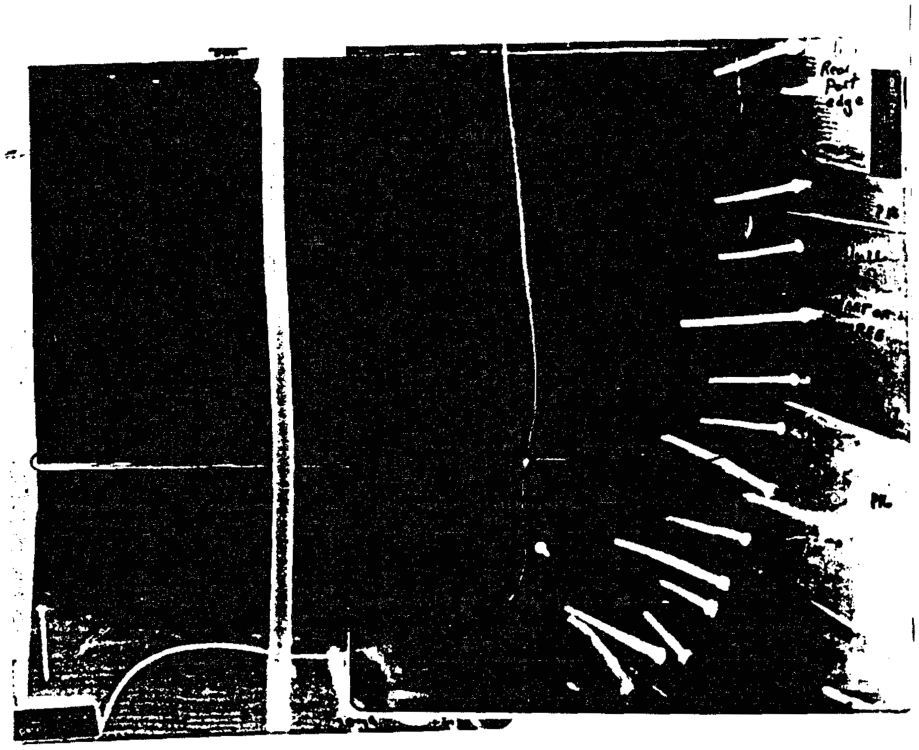

FIGURE 7. Conventional x-ray of stern.

FIGURE 8. Real-time x-ray of stern.

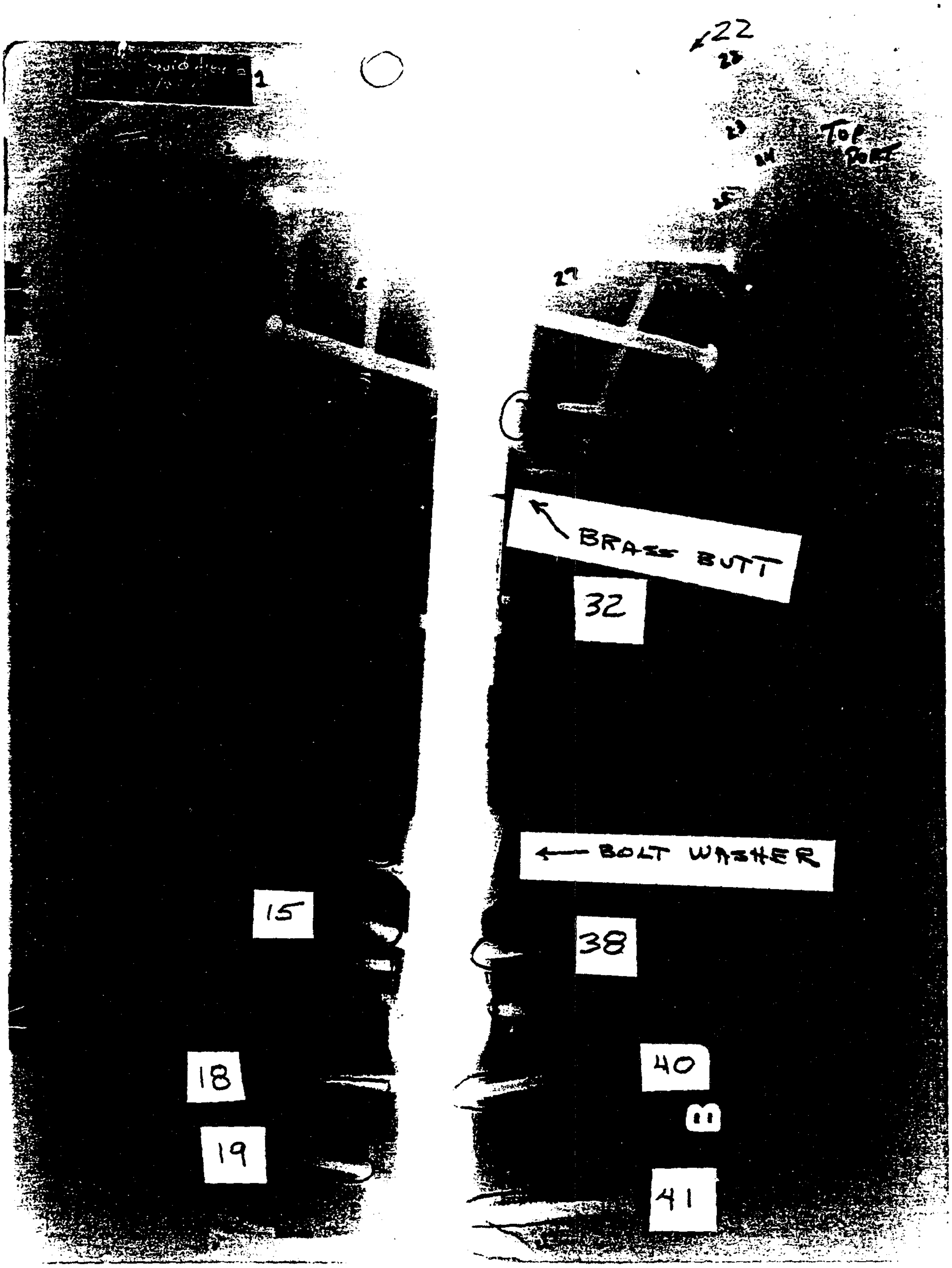

FIGURE 9. Conventional x-ray of bow

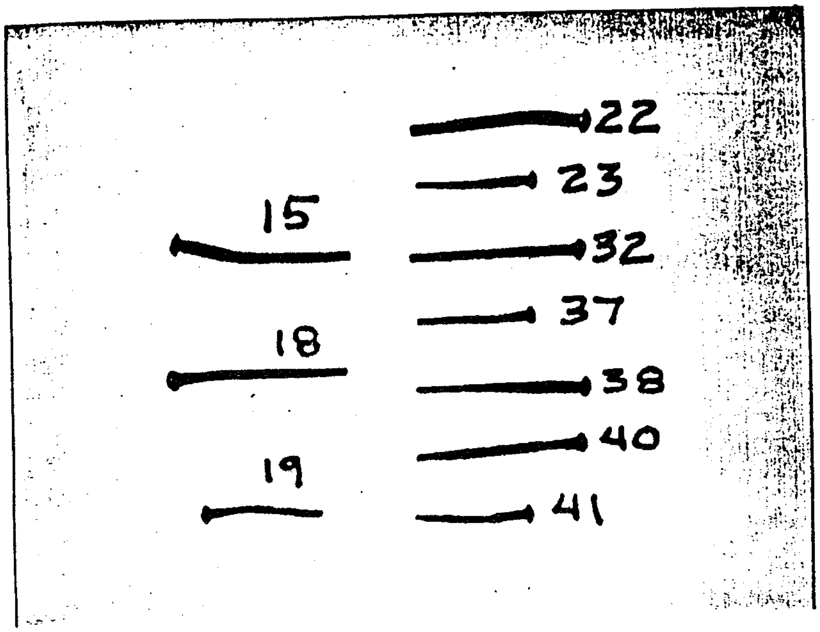

FIGURE 10. Fasteners removed from bow.

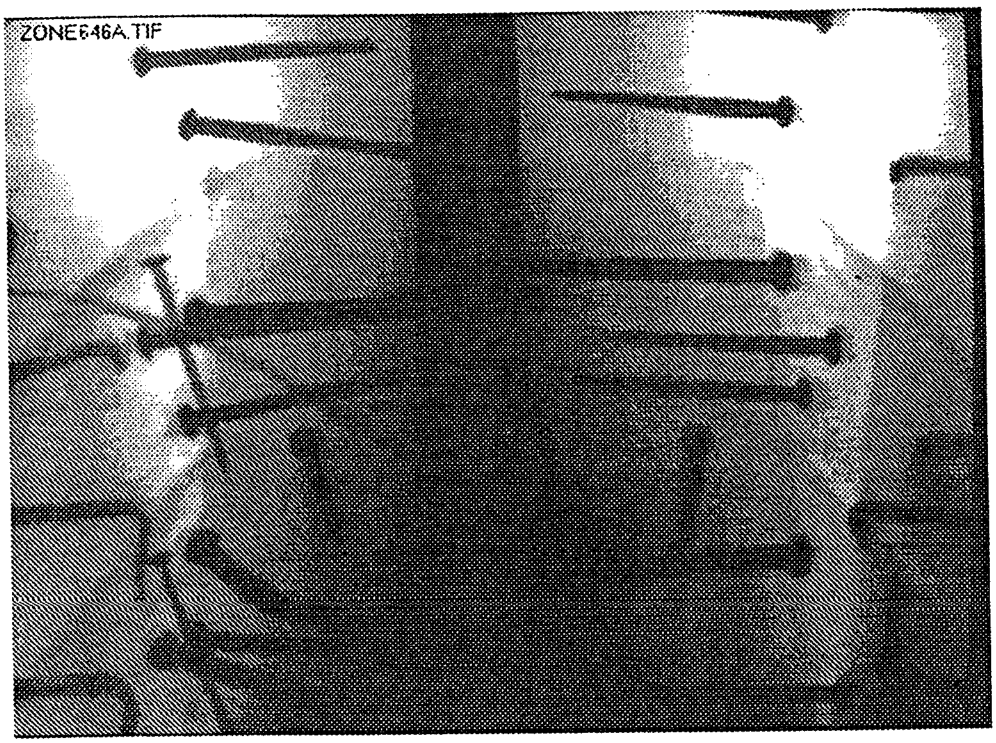

FIGURE 11. Real-time x-ray of bow.

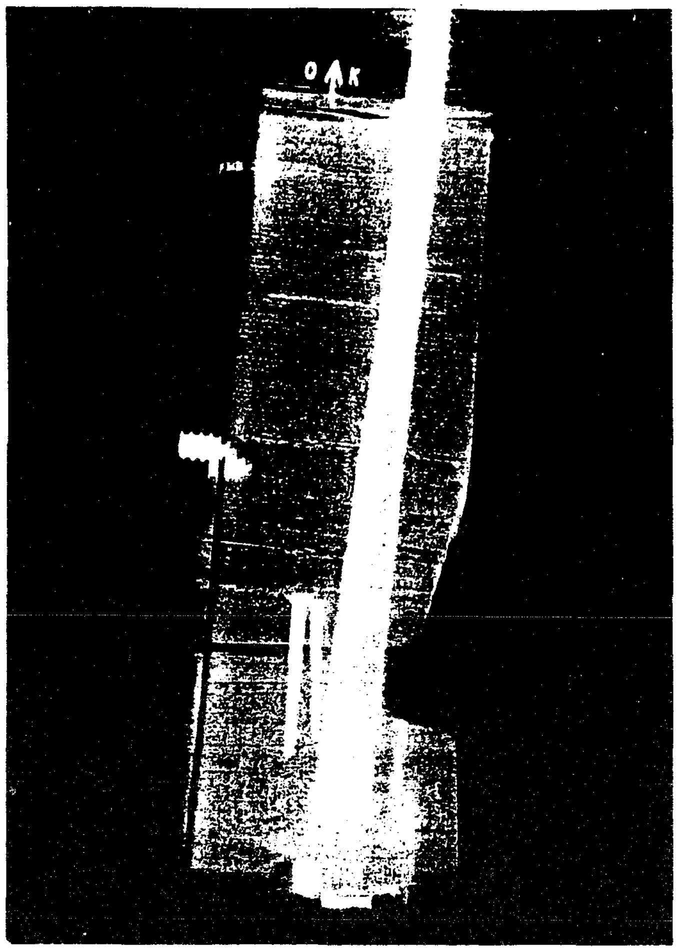

FIGURE 12. Conventional x-ray of bolts taken at zero degrees.

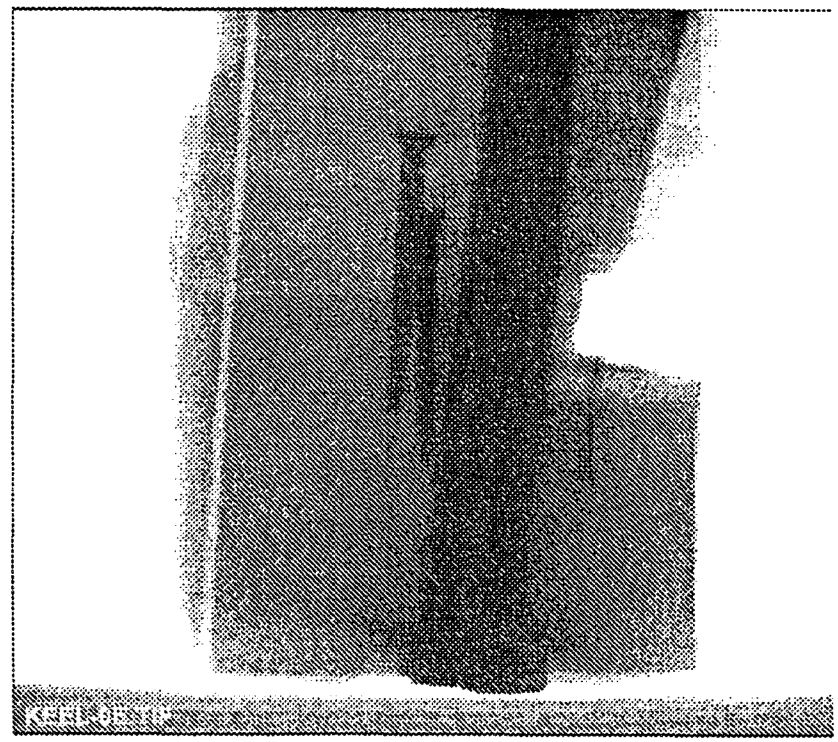

FIGURE 13. Real-time x-ray of bolts taken at zero degrees.

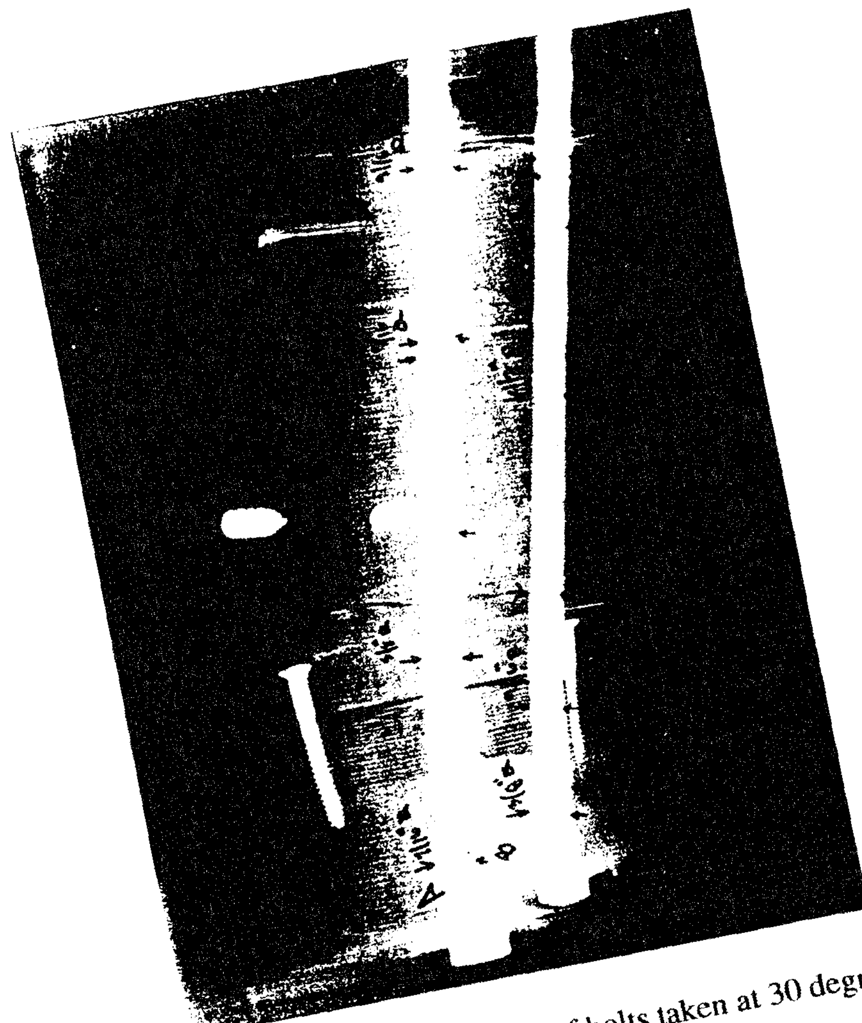

FIGURE 14. Conventional x-ray of bolts taken at 30 degrees.

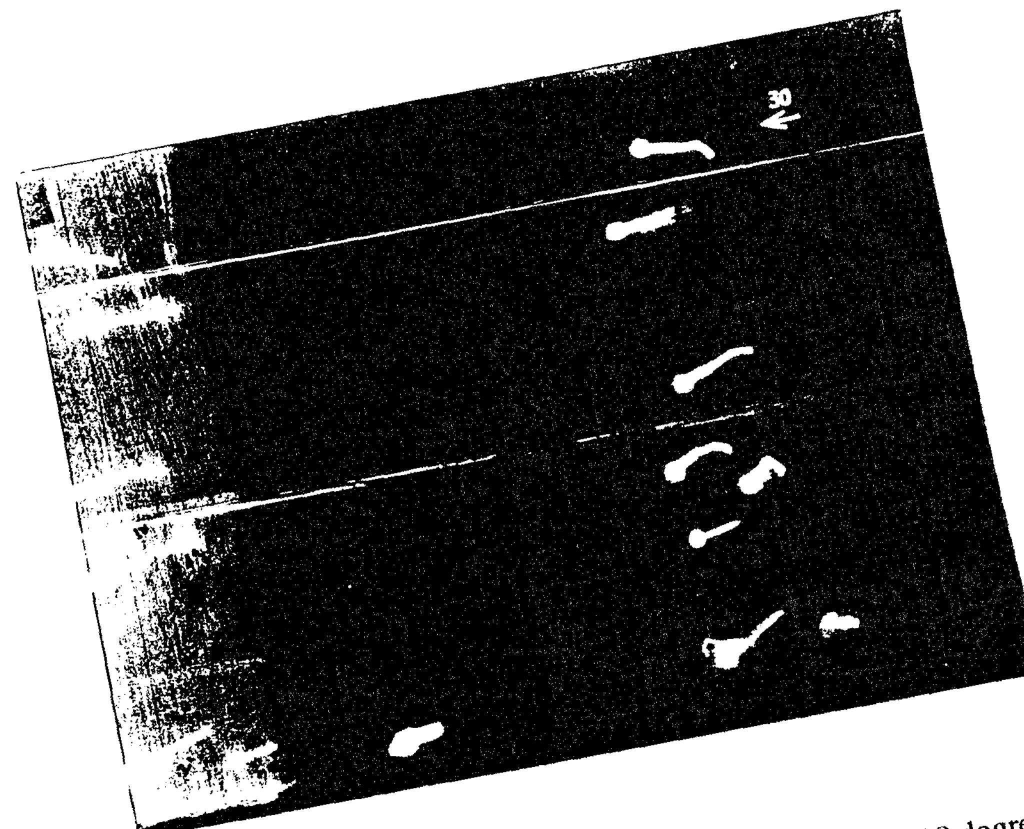

FIGURE 15. Conventional x-ray of planks taken at 30 degrees.

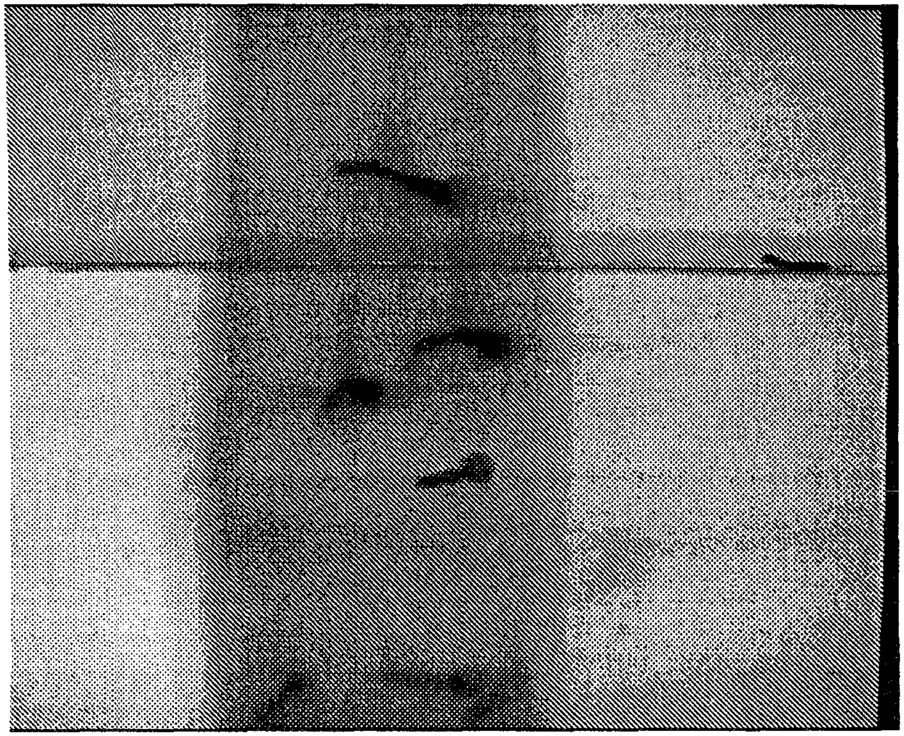

FIGURE 16. Real-time x-ray of planks taken at 30 degrees.

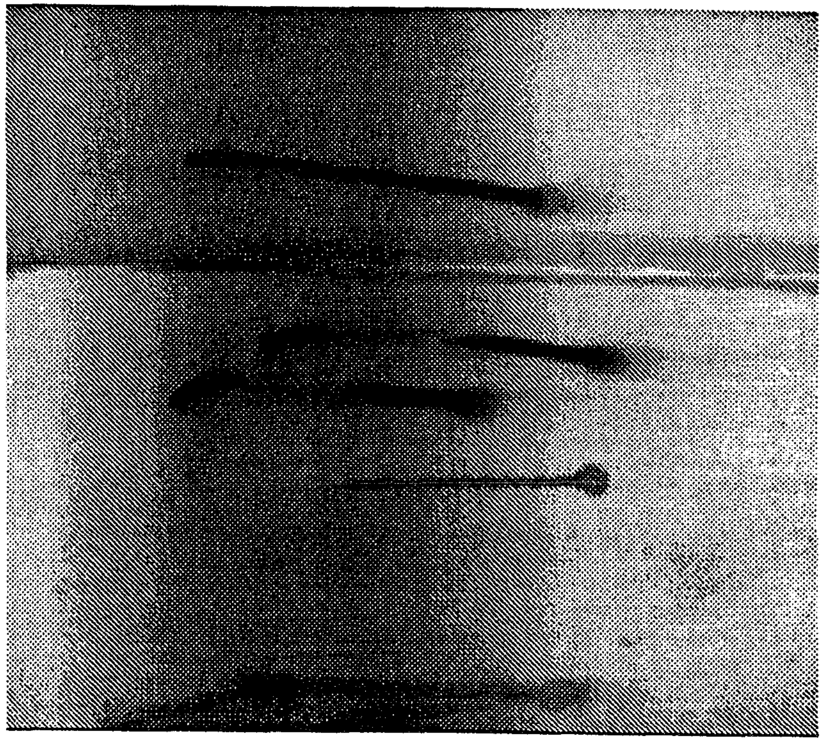

FIGURE 17. Real-time x-ray of planks taken at 60 degrees.