NASA TECHNICAL MEMORANDUM

NASA TM X-73504

NASA TM X-73504

(NASA-TM-X-73504) INSPECTION OF COMPOSITES
USING A COMPUTER-BASED REAL-TIME
RADIOGRAPHIC FACILITY (NASA) 12 p HC $3.50
CSCL 14D
G3/38

N76-33526
Unclas
05702

INSPECTION OF COMPOSITES USING A COMPUTER-BASED REAL-TIME RADIOGRAPHIC FACILITY

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TECHNICAL PAPER to be presented at the
Second Conference on Automated
Inspection and Product Control
Chicago, Illinois, October 19-21, 1976

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ABSTRACT

A radiographic inspection facility is being developed at the NASA Lewis Research Center. The facility uses a computer to provide enhanced images in near real-time. Some capabilities of the facility are demonstrated in the inspection of a fan frame ring for an experimental aircraft gas turbine. The ring was fabricated from a carbon-fiber-reinforced epoxy composite material. Inspection procedures are evaluated. Comparisons are made with an ultrasonic C-scan and conventional film X-ray.

SUMMARY

A new computer-assisted radiographic research facility was used to inspect a composite materials structural element. The test object was a part from a fan frame ring for an experimental aircraft gas turbine. The results of inspections by ultrasonic C-scan and paper radiography are also shown. Two methods of digital image enhancement were used: brightness expansion and high-pass filtering.

The test object was selected because it clearly showed the extent of damage incurred in a previous proof test. The ultrasonic C-scan showed the extent of delamination damage, while the radiograph clearly delineated the damaged areas. The electronic images showed the same damaged areas as the radiograph as well as subtle variations in the damaged zones that were not evident in the radiograph.

This preliminary study shows that digital image analysis offers the advantage of immediate results, furthermore revealing radiographic information that would not otherwise be evident in a conventional radiograph.

INTRODUCTION

Dr. George Martin, in his keynote address for the first Conference on Automated Inspection and Product Control (ref. 1), made the following statement. "...(T)he most important and

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promising (reason) in this whole field of automatic inspection, is the use of those data automatically for a feed-back loop for the immediate control of the production process." One immediately visualizes computer controlled inspection processes examining every part at every manufacturing step, automatically sending signals to the machinery, making minute and subtle adjustments which result in a 100 % flaw-free production run. However, that is not necessarily desirable.

At that same conference, Mr. R. L. Davies (ref. 2) emphasized that computers can augment, but not replace human judgement. And Dr. D. P. Johnson (ref. 3) demonstrated that it is neither necessary nor desirable to reject all but flaw-free products. Economics dictates that discontinuities smaller than some limit-value should not be rejected. Thus the major reason for introducing a computer into the inspection process is to reduce variability, not necessarily to increase sensitivity.

The emphasis in this paper is that computer-based radiographic inspection of certain structures potentially reduces response time sufficiently to close the loop in a manufacturing-inspection process at minimal loss of sensitivity.

Holloway, Shelton and Mitchell (ref. 4) have overviewed the field of radiographic image processing. They conclude that many trade-offs exist between resolution, sensitivity and speed. Whatever trade-off is made, the improvements frequently come at the expense of greater initial capital investment. The results of their paper suggest several potential advantages:

greater operator convenience and less fatigue,
less time between discovery of an anomaly and initiation of corrective action,
decreased direct inspection cost, and
fewer rejects at later stages of a production run.

The greatest disadvantage is the increased cost of the equipment.

Because of the potential advantages of computer-aided radiography for aerospace applications, NASA Lewis Research Center has been developing such a research facility. The prime intent of the facility is to permit real-time assessment of radiographic images, to improve the quality of radiographic inspection, and to reduce inspection time. The facility is now operating and research studies have started. This paper summarizes some initial research results which demonstrate its capabilities.

OVERVIEW OF FACILITY

The test facility is composed of discrete modules, both state-of-the-art and developmental. Figure 1 illustrates its various elements schematically. Referring to that figure, the facility will be described briefly here.

The facility consists of 3 major components: an image acquisition system, an image conditioning system and an image processing system.

The X-ray signal is sensed by a Radiographic Amplification Screen (RAS). This is a solid-state, electronically-excited, thin-film screen which senses an X-ray field on one face and displays a visible image on its opposite face. (This device is described in greater detail in ref. 5.) A television camera accepts the visible radiation from the RAS and converts it to a standard television signal.

The television signal is converted at the standard 10 MHz rate to a digital signal at the image conditioning station. It is stored on a high-speed magnetic-disc refresh memory. It is simultaneoulsy displayed on a TV monitor. The refresh memory may be modified by the image processing system and the results redisplayed on the monitor. All photographs in this papter were made directly from the display monitor.

The image processing system is a mini-computer system. Because of the large volume of data which is contained in each image, the computer cannot keep up with the rest of the system. A short time-lag occurs for each process applied to the image, varying from a few seconds to a few minutes. Production systems can be hard-wired to radically reduce the processing time, but the slower software approach provides the versatility needed for a research installation.

The image is represented by a field of 490 lines, each consisting of 512 picture elements. Each element is 8 binary digits wide, producing the capability of representing 256 discrete shades of brightness, ranging from black (0) to white (255).

DESCRIPTION OF TEST OBJECT AND INSPECTION PROCESS

The test object was a portion of a fan frame ring for an experimental aircraft gas turbine. Its plan view is shown in figure 2. It was fabricated from 10 plies of carbon-fiber-reinforced epoxy composite material. Each ply is approximately 2.5 mm thick, laid-up from pre-impregnated fibers at angles of 0, 45 and 90 degrees. The plies were cured and adhesively bonded together. The region inspected was the junction of the foot with the upright member. Photographs of this region are shown in figure 3, which shows extensive damage near this junction. This damage was incurred during a previous proof test. The purpose of the ultrasonic and X-ray inspections was to reveal the extent of any internal damage. This particular test object was selected because of the ability to confirm the ultrasonic and X-ray indications.

The test object was given two corroborative inspections. The first was an ultrasonic C-scan. This was a conventional immersion, dual-transducer scan using a graytone recorder. The test was conducted at 2 MHz. The result is shown in figures 4(a) and 4(b). Figure 4(a) shows the scan of the entire object. Figure 4(b) is a close-up of the area of interest. Because of extensive delamination in the damaged zone, little information is apparent in that figure. However, it indicates the existence of damage, and shows its location and approximate extent.

More detail is produced by radiography. In this case, the radiography was done on opaque photosensitive paper, rather than film. A short exposure at low voltage produced the image shown in figure 5. It was produced in approximately 15 seconds at 50 Kv and 6 Ma. There was no filter, but an image intensifier screen was used with the paper. This method emphasized the major shortcoming of conventional radiography. The basic drawback is that intermediate steps must be taken before the image is available, introducing a time-delay.

IMAGE PROCESSING TECHNIQUES UTILIZED

Once it is digitized, the image appears to the computer as an ordered array of approximately 250,000 numbers ranging in magnitude between 0 and 255. Any desired mathematical operation may be performed on those numbers. When the numbers are converted to an electronic signal and are redisplayed on a television monitor, the resulting image is said to be a "processed" image.

Previous experience has indicated that two types of processing are most helpful. The first is transforming the numbers representing subject brightness to increase the contrast over a given area of the image. The second is modifying the numbers defining the edges of the object to increase the edge sharpness of a given region of the image.

The brightness expansion can be performed relatively simply. First the gray values of a dark area and a bright area are measured. (The measurement is performed by reading the appropriate numbers in the memory of the computer.) Then a linear transformation is applied to all the brightness numbers stored in the computer. All numbers between the low and high values read are expanded to the limits of 0 and 255. Any numbers outside these limits are set to the limits.

There are several ways of performing the second operation. The one used here is "high-pass filtering". To understand this operation, it is helpful to visualize every point of the image as being represented by a spectrum of "spatial" frequencies. The units of spatial frequency are cycles per millimeter, rather than cycles per second. In a region of an image where the brightness values are changing only gradually, the spatial frequencies are defined to be low in magnitude. In a region where there are rapid changes, the spatial frequencies are high. It is easily seen than an edge is a region of high spatial frequency.

Furthermore, if the low frequencies are filtered out, the edges appear more pronounced. That is the definition of high-pass filtering.

The process described here does not actually assign frequencies to the various points of an image and then filter them. Instead, a faster, more approximate method is used. First a "low-pass" filtered image is formed. Then that image is subtracted, point-by-point, from the original, producing a high-pass filtered image. The low-pass filtered image is produced by resetting the brightness value of each point to the average value of some small region surrounding it.

The procedure developed was completely empirical. It was found that the best images were produced by subtracting a low-pass filtered version of an image from a brightness- expanded version of that image. Three aperture sizes were investigated: 3 X 3 elements, 7 X 7 elements, and 15 X 15 elements. The latter produced the enhanced images included in this paper.

RESULTS OF RADIOGRAPHIC IMAGE PROCESSING

The original direct video image, figure 6(a), is very good. In a manufacturing situation, an experienced operator would probably need no further processing to make a judgment on the test piece. The horizontal bright band near the base of the upright indicates that the mechanical damage is extensive. The vertical lines at the lower part of the fillet show the junction, or separation, of two differently oriented plies. A comparison with figure 3(a) shows that this discontinuity occurs at a different location than the external damage at the root of the fillet. (The dark spot near the right edge is a blemish in the RAS.)

Further processing confirms the nature of the mechanical damage. Figure 6(b) shows a contrast expansion and figure 6(c) shows a high-pass filtered image. The latter shows that the damage is quite extensive, and clearly outlines what appears to be a large through-crack.

Magnifying the fillet region by moving the camera in closer produces the result shown in figure 7(a). (The four spots near the right edge are blemishes in the RAS.) Although the vertical lines at the root of the fillet are apparent, they are not clear and sharp. A contrast expansion is shown in figure 7(b), and a high-pass filtered image in 7(c). In the latter image the lines stand out quite clearly. Furthermore, a subtle gradation in density, not readily apparent in the paper radiograph, becomes prominently revealed.

These photographs illustrate that computer processing can can extract and display key properties of a radiographic image. This provides convenience, speed and freedom from the eye fatigue that accompanies conventional radiographic inspection processes.

DISCUSSION

Two types of irregularity were evident in this multiple-ply carbon-fiber-reinforced epoxy composite structural element. One was major mechanical damage producing broken fibers and separated plies. The other was the junction of differently-oriented plies. For those types of irregularities in that type of material, computer-assisted radiographic inspection was clearly superior to either ultrasonic C-scan or film-based radiography.

The ultrasonic C-scan produced little useful information. A washed-out area was apparent at the junction of the foot and upright members; this may be indicative of extensive damage or delamination. However, the only definite conclusion which could be reached is that additional inspection must be performed.

The radiograph was much more informative. The irregularities known to exist in the test object were evident. Fine details were easily resolved, and there was little extraneous noise in the image. However, those advantages occurred at the cost of an interruption in the continuity of the manufacturing process: that is, a delay for photographic image development was required.

The electronic image was instantly available. Even the unenhanced image displays a considerable amount of information. The damage in the upright portion was immediately apparent. A simple brightness expansion displayed additional information that was not available from the original image. The high-pass filtered image clearly delineated other factors.

CONCLUSION

Computer -enhanced real-time radiography promises to afford a quick and convenient inspection tool. In a manufacturing situation, there would be little delay between the discovery of anomalies and the opportunity to take corrective action in the pieces still in production. Moreover, with automatic processing of the radiographic image, the operator is relieved of the need to interact with all but the essential details of a given image. This is made possible by the facts that image processing routines can extract and emphasize only the essential features and make it easier and less fatiguing for the operator to concentrate on key factors.

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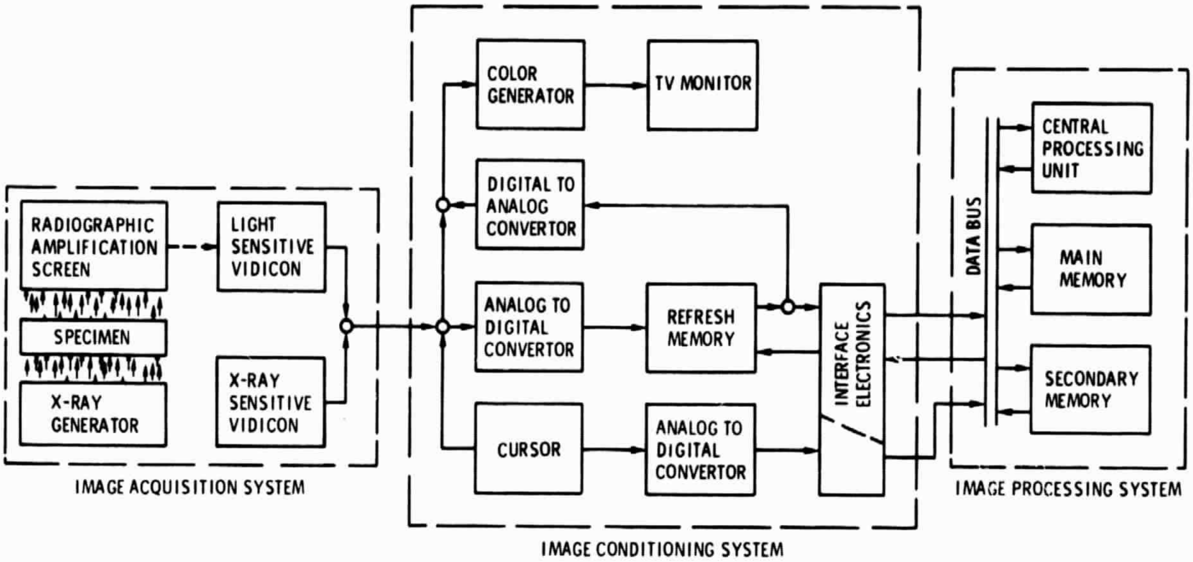


Figure 1. - Schematic of radiographic inspection facility.

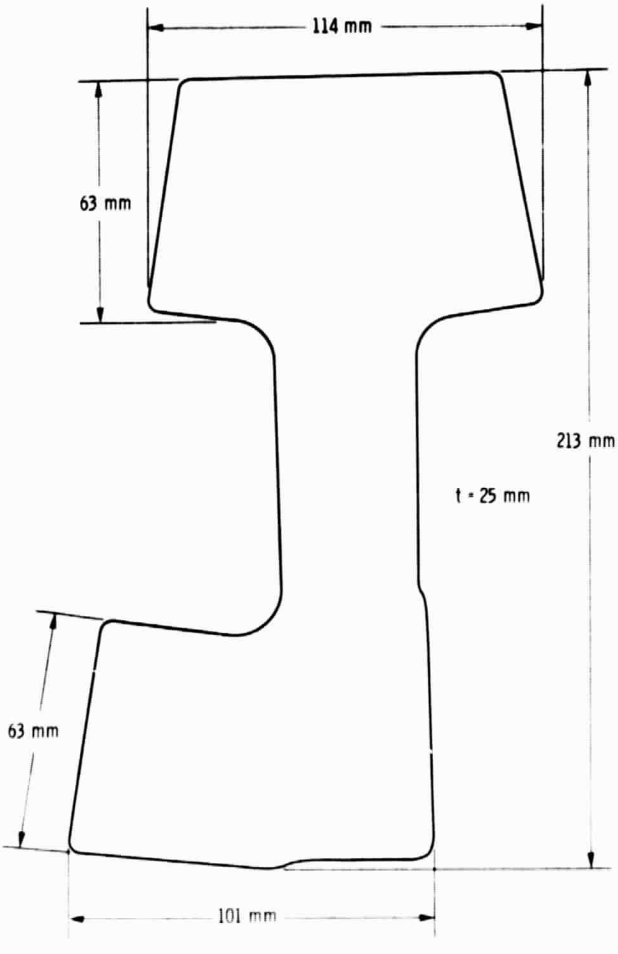
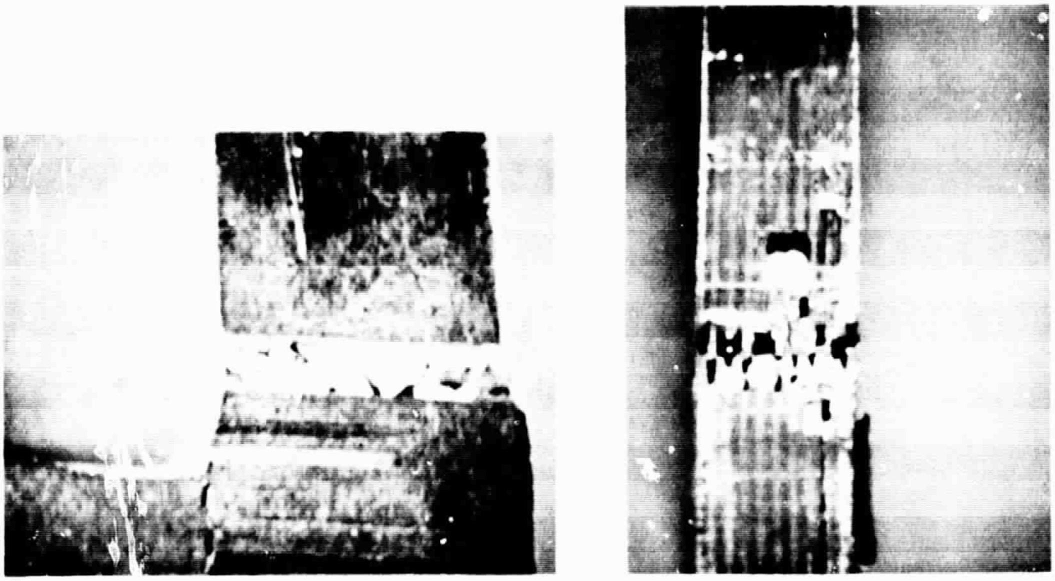


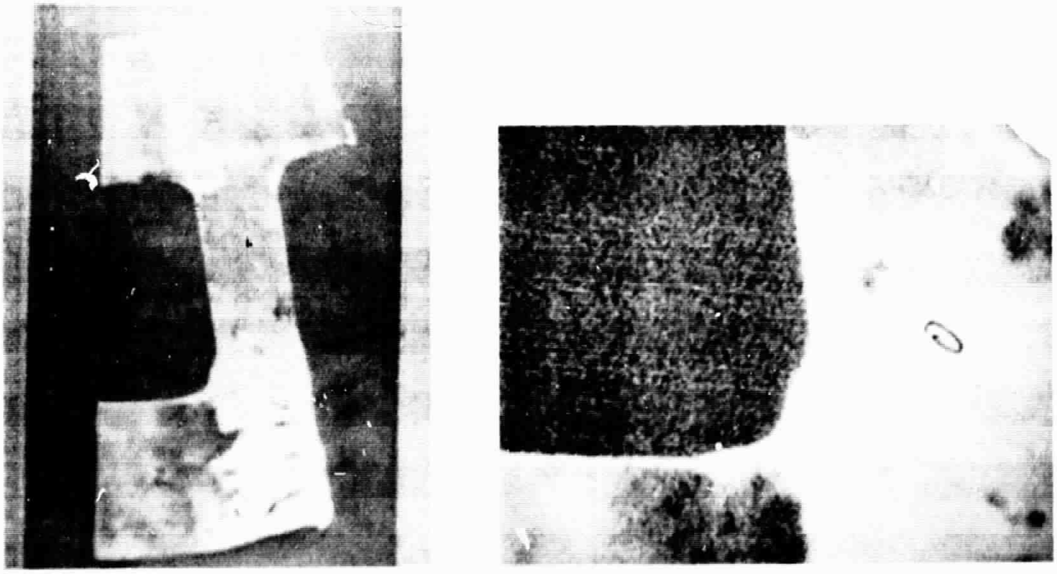
Figure 2. - Sketch of test object.



(a) TOP VIEW.

(b) END VIEW.

Figure 3. - Damaged area.

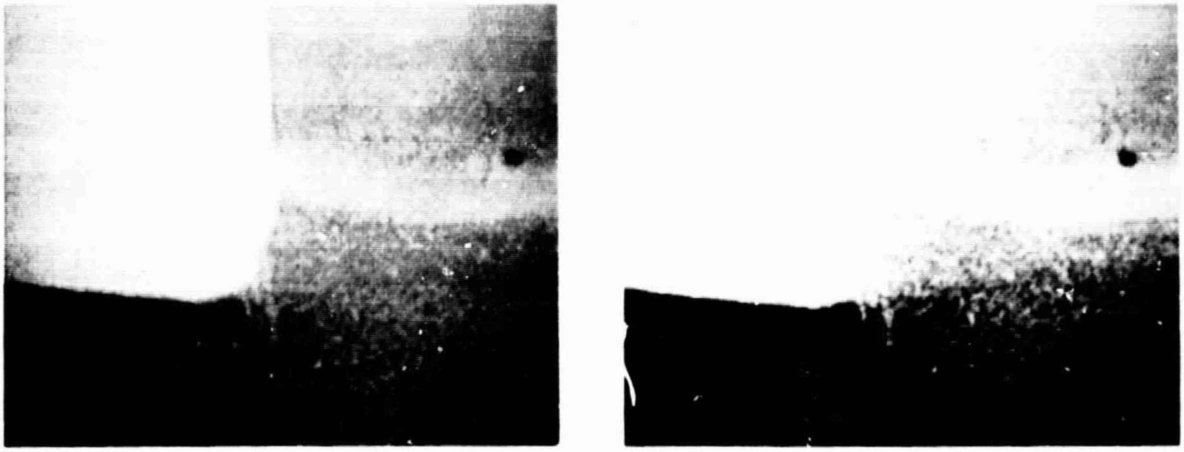


(a) ENTIRE OBJECT.

(b) DAMAGED AREA.

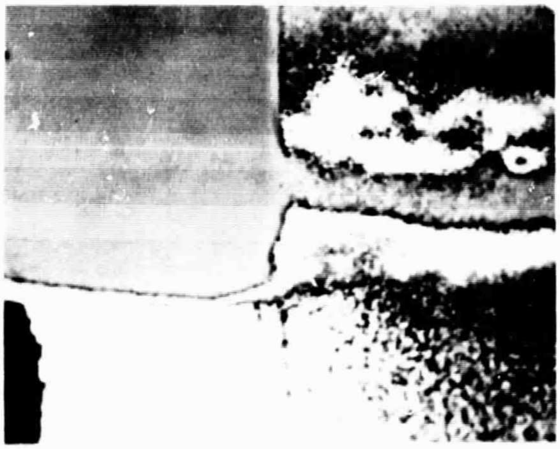
Figure 4. - Ultrasonic C-scan of test object.

Figure 5. - Radiograph of damaged area.



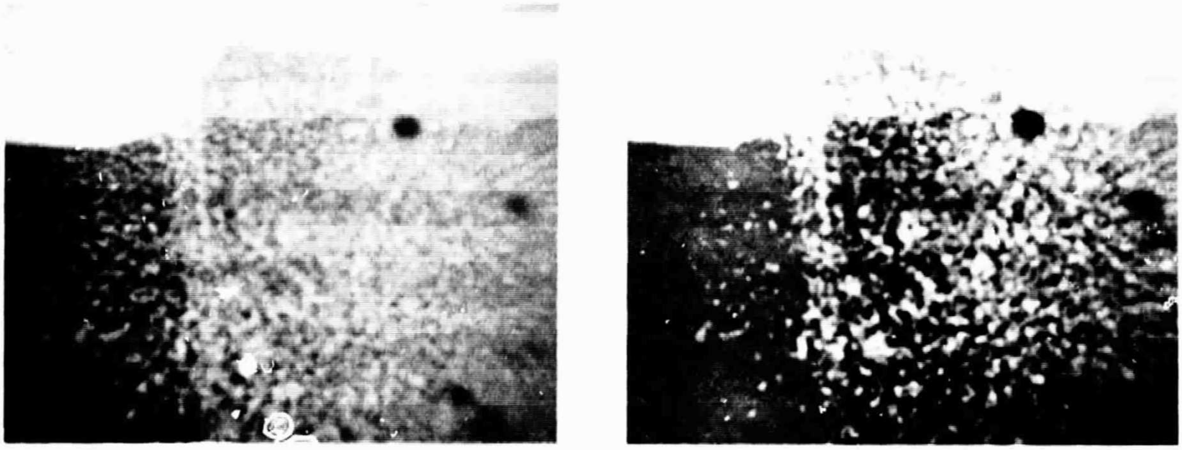
(a) UNENHANCED IMAGE.

(b) BRIGHTNESS EXPANDED IMAGE.



(c) HIGH-PASS FILTERED IMAGE.

Figure 6. - Electronic image of damaged area.



(a) UNENHANCED IMAGE.

(b) BRIGHTNESS EXPANDED IMAGE.

(c) HIGH-PASS FILTERED IMAGE.

Figure 7. - Electronic image of section of damaged area.

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