THE APPLICABILITY OF INFRARED THERMOGRAPHY IN THE DETECTION OF DELAMINATION IN BRIDGE DECKS

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ABSTRACT

The use of infrared thermography to very accurately define variations in surface temperatures was evaluated as a means of identifying delaminated areas caused by corrosion of reinforcing steel in concrete bridge decks. It was found that because of the vast differences in the volumetric heats of the solid concrete and the air in the cracks around a delaminated area, the separated concrete was warmer when exposed to solar heating than was the adjacent sound material. Differences in the temperatures of the deck surface, shown in various shades or colors on a cathode-ray tube, were photographed to provide a permanent graphic record of the location of the warmer, distressed areas.

In a comparative study of infrared thermography and conventional deck evaluation techniques, including the sounding of the surface with a hammer and chain drag and the use of a rolling delamination detector, all methods were found generally satisffactory in locating severe to medium delaminations. However, the infrared thermography procedure had an important advantage in disclosing incipient delaminations, those in which the cracking is confined to the close vicinity of the reinforcing steel. In every case the thermographic technique seemed to provide better detailed records of the delaminated areas, which were confirmed by coring of the concrete.

The rationale behind the use of thermography for detecting delaminations, a brief description of the technique, and a discussion of some experimental results are provided.

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INTRODUCTION

In the repair of bridge decks, locating the areas of delamination is a major problem.(1) Until the recent introduction of the delamination detector,(2) the only available means for detecting such areas was by sounding the surface with a hammer and chain drag. This method of detection is useful only in identifying relatively advanced stages of delamination, and its effectiveness relies upon the operator's subjective judgement of the sound produced by the hammer and chain drag. Interference from traffic noise can make use of the method difficult and the locations of delaminated areas must be carefully plotted in the field or marked on the deck for later reference. Consequently, the method is slow and, at times, ineffective.

The delamination detector is based essentially on the same "sounding" principle, but it utilizes a piezoelectric hydrophone to characterize vibration waves bouncing back from a delaminated area and thereby minimizes the subjective factor inherent in the method of sounding with a hammer and chain drag. The detected vibration waves are recorded to yield a profile graph that is used to outline the delaminated areas. Although it is an improvement over the hammer and chain drag, the vibratory detector is still far from being an ideal device in that it spots only delaminations more than 10 cm (4 in.) in area and has a narrow coverage per scan.

As indicated in the preceding discussion, current methods for detecting bridge deck delamination are not completely satisfactory and there is a need for a better method.

CONCEPT OF DELAMINATION DETECTION WITH INFRARED THERMOGRAPHY

In seeking to develop a new method of detecting delamination, the authors visualized a severely delaminated area of reinforced concrete such as that illustrated in Figure 1*, where the cracks are filled with entrapped air. Considering the three orders of magnitude difference between the volumetric heats of concrete and air, which are 30.0 and 0.019 Btu/(yd^3)(^{o}F), respectively,(3) a severely delaminated area of a concrete deck would have a volumetric heat lower than that of the surrounding solid concrete. Consequently, given the same amount of direct solar heating, the delaminated area would be warmer than the surrounding concrete; and, when the solar radiation disappears and the deck starts to cool, the delaminated area would be cooler than the surrounding concrete. It probably also follows that, under solar heating, the more delaminated a spot is, the warmer it is compared to the surrounding area. This temperature differential can be used as the basis of a new method of detecting delamination, if one has a means for rapidly mapping the temperature profile of a bridge deck. Fortunately, recent developments in infrared detector and solid state circuitry have provided such a means — the technique of infrared thermography — for instantaneously obtaining the thermal image of any object with an infrared scanner. A brief discussion of the principle of infrared thermography is given in the Appendix.

This report describes the results obtained in field testing the concept of detecting delaminations in bridge decks by infrared thermography.

STUDY METHODOLOGY

In the study, several deck areas, mostly 1.8 m x 3.6 m (6 ft. x 12 ft.) in size, were tested for delamination with an infrared scanner. For comparison, the same areas were evaluated by (1) sounding with hammer and chain drag, and (2) by use of a delamination detector. In addition, 10.2 cm (4 in.) cores were obtained from selected spots in the test areas for visual examinations.

Infrared Scanner System

The scanner system used is the Thermovision 750 model manufactured by the AGA Corporation of Secaucus, New Jersey. As shown in Figure 2, it consists of a camera unit, a display unit, a power supply, and a color monitor.

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*All figures follow Appendix.

The camera unit provides realtime electro-optical prism scanning, and is equipped with a liquid-nitrogen cooled InSb detector having a spectral response of 2 to 5 µ and a minimum detectable temperature difference of 0.2°C at 30°C object temperature. The display unit also serves as a control unit for the selection of various parameters, among them the proper temperature level, the desired temperature range, and the visual qualities of the thermal image (thermogram) displayed on its 5.0 cm x 4.5 cm (2.0 in. x 1.8 in.) cathode—ray tube in a continuous range of gray tones.

The infrared lens used was a f/1.8 silicon optics, with a 20° x 20° field of view. With the camera set at a comfortable working height of 150 cm (5.0 ft.) above a bridge deck, the deck area covered was slightly larger than 45 cm x 45 cm (1.5 ft. x 1.5 ft.). With this limited coverage, individual profiles of 45 cm square areas had to be made into mosaics to obtain composite thermograms of the 1.8 m x 3.6 m (6 ft. x 12 ft.) deck areas evaluated. For the mosaic to be feasible, the camera must be aimed at a right angle to the deck since any other angle would give rise to problems due to perspective. However, it is not possible to aim the camera straight down without spilling the liquid nitrogen in it. Therefore, the unconventional setup shown in Figure 3 had to be used. In this setup, the camera, which was mounted beside the display unit (Figure 4) on a rolling tripod, was aimed at a direction horizontal to the surface of the deck. Then a surface reflective mirror, about 10.2 cm x 11.4 cm (4.0 in. x 4.5 in.) in size, was mounted at 45° with its reflective surface directly facing the camera lens, which was 19.0 cm (7.5 in.) away. This setup allowed the focusing of the infrared camera indirectly downright at a deck area and thereby eleminated the perspective problem in constructing a mosaic of the thermal profile. The thermogram obtained in this manner is an inverted image, but this presents no problem.

In addition, it was found that solar radiation reflected from the deck surface interfered with the thermogram. Therefore, a filter was needed to eliminate the reflection. This filter transmits only radiation with wavelengths longer than 3.5 µm, and renders negligible the interference of reflected shorter wavelength radiation from the sun.

To enhance the interpretability of the thermogram, a color monitor (Figure 5) was used so that different temperatures are represented by various colors. Specifically, the selected temperature range ($T_2 - T_1$) is divided into 10 isotherm units presented in white, yellow, orange, red, pink, violet, aquamarine, green, light blue, and dark blue, corresponding to the decreasing order of temperature level. Type 108 color Polaroid film was used to record each individual thermogram.

Sounding by Hammer and Chain Drag

In the sounding method delamination is detected, based on the subjective judgment of the testing personnel, as a "hollow sound" produced by striking the deck with a hammer or dragging chains across it. The method is very dependent upon the ability of the person using it to discern the hollow sound and is made difficult to use by interference from traffic noises.

In this study, in addition to listening for the hollow sound produced by the hammer, the person doing the testing placed one hand on the deck to feel for vibrations. This practice is believed to enhance the reliability of the hammer sounding. The chain drag apparatus (Figure 6) made of five 75 cm (2.5 ft.) steel chains connected to a metal rod by ropes, was used to make a rapid initial survey. Then, the hammer was used to precisely define the delaminated areas.

Delamination Detector

A detailed description of the delaminator detector is given by its developers from the Texas Transportation Institute.(2) Briefly, the detector (Figure 7) consists of a set of solenoid-controlled, rigid, steel-rimmed wheels, 15 cm (6 in.) apart that tap the bridge deck surface. The tapping generates vibrations from delaminated areas with which the wheels come in contact. The vibrations are picked up by pressure-sensitive hydrophones, spaced 30.5 cm (12 in.) apart, that transform them into electrical signal. The signal is electronically processed to enhance the distinction between delaminated and solid concrete, and is recorded on a dual-channel chart recorder as a voltage varying in magnitude to provide a direct measure of the degree of delamination. Since the unit senses delamination only when a receiverand a tapping wheel are simultaneously over a delaminated area, it surveys two 7.6 cm (3 in) wide parallel paths 15.2 cm (6 in.) apart.

The delamination detector was rolled longitudinally over each of the test areas at intervals of 46 cm (1.5 ft.).

RESULTS AND DISCUSSION

Optimum Time for Using Infrared Thermography

Since the thermal profile of a deck is influenced by the strength of insolation it has received, which varies diurnally, it was necessary to determine the optiumum time of day to apply infrared thermography in the detection of delamination. For this purpose, the temperature fluctuation of a well-delaminated spot was monitored with a thermocouple for three consecutive days. A plot of the temperature, Figure 8, showed a plateau with a relatively high and stable temperature between 12:00 noon and 3:00 p.m., when the solar radiation being received by any surface is at its maximum. As expected the trend clearly corresponded to the rising and the setting of the sun; so the width of the plateau will depend upon the time of year. Similarly, the highest temperature would also depend on the time of the year.

When the difference in the temperatures of the delaminated spot and its surrounding solid concrete were measured, it was found, as expected, that the delaminated spot was warmer than the solid concrete, and the temperature differential stayed relatively stable from 11:00 a.m. to 4:00 p.m.(Figure 9). Then, as the sun started to decline, the delaminated spot cooled faster than did the solid concrete so that the former became temporarily cooler than the latter, as indicated by the depression in the curve. After this depression, a temperature equilibrium was reached in the deck. For maximum efficiency, i.e., for obtaining a good definition of severe and even incipient delaminations, the "depression" period is probably the best time to use infrared thermography, because the temperature differentials then are generally higher than at any other time. However, during this period the temperature profile of the deck would change fairly fast due to rapid cooling (see Figure 8) so that unless the profile of a whole deck could be recorded rapidly, it could be extremely difficult to interpret the profile and define the delaminated areas.

Clearly, there is a need to achieve a good compromise between the detectability of delaminations and the stability of the profiles of the distressed areas. With only the particular photographic systems available and the limited area that could be covered per scan, consideration of the stability factor was especially critical. Therefore, the authors opted to evaluate the test areas with infrared thermography during the period from 12:00 noon to 2:00 p.m. Note that this period corresponds to the plateau in the temperature fluctuation curve shown in Figure 8.

Typical Thermogram and Its Interpretation

In obtaining the thermogram of an area, it was necessary to adjust the temperature level setting of the infrared scanner so that a severely delaminated spot would show up as the "warmest," or white, in the color monitor. This procedure allowed an interpolation between the warmest and coldest colors so that a mediumly delaminated spot might appear one or two isotherm units below white, i.e., as yellow or orange, and an incipient delamination would appear either two or three isotherm units below white, i.e., as orange or red. The remaining cooler colors of pink, violet, aquamarine, green, etc., would represent the solid concrete. It must be emphasized that the classification of different stages of delamination is relative.

One of the typical thermograms taken in the above described manner is shown in Figure 10. This mosaic thermogram covering a 180 cm x 360 cm (6 ft. x 12 ft.) deck area was made from individual thermograms of 45 cm (1.5 ft.) squares. In terms of pattern, the thermograms are exact duplications of the original photographs of color thermograms. However, because of the high expense of color reproductions, the warmer colors of white, yellow, orange, and red, in order of decreasing temperature, are replaced with shades of correspondingly decreasing intensity, while the relatively cooler colors are left unshaded because of their relative inconsequentiality.

Figure 10 shows that there were few delaminations in the medium stages; namely, the narrow band of intense shade around a spalled area that has been patched with asphaltic concrete (dark area), which overlaps squares 2-8 and 3-8, and the similarly shaded spots in squares 2-6 and 3-5. (The bands of relatively medium to incipient delamination around the patched area indicate that repairing a spalled area by patching probably does slightly more than improve the rideability of the surface.) In addition, the thermogram shows semi-regular patterns, the lightly shaded areas that run approximately 50° with respect to the X-axis of the thermogram. Since this angle is similar to the skew angle of the reinforcing steel and to the direction the two medium delaminations in squares 2-6 and 3-5 run with respect to each other, these lightly shaded areas are most likely incipient delaminations occurring around some of the reinforcing steel. Support for this conclusion is presented in a latter section.

In order to preclude misinterpretations, infrared thermography must be supplemented with visual examinations. This necessity is evident in the following examples: the dark spots in square 2-1 were spots of asphalt on the deck surface, and the narrow, vertical band of mediumly shaded spots in square 4-1 were tire marks left by a vehicle braking to an emergency stop. The spots of asphalt and the tire marks appeared warmer than the concrete because they have a relatively higher infrared emissivity. Incidently, the irregular circles at the corners of each square in the thermogram are spray-paint markers, which apparently make the spots cooler than the rest of the concrete.

Comparison of Techniques

As mentioned earlier, the test areas were also evaluated with the conventional methods of sounding and with the delamination detector for comparison with infrared thermography. Figures11-17 show the delamination located by the different techniques in some test areas.

Severe and Medium Delaminations

In the comparative evaluations, approximately 95% of the delaminations in the medium and severe stages that were located by infrared thermography were also located by sounding, and approximately 85% were also located by the delamination detector. Figures 18 and 19 show a core taken from a typical severely delaminated spot (square 2-7 in Figure 14) that was located by all the techniques compared. Notice that the core broke at about the depth at which the delamination occurred. Figure 19 shows the corresponding hole left in the deck, where the wide vertical separation between two layers of concrete can be seen. Other cores taken from similar spots have also confirmed the indications from the techniques used.

One obvious inadequacy of sounding and the delamination detector is their inability to provide detail, which made it difficult to define the extent of the delamination accurately. Consider square 2-6 in Figure 12. According to thermography, the upper medium delamination extended close to square 1-6 and was at least 15 cm (6 in.) across. The lower one, located in the middle of the square, was approximately of the same size. These delaminations were detected by sounding as indicated by their inclosure in the area bounded by the dashed line. However, the delamination detector did not detect these completely, as indicated by the presence of the detector signal only on the right side of the square. A core taken from the left side of the square, Figure 20, revealed the medium delamination indicated by the thermogram. It is interesting to note that one end of the reinforcing steel was corroded while the other was unaffected. An examination of the cores indicated that the corrosion actually extended through three-fourths of the steel, and that the separation between the layers of concrete (Figure 21) was not as wide as that previously shown for a severely delaminated concrete (Figure 19). The inadequacy of the delamination detector is also shown in Figure 14, where a medium delamination extending from the upper left corner of square 3-3 down almost to the middle left of square 3-4 and confirmed by coring was not completely detected.

A similar problem occurs with sounding, as shown in Figure 17, where severe delaminations that extended across the top of squares 1-1 and 2-1 were dislocated by sounding. In addition, the medium delamination extending from square 2-2 down to square 2-4 was not located by either sounding or the delamination detector.

Incipient Delamination

In the preceding discussion, it was shown that infrared thermography has an advantage over the other techniques in providing detailed pictures of the extent of severe and medium delaminations. As described below, a more important advantage of thermography is its ability to locate incipient delaminations.

A core taken from an incipiently delaminated spot in square 3-8 of Figure 11 is shown in Figure 22. Notice that the delamination was in its early stage and that the crack had not yet completely extended across the core to separate the concrete into at least two layers, as was the case for the cores from severe and medium delaminations (Figures 18 and 20). A core taken from square 3-3 showed a similar type of delamination. Cores from other incipiently delaminated spots in other test areas have provided similar confirmation of the ability of thermography to detect such spots.

A core taken from square 2-4 of Figure 16, which provides perhaps the best illustration of the very beginning of delamination, is shown in Figure 23. The figure shows that the reinforcing steel had corroded and that a crack had started to propagate from the left end of the steel. An examination of the hole (Figure 24) left on the deck showed that slightly better than tiny cracks had actually started from both ends of the corroded steel.

It must be pointed out, however, that occasional inconsistencies were observed in the correlation between warmness (expressed in terms of colors in the original thermogram, and by shades in this report) and the severity of delaminations. Examples are provided by cores from squares 2-7 and 3-8 in Figure 13 and shown respectively in Figures 25 and 26. The cores showed that the spots from which they were taken were of slightly more advanced delamination than the incipient delamination indicated by the thermogram. It is interesting to note, though, that these spots were not located by the delamination detector but were by sounding. A similar example is provided in Figure 27, which shows a core taken from a supposedly incipiently delaminated spot in square 1-3 from the thermogram in Figure 15. Again, notice that this delamination was located by neither of the conventional techniques.

It is uncertain whether the observed inconsistency is real or was caused by the observed slight changes of colors in the thermograms when these were being taken. Such changes had been encountered on days with scattered clouds that interfered with incoming solar radiation. If the inconsistency results from this cause, it can be minimized or probably eliminated by a setup incorporating videotape for rapid recording of the thermogram. With such a setup a deck could be surveyed so rapidly that its thermal profile would not be affected by clouds.

SUMMARY OF FINDINGS

1. When exposed to solar heating, a delaminated spot generally becomes warmer than the surrounding solid concrete; however, after the sun has set, the delaminated spot will initially cool faster, thereby becoming colder than the surrounding solid concrete.

2. This temperature differential between delaminated and solid concrete can be utilized to survey concrete bridge deck delamination by infrared thermography.

3. The daytime interval between 11:00 a.m. and 2:00 p.m. is probably the optimum period for conducting surveys of bridge deck delamination with infrared thermography, since that period provides the best compromise between the difference in the temperatures of delaminated and solid concrete and the stability of the deck's temperature profile.

4. The conventional techniques of sounding and using the delamination detector were generally satisfactory in locating severe to medium delamination, although the extent of the delaminated areas was better defined by infrared thermography.

5. An especially important advantage of infrared thermography is its ability to locate and define incipient delaminations, those in which the cracking occurs only close to the steel and completely within the concrete.

6. The direct correlation between the relative warmness of a delaminated area and the severity of its delamination varied to some extent. Specifically, some spots indicated to be incipiently delaminated from thermograms were actually slightly more severely affected.

7. It is uncertain whether such inconsistency is real or whether it is caused by the slight changes of colors in the thermograms occasionally observed when thermograms were being photographically recorded.

8. Infrared thermography should be supplemented by visual examination of the bridge deck to avoid misinterpreting such surface irregularities as asphalt spots and heavy tire marks as being delaminations, since such irregularities tend to appear warmer in a thermogram due to their relatively higher emissivities.

RECOMMENDATIONS

The applicability of infrared thermography in the detection of delaminations has been demonstrated in the present study. Since the technique has the potential of a good all-around technique for such use, the authors make the following recommendations.

1. Explore the use of faster systems (such as videotape or other continuous recording devices) for recording thermograms, infrared lenses with wider fields of view, and different camera setups so that a bridge deck can be surveyed faster than was feasible with the equipment used in the present study. A desirable goal is to be able to cover at least the width of a traffic lane at a single scan; maybe with the camera mounted high in front of a vehicle, a thermogram of the whole length of a bridge, by a lane width, can be obtained rapidly. With such a setup, the occasional problem of color inconsistency observed in the present study would be considerably minimized, if not completely eliminated. Furthermore, the technique would thereby be rendered faster and more practical for use in actual bridge deck surveys.

2. Use the setup resulting from implementation of the first recommendation to study numerous bridges, including those with asphalt covered decks, which have not yet been studied. In addition, to determine its applicability for use on asphalt covered decks, it is hoped such experimentation would uncover any anomalies in infrared thermography that may not have been discovered in the present study and develop ways to smooth the potential transition of this technique from experimental to operational phase use.

3. Make a comparative study of the effectiveness of infrared thermography in locating and defining delamination when used at different times of the day and in different seasons of the year.

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APPENDIX

PRINCIPLE OF INFRARED THERMOGRAPHY

Any object, be it a black body or otherwise, whose temperature is above absolute zero (-273°C or 0°K) emits IR radiation generated by the vibration and rotation of its atoms and molecules. The IR radiations of most objects occur over a band of wavelengths from about 2 to 15 microns (μ). According to the Stefan-Boltzman law(4), the total intensity of the emitted radiation is given by

$$W = \sigma \varepsilon T^4$$

where,

W = the total radiant emittance, measured in watts/cm^2, of the radiating surface;

ε = the emissivity factor of the object, which is ≤ 1;

T = the absolute temperature of the object, °K; and

σ = the Stefan-Boltzman constant, which is 5.673×10^{-12} watt/cm^2 - °K^4.

This equation, which implies that the temperature of any object can be indirectly determined by measuring the intensity of its emitted IR radiation, serves as the basis of all infrared thermometers and image scanners.

In IR thermography, an IR camera (or scanner) that incorporates a sensitive and fast response IR detector is used to automatically scan an object and produce a thermal image of it on a cathode-ray tube. The two types of detectors most commonly used are the Indium-Antimonide (InSb) photovoltaic detector and the Mercury-Cadmium-Telluride (HgCdTe) photoconductive detector, both of which can detect a fraction of a degree temperature difference at 300°K. Indium-Antimonide has a spectral response of 2 to 5.6 μ, while Mercury-Cadmium-Telluride responds over a range of from 8 to 14 μ. These spectral ranges are different from that detectable by IR photographic film, which is 0.7-0.9 μ. Since this narrow band is lower than the range of wavelengths emitted by most objects, use of the film has not proven successful in disclosing deck delaminations.(5)

The thermal image obtained with the scanner represents the surface temperature profile of the object under examination. In a black and white picture, which looks something like an ordinary photographic negative, the warm areas are light and the cold areas are dark. In some thermal imaging systems, the picture comes out in brilliant colors, with the various tones representing different temperatures.

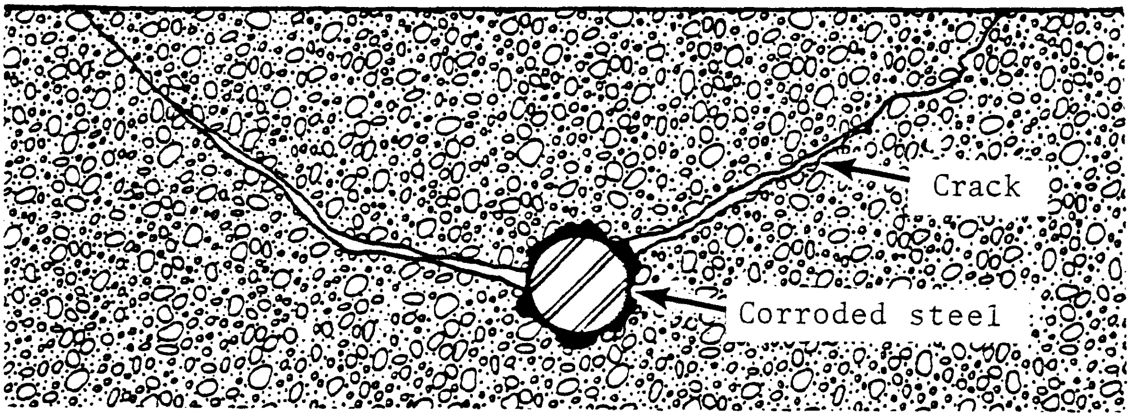

Figure 1. A simplified view of a concrete delamination.

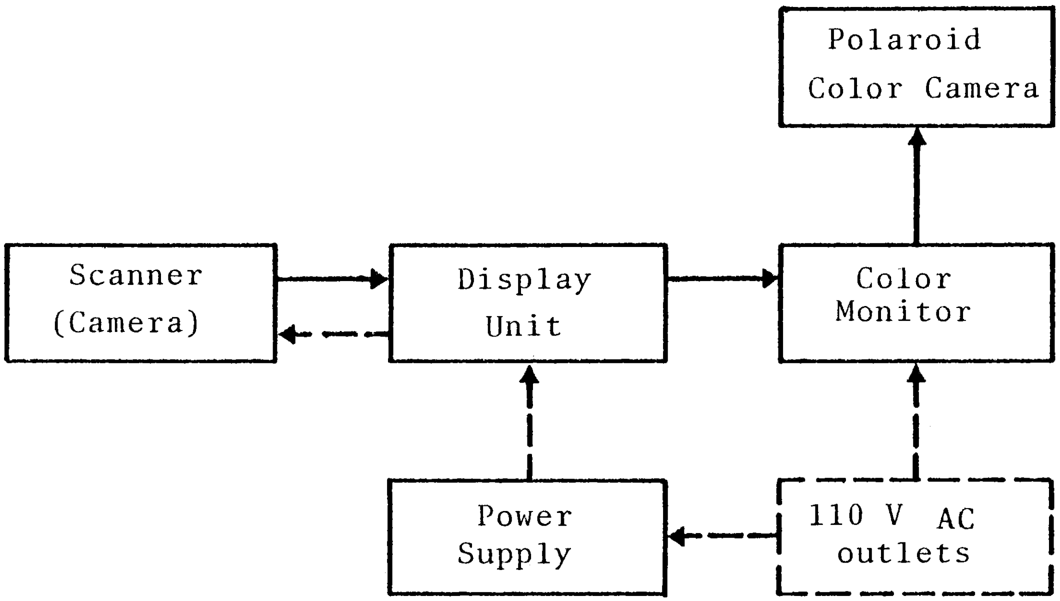

Figure 2. A diagram of the infrared scanner system used.

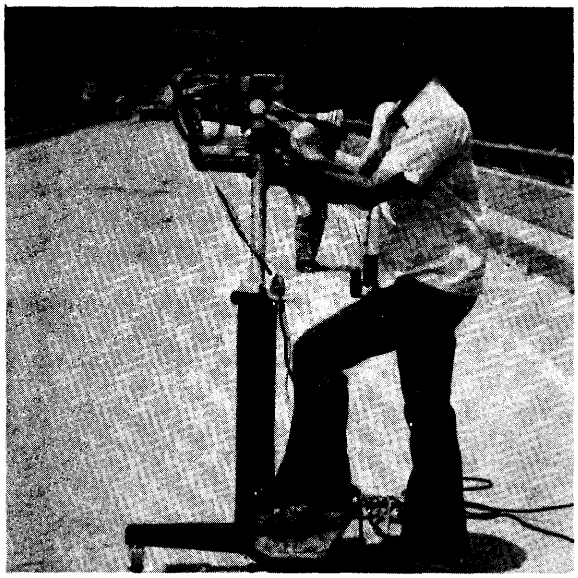

Figure 3. The infrared camera and mirror mounted beside the display unit on a rolling tripod.

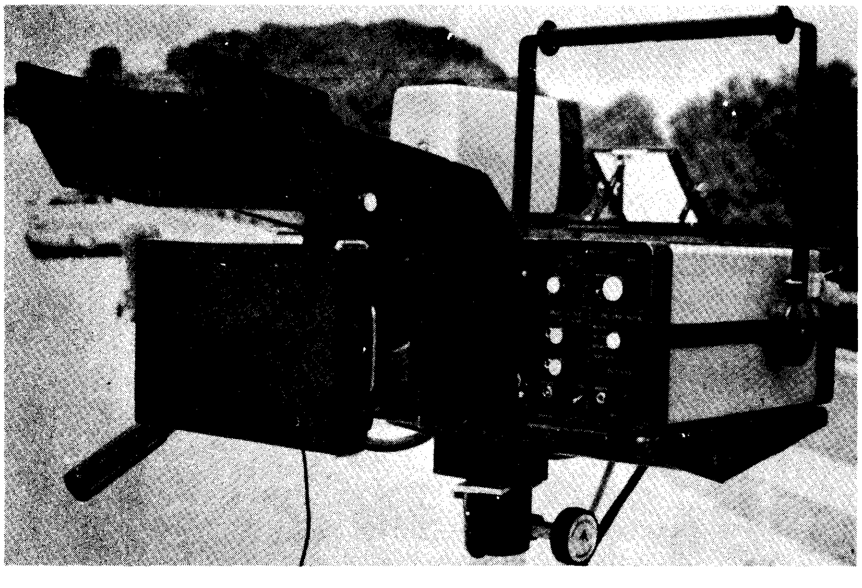

Figure 4. Close-up of the display unit with adapter for Polaroid black and white camera.

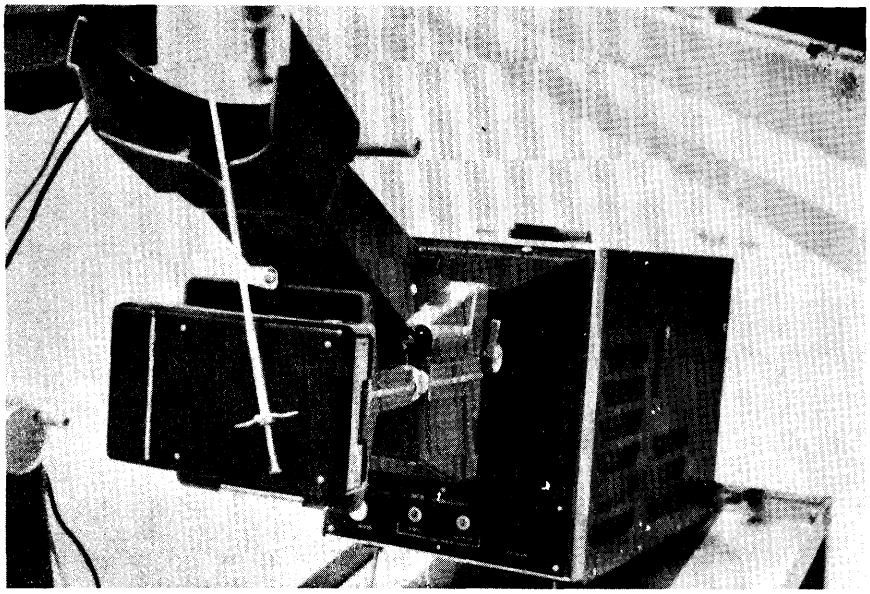

Figure 5. Close-up of the color monitor with adapter for Polaroid color camera.

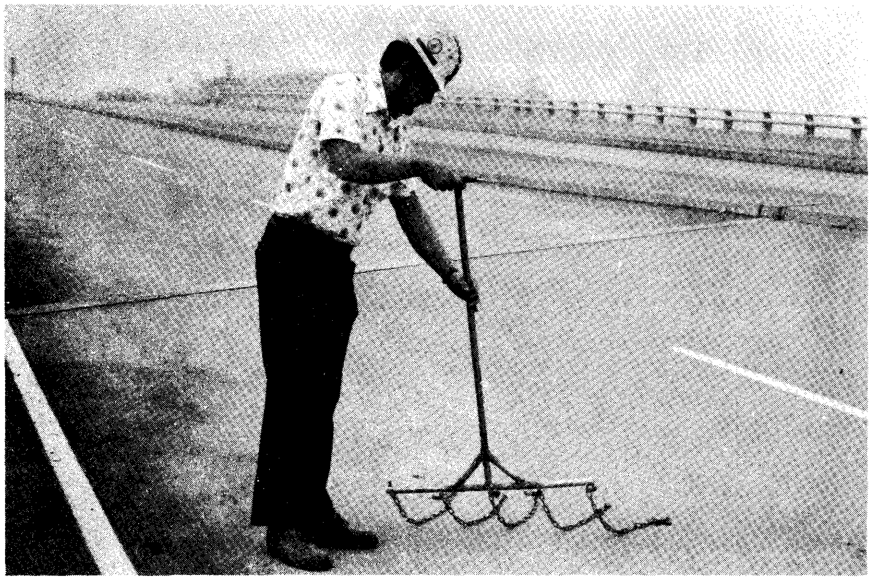

Figure 6. Sounding with chain drag.

Figure 7. Delamination detector in operation.

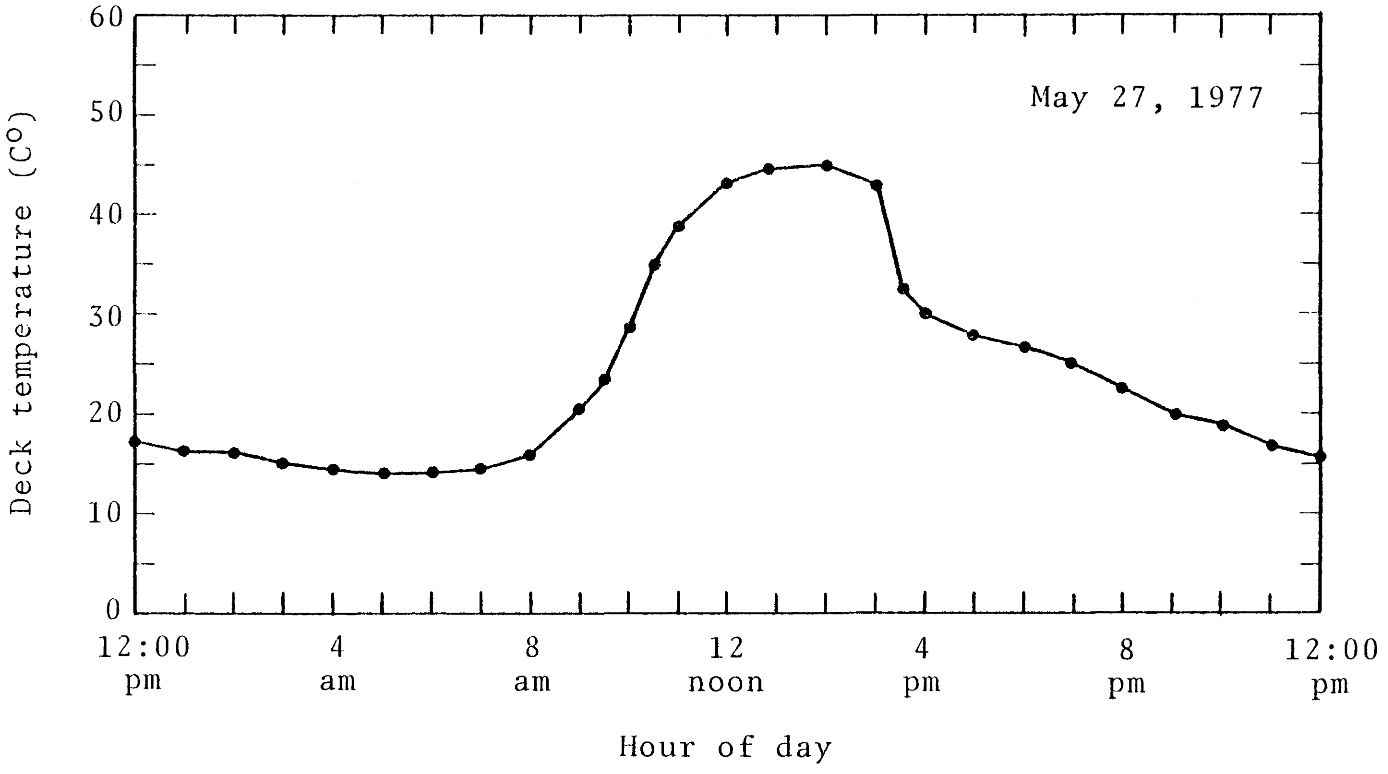

Figure 8. Diurnal variation in temperature of bridge deck surface.

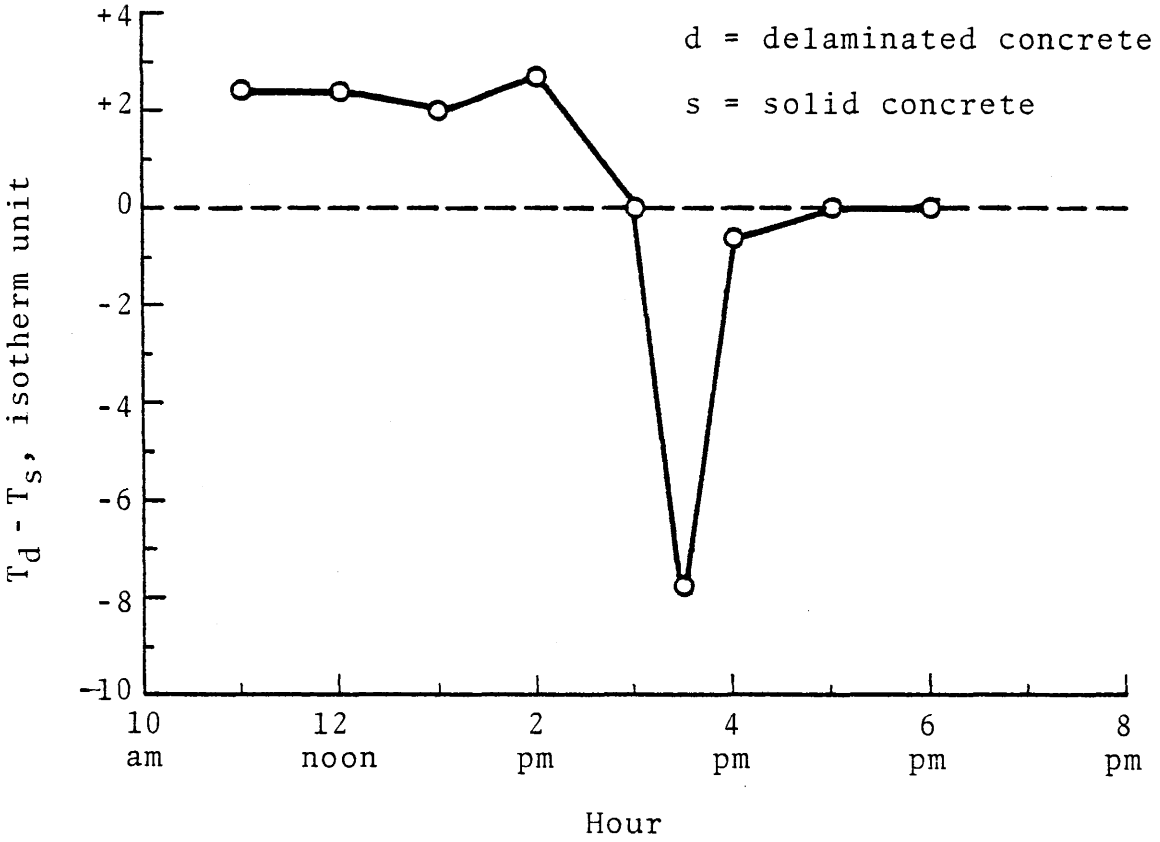

Figure 9. Temperature difference between a delaminated and a solid concrete. (Note the difference is expressed in isotherm units.)

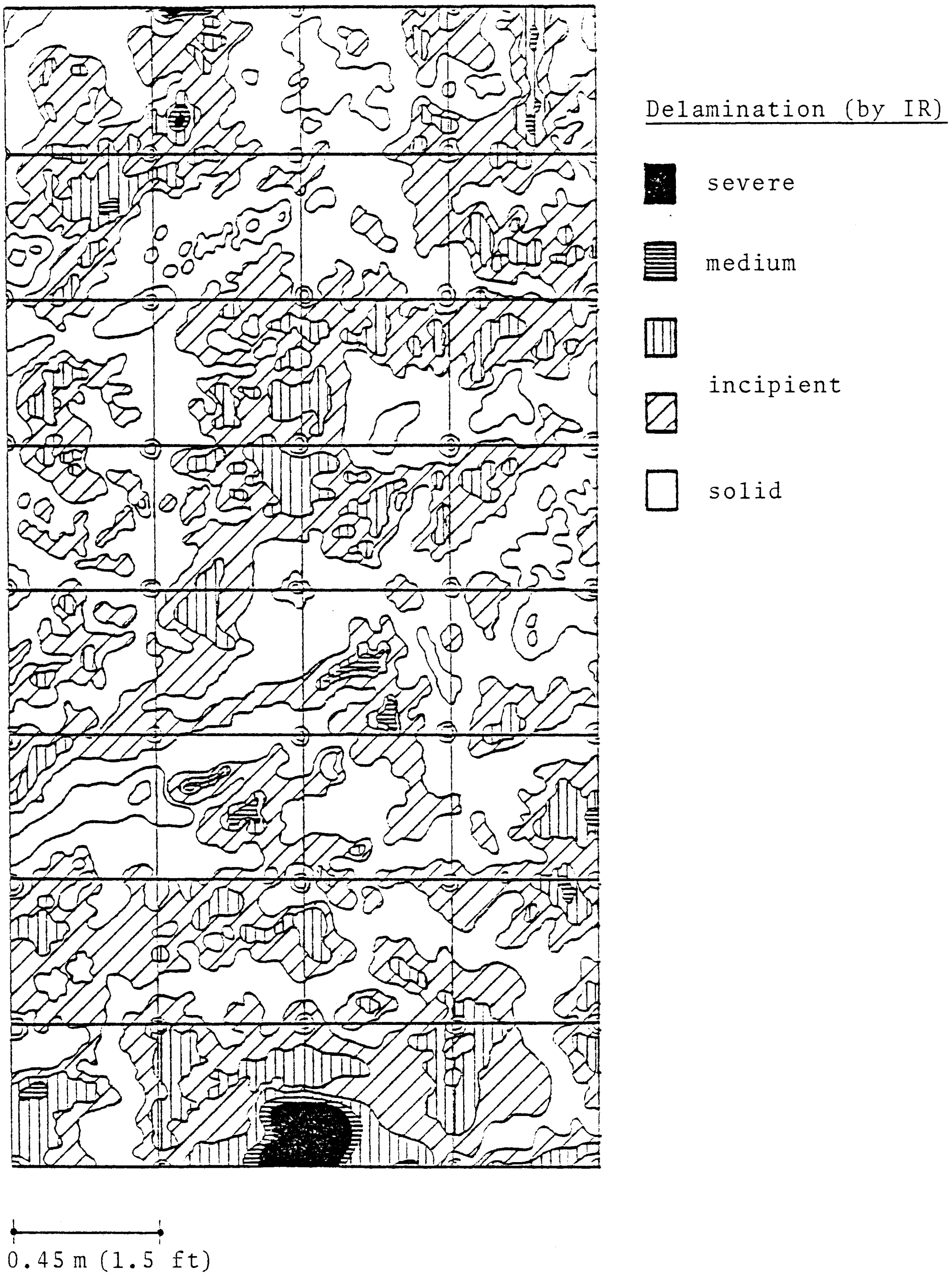

Figure 10. Typical thermogram.

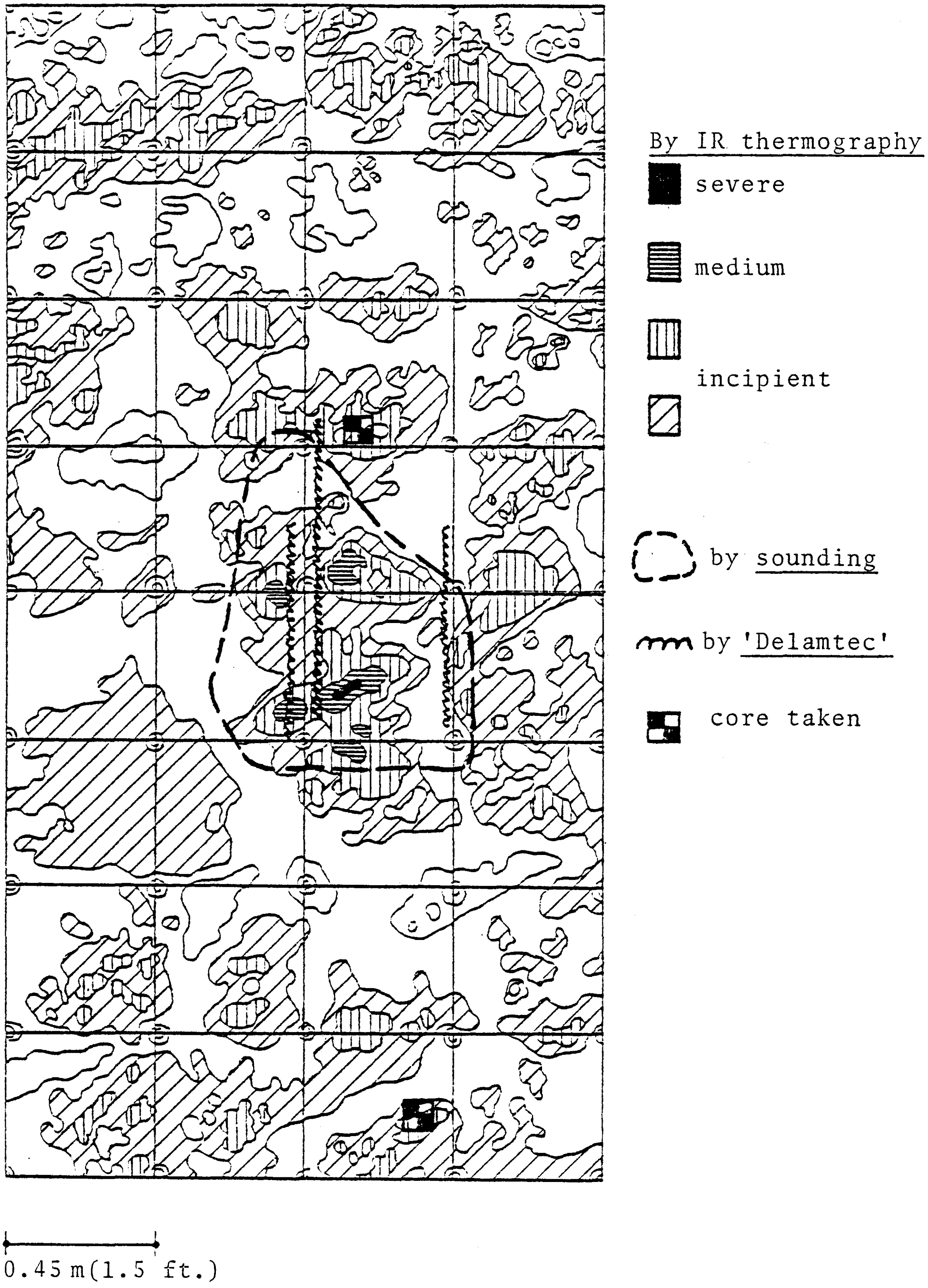

Figure 11. Delamination in test area 4 located by different techniques.

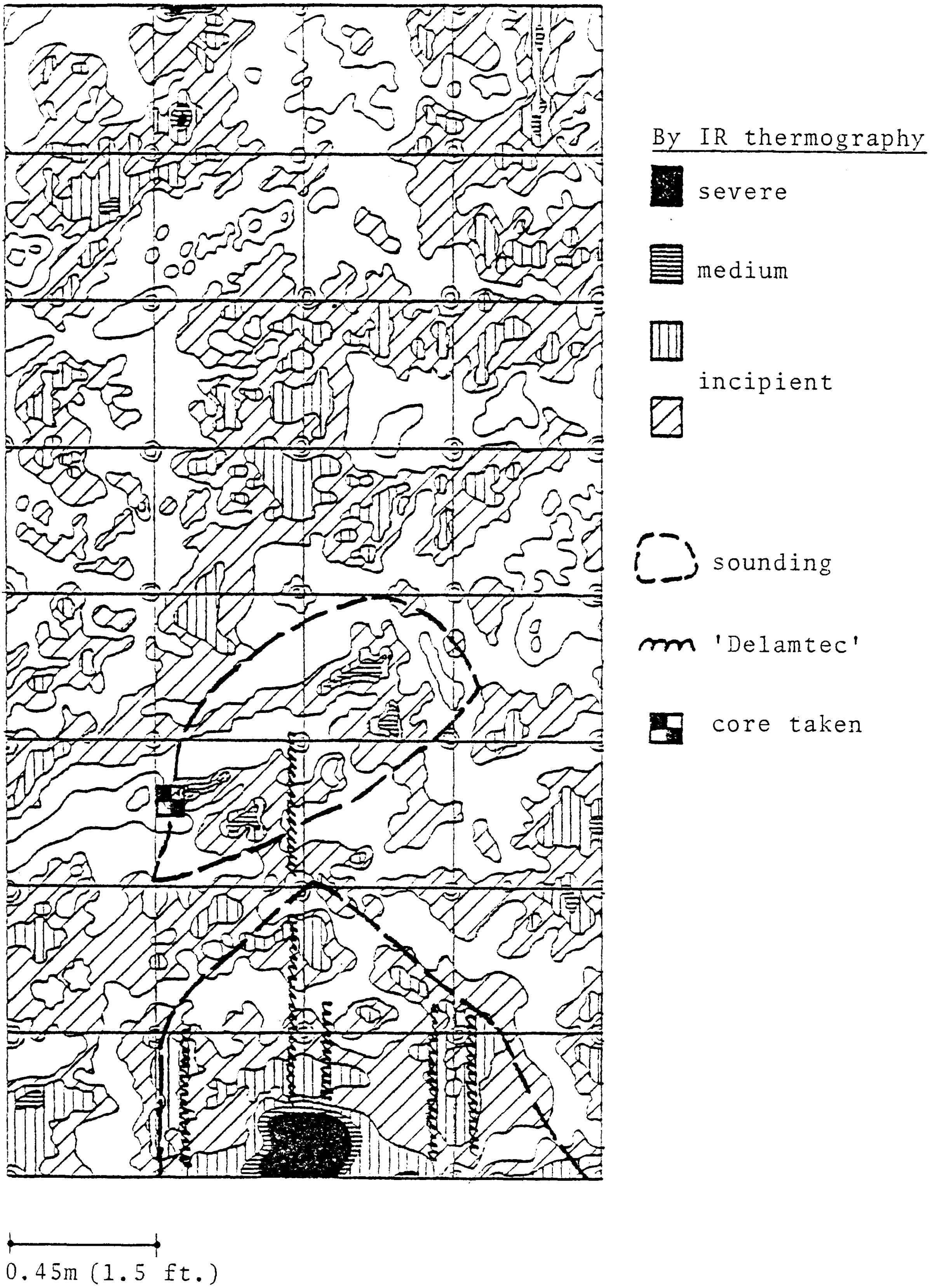

Figure 12. Delamination in test area 5 located by different techniques.

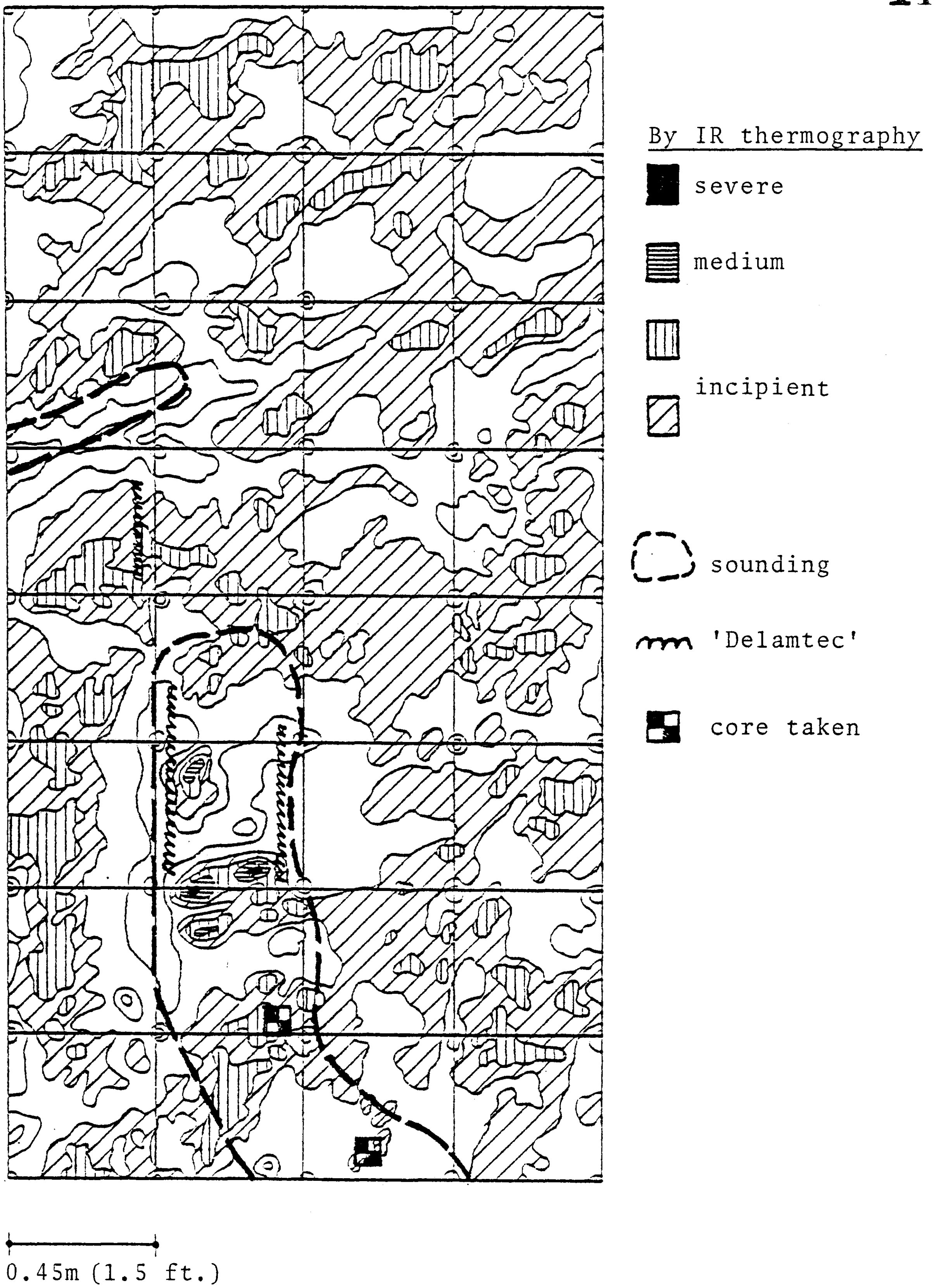

Figure 13. Delamination in test area 6 located by different techniques.

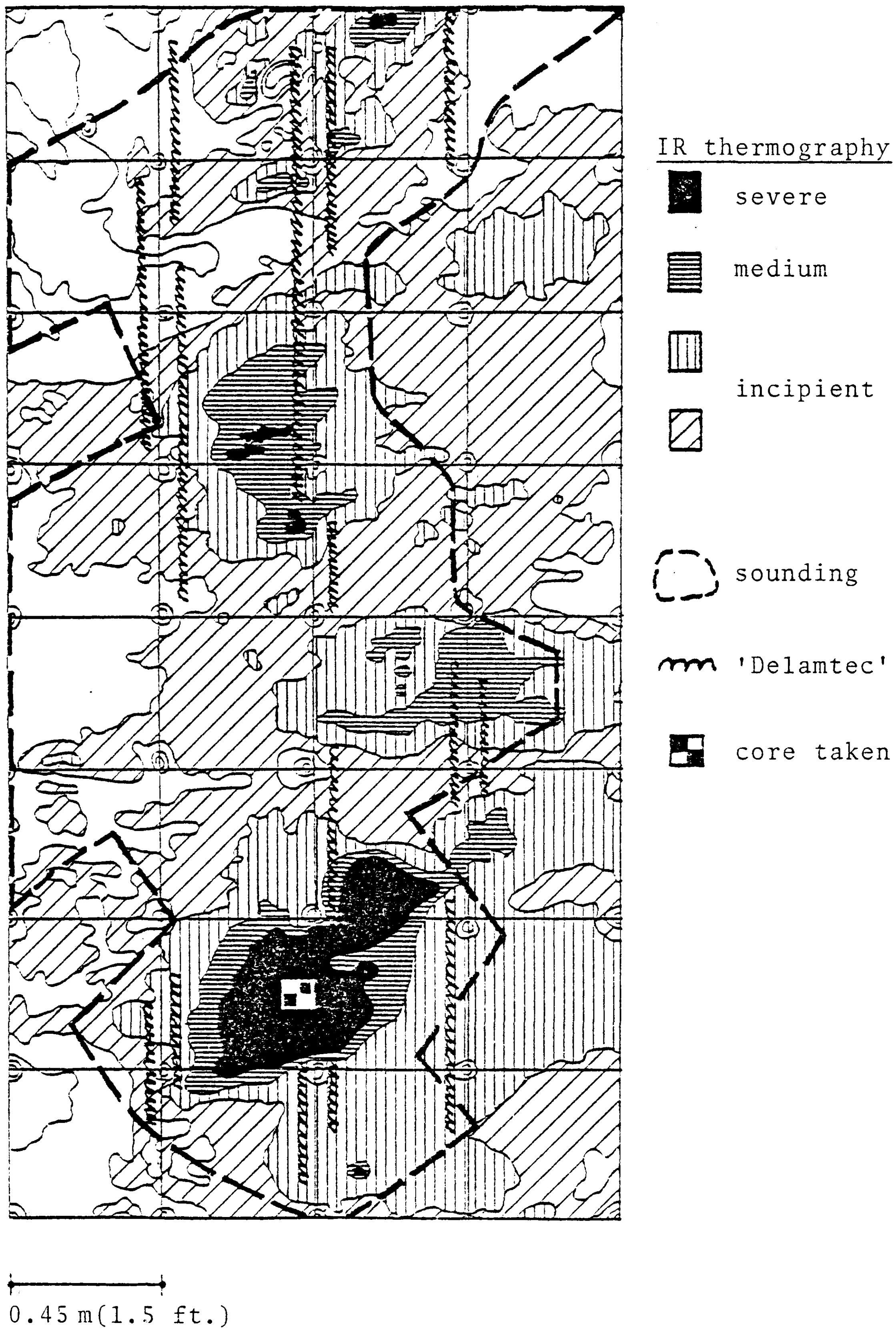

Figure 14. Delamination in test area 1 located by different techniques.

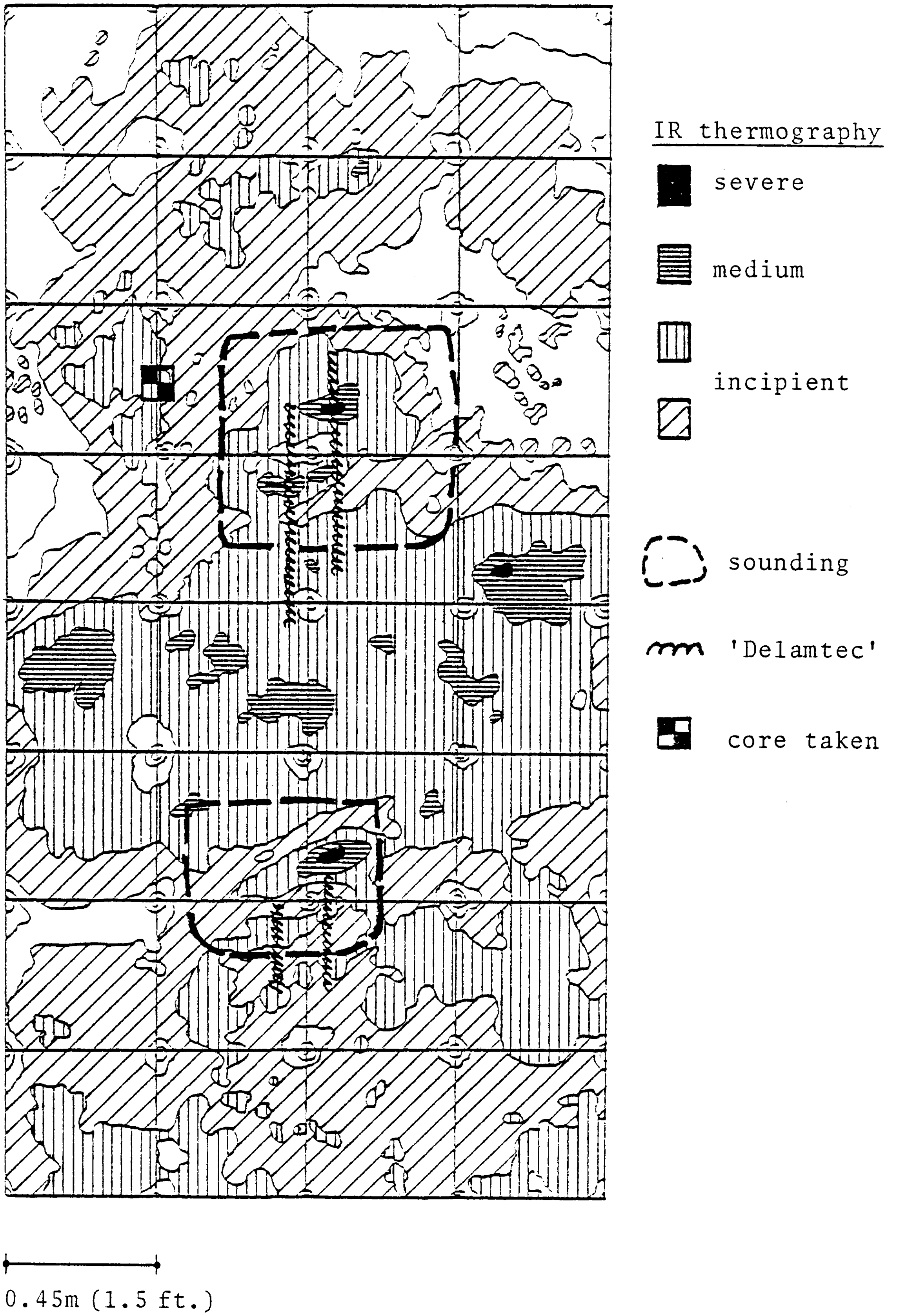

Figure 15. Delamination in test area 2 located by different techniques.

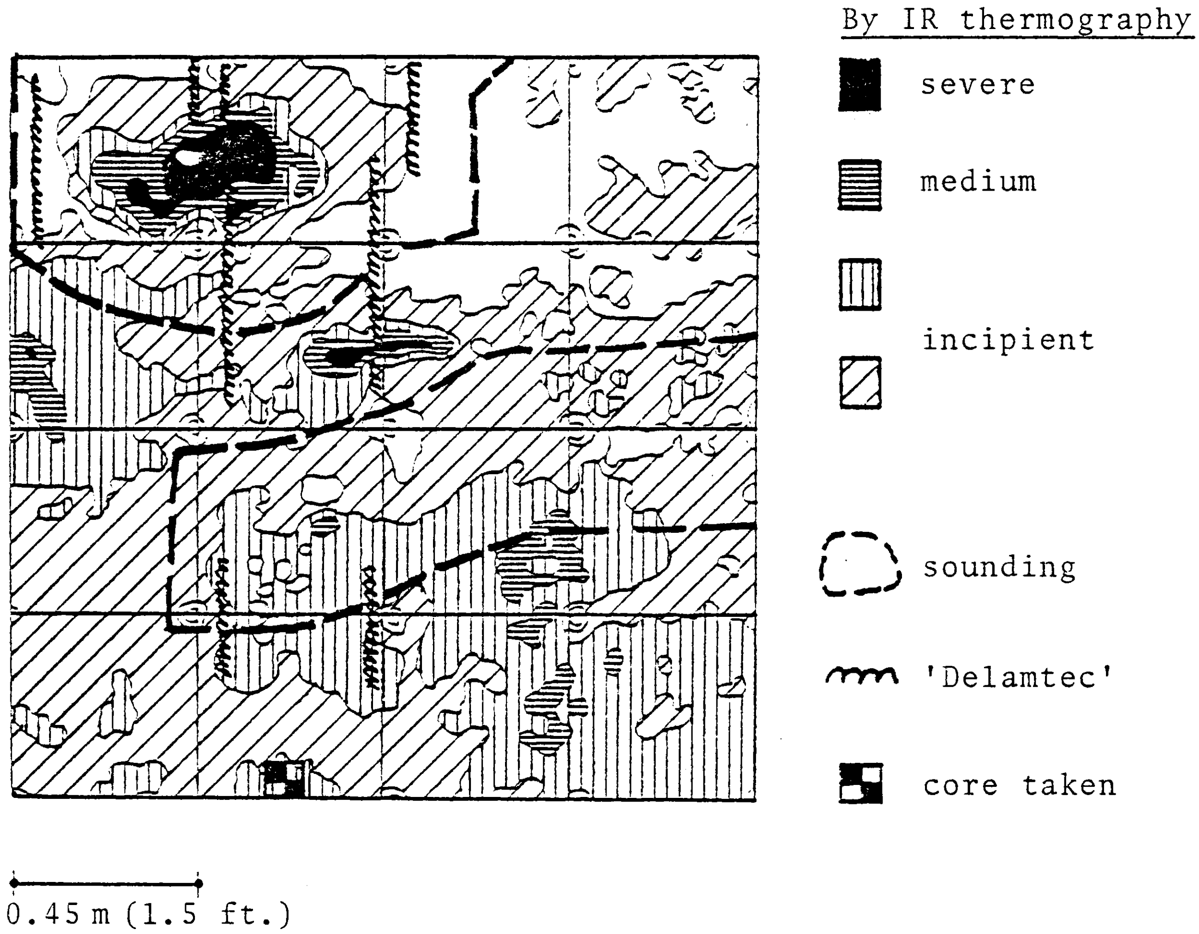

Figure 16. Delamination in test area 3 located by different techniques.

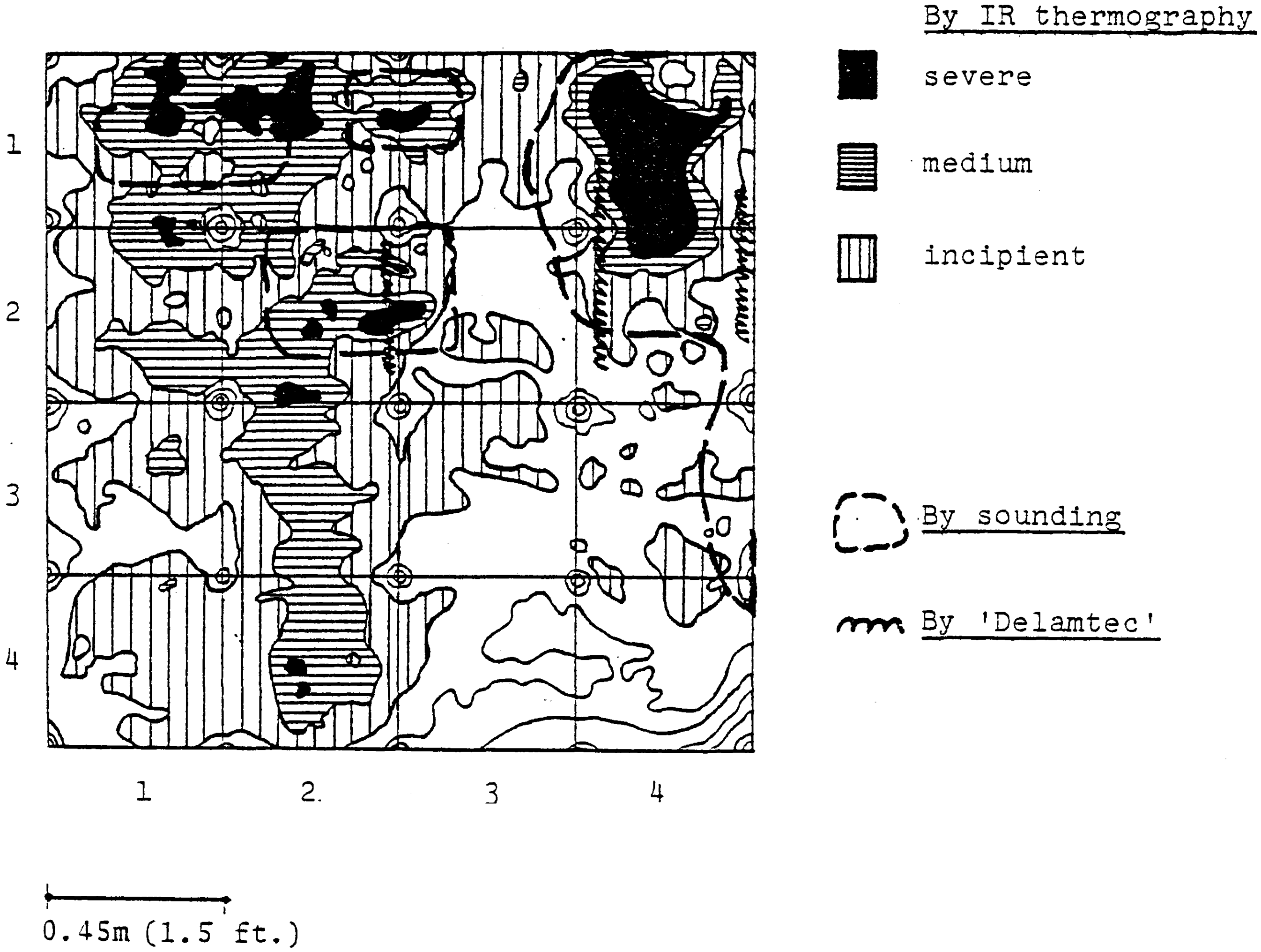

Figure 17. Delamination in test area 7 located by different techniques.

Figure 18. Side view of a core from a severely delaminated spot in square 2-7 of Figure 14.

Figure 19. Cross section view of the delaminated spot showing extremely wide separation of concrete layers.

Figure 20. Core taken from a mediumly delaminated spot in square 2-6 of Figure 12. shows no corrosion at one end of the steel

Figure 21. A cross-section view of the delaminated spot. Notice that the separation between concrete layers is narrower than that shown in Figure 19.

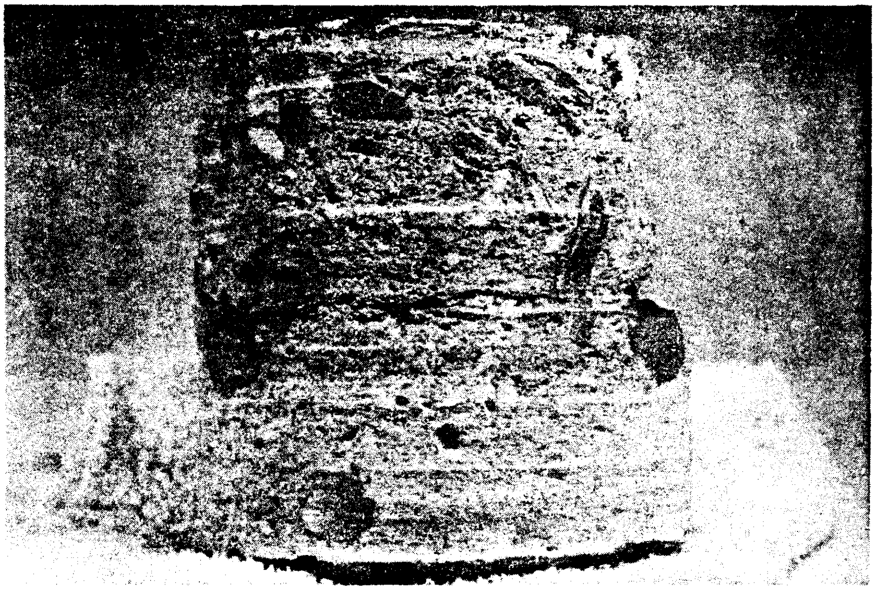

Figure 22. Core from incipiently delaminated spot in square of Figure 11 showing crack extending almost around its circumference.

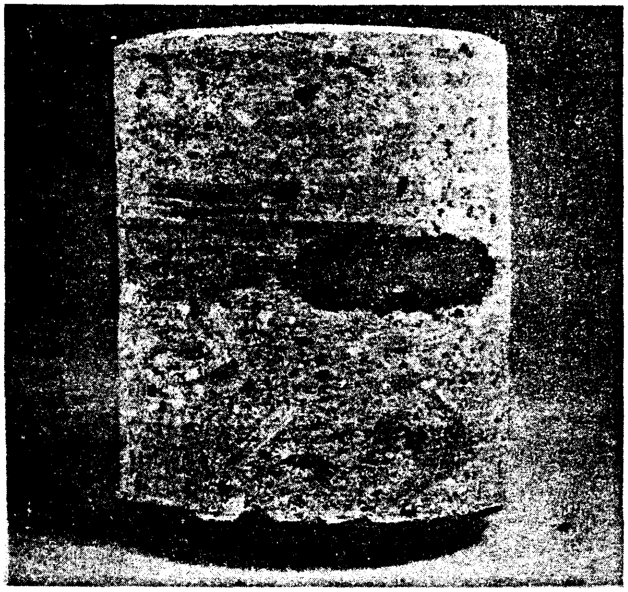

Figure 23. Core taken from square 2-4 of Figure 16 illustrating the very beginning of a delamination. Tiny crack started to propagate from the left end of the rusted steel.

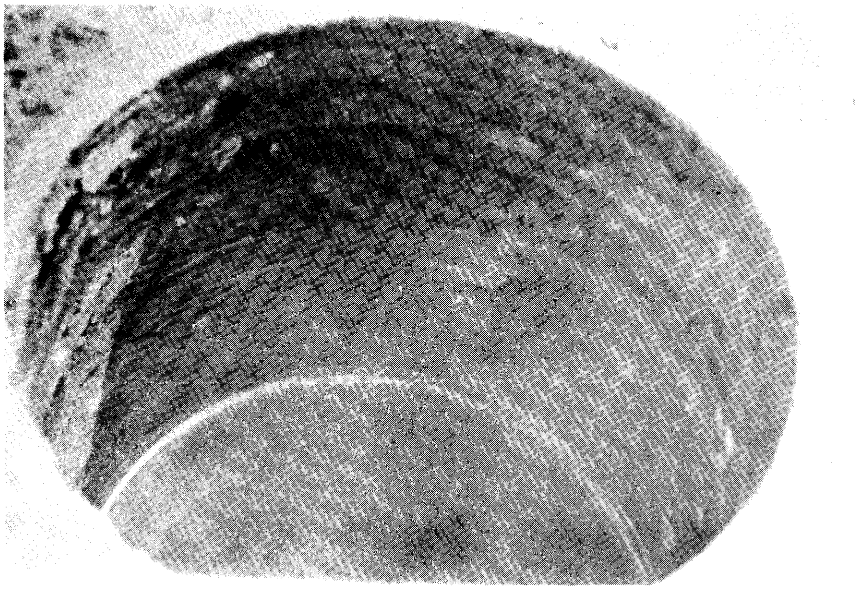

Figure 24. Cross section view of the spot showing tiny cracks originating from the rusted steel.

Figure 25. A core from a delaminated spot in square 2-7 in Figure 13.

Figure 26. A core from a delaminated spot in square 3-8 in Figure 13.

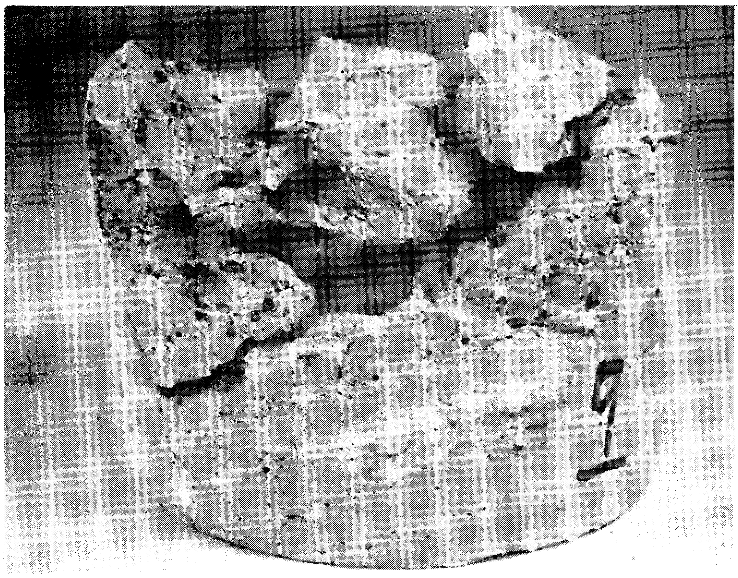

Figure 27. A core from a delaminated spot in square 1-3 in Figure 15.