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Imaging Radar for Bridge Deck Inspection

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ABSTRACT

Lawrence Livermore National Laboratory (LLNL) is developing a prototype imaging radar for inspecting steel reinforced concrete bridge decks. The system is designed to acquire Synthetic Aperture Radar (SAR) data and provide high-resolution images of internal structure, flaws, and defects enabling bridge inspectors to nondestructively evaluate and characterize bridge deck condition. Concrete delamination resulting from corrosion of steel reinforcing bars (rebars) is an important structural defect that the system is designed to detect. The prototype system uses arrays of compact, low-cost Micropower Impulse Radar (MIR) modules, supported by appropriate data acquisition and storage subsystems, to generate and collect the radar data, and unique imaging codes to reconstruct images of bridge deck internals. In this paper, we provide an overview of the prototype system concept, discuss its expected performance, and present recent experimental results showing the capability of this approach to detect thin delamination simulations embedded in concrete.

1. PROTOTYPE IMAGING RADAR CONCEPT

Nondestructive evaluation (NDE) techniques are playing an increasingly important role in the inspection of high-value civil structures like bridges, dams, and buildings. These powerful techniques have the capability to quickly provide accurate information enabling inspectors to assess structural condition, residual strength and life, and, in cases where deterioration has occurred, the nature and extent of damage. The comprehensive data provided by these techniques offers the potential to facilitate assessment, and prioritization of maintenance and replacement actions in light of often restricted budgets for those activities.

The goal of the project described here is to develop a prototype NDE tool for inspecting bridge decks. The system design is based on concepts developed at LLNL under its Ground Penetrating Imaging Radar (GPIR) development project [1, 2]. The prototype is intended to demonstrate concept feasibility and enable the Department of Transportation (DOT) to demonstrate the technology to its customers. The system will collect inspection data and produce high-resolution images enabling users to visualize bridge deck internal structural features and flaws.

1.1. Inspection problem description

There are more than 578,000 highway bridges in the US and more than 40 percent of them have structural deficiencies or are functionally obsolete. These conditions limit bridge utility, and if they are not adequately monitored and maintained, could pose a threat to bridge user safety. The bridge deck and its wearing surface are the most vulnerable parts of the bridge to damage from routine service and they are subject to significant damage resulting from corrosion of internal structural members.

Damage caused by corrosion is hidden from the view of inspectors by concrete and overlaying asphalt layers. Corrosion problems are usually found in the top layer of rebar in the deck, under a 2 inch cover layer of concrete and up to 4 inches of asphalt pavement. Delamination of deck concrete occurs when rebars corrode after long-term exposure to chloride ions and moisture that penetrate into the concrete. Corrosion products generated during this process produce tensile forces within the surrounding concrete which eventually cause fracturing and cracking. As the corrosion process progresses, cracks form between adjacent rebars which delaminate the top layer of concrete from the underlying structure. Figure 1 illustrates the effects of corrosion and resulting concrete delamination.

Delaminations effectively decouple the concrete from rebar strengthening members resulting in a loss of structural strength and a rapid deterioration of the deck wearing surface. The resulting damage is costly to repair and usually results in bridge closure during restoration. If it goes undetected, delamination can progress to a point where the entire bridge deck, including structural reinforcement, must be replaced. Timely identification and location of this condition would permit remedial action to be taken before failure could occur, and it could enable bridge operators to prioritize spending on bridge maintenance on the basis of structural need.

A vehicle mounted imaging radar for bridge deck inspection, designed to collect inspection data at or near normal traffic speeds, has the near-term potential to address a critical national and international need for reliable, cost effective NDE of bridges. To be effective, it is important that the bridge deck inspection system have a high probability of detecting rebar delaminations. Detection capabilities will depend primarily on the ability of the radar to detect thin layers or voids. We are evaluating that capability experimentally. In addition, high cross-range resolution resolution will be required to accurately characterize and map the extent of delaminations that are detected.

1.2. System design concept

The prototype bridge deck inspection system is mobile, permitting data to be acquired and stored in vehicle-mounted equipment. The system is designed to roll over the bridge deck pavement at speeds that approach those of normal traffic flow while acquiring inspection data. Vehicle-mounted radar equipment consists of MIR arrays, real-time display hardware for displaying raw data, data acquisition and control hardware, and data storage subsystems. One-meter long arrays of MIR modules are mounted on the front and rear of the vehicle. The arrays are offset from each other enabling the vehicle to cover a contiguous two-meter wide swath of bridge deck with each vehicle pass. After radar data are collected, image reconstruction and processing are performed on-board the vehicle using a workstation system. Figure 2 illustrates the inspection vehicle concept system concept.

The proposed concept includes three inspection modes to provide operational flexibility. These modes are:

Quick Inspection mode: Provides a means to collect inspection data while minimizing the impact of the inspection on traffic flow. This mode offers the highest inspection vehicle speed, the lowest resolution, and the highest data storage capacity. This mode is intended for preliminary assessments of deck condition and should provide an inspector with data that is adequate to determine if more detailed inspections are needed.

Limited Depth Inspection mode: Provides a means for collecting high-resolution data to a depth that permits evaluation of the top layer of rebars while maximizing inspection vehicle speed. The resolution in this mode is the same as for the detailed inspection mode enabling identification of areas of bridge deck where delaminations in the top layer of rebar are a problem.

Detailed Inspection mode: This mode provides the highest resolution and the lowest vehicle speed. It also enables collecting inspection data for the full thickness of the bridge deck, up to a maximum thickness of 40 cm.

1.3. Micropower Impulse Radar (MIR) technology

Micropower Impulse Radar is the key technology that enables the use of low-cost compact arrays for the prototype system. MIR is a fundamentally different type of radar that was invented and patented by LLNL. It is an impulse radar like other ultra-wideband radars, but it is unique because it radiates much shorter pulses than most and it is constructed using a small number of off-the-shelf electronic components. These features also make it very compact and inexpensive to manufacture. The MIR circuit board shown in the photograph in Figure 3 is a complete impulse radar transceiver when integrated with appropriate antennas. MIR technology was developed at LLNL in 1993 as an outgrowth of the development of the R&D 100 Award Winning Single-shot Transient Digitizer (SSTD). The SSTD records very high speed transient events in the Laboratory's high power pulsed Nova laser.

The prototype bridge deck inspection system uses arrays of MIR modules configured as range-finding radars. The range-finder is a compact, low-cost ultra-wideband radar with a swept range gate. The range-finder uses a unique equivalent-time sampling system (similar to those used in sampling oscilloscopes, but much lower in cost) which reduces ultra-wide-band signal bandwidth by as much as three orders of magnitude, with no loss of information content. Lower bandwidth, equivalent-time radar return signal replicas can then digitized using low-cost analog-to-digital converters. Technical specifications for a single range-finder module, designed for use in the bridge deck inspection prototype, are summarized in Table 1.

1.4. Imaging with MIR arrays

For bridge deck inspection, high resolution in both range and cross-range is desired. High range resolution is achieved using the ultra-wide-bandwidth of the MIR transmitter. The 100 ps rise-time pulse yields range resolution of about 2 cm in concrete. While this resolution is greater than the thickness of a typical delamination, we have shown experimentally that we can reliably detect thinner delamination layers in concrete; some of those results are presented later in this paper. Although the higher frequency components of the MIR impulse do not penetrate well into concrete (typically 20 to 40 dB/meter loss at 3 GHz), the structural features of interest are typically not deeply embedded so the frequency dependent attenuation losses are not a significant source of range resolution degradation.

Cross-range resolution is achieved by forming a large aperture and populating it with sensors like the MIR modules. Since individual MIR elements are low in cost and compact, it is feasible to connect several elements into a compact array to span the desired aperture. The resolution achieved depends on the wavelength, range, single element beam pattern, element spacing, and overall dimension of the aperture. A large aperture can be real or it can be synthesized by scanning a smaller aperture device (a single antenna or a small array) to fully sample the desired aperture. In our most recent experiments (reported below), we synthesized a 0.8 meter aperture, using a single MIR module, with 1.6 cm element spacing and achieved cross range resolution of <5 cm at ~12 cm depth (beneath 5 cm of asphalt and 7 cm of concrete).

To achieve high resolution in both cross-range directions, it is necessary to form a 2-D synthetic array. In our experiments, we did this synthetically by scanning a single MIR element in a raster scan pattern. In a bridge deck inspection operation it is more practical to use a 1-D array and scan once in the orthogonal dimension to form the synthetic 2-D aperture.

LLNL has developed diffraction-tomography and time-domain based imaging software necessary to reconstruct the 2-D and 3-D images [3, 4]. The software is written in portable C code, and can run on a workstation or laptop portable computer.

2. EXPECTED SYSTEM PERFORMANCE

The baseline performance goals for the prototype system are summarized in Table 2. These goals represent our best estimates of system performance parameters needed to satisfy minimum bridge deck inspection requirements. Of particular importance is the requirement to reliably identify and characterize rebar delaminations during inspections. The baseline goals also address the need to minimize the impact of inspections on traffic flows. Since a significant portion of bridge deck inspection costs are attributable to traffic controls, important cost savings can be realized if the new inspection method reduces traffic control requirements.

3. RECENT EXPERIMENTAL RESULTS

Recently experiments have shown that MIR arrays and SAR imaging can be used to effectively detect thin delaminations embedded in concrete. The experiments were conducted on two specially prepared concrete slabs designed to emulate steel reinforced bridge deck construction in which simulated delaminations were embedded. The slabs were constructed approximately 1 year before these experiments were conducted, and they were stored outdoors after construction. Slab 1 was constructed entirely using concrete without an asphalt cover layer and Slab 2 was constructed using concrete with an asphalt overlay. Figures 4, 5, and 6 show some details of the construction for Slab 1 and Figure 7 provides dimensional details such as location and size of embedded defects, as well as an outline of the area included in the images that follow.

In our experiments, we used a single MIR module to synthesize a 2-D aperture. Data collected in this manner was used to calculate a 3-D image of the volume and internal details of each slab. The aperture size used for these experiments was 80 cm by 75 cm, and the radar was maintained at a distance of 3 cm above the surface of the slab. The radar used to collect this data has a peak radiated power of < 100 mW, usable spectrum from ~800 MHz to >4 GHz, pulse repetition frequency of 2 MHz, and receiver gain of ~90 dB. In our experiments, we focussed our attention on the smallest and thinnest delamination simulations.

Figure 8 is a set of 2-D planar slices through the calculated 3-D image of Slab 1; the slices are parallel to the surface of the slab. In the figure, at a depth of 5.5 cm, both the 4-inch by 4-inch by 1/8-inch thick and the 6-inch by 6-inch by 1/8-inch thick delaminations are clearly visible. At the 5.5 cm depth, rebar used in the construction also begins to appear. The rebars appear here because of the construction of the rebar mat used in the slab. Note in Figure 4, the top layer of rebar is constructed with overlapping rebars placed at the edge of the slab. It is the overlapping rebar pieces, which are positioned above the spanning rebars, that appear first at the 5.5 cm depth in the 3-D image. The overlapping rebars are also evident at the 8.5 cm depth, and the second (orthogonal) layer of rebar appears at the 10 cm depth.

Figure 9 is a set of 2-D planar slices through the 3-D image of Slab 2. This slab has a 2 inch thick overlay of asphalt over the reinforced concrete. In the figure, at a depth of 10.5 cm beneath the asphalt surface, the 1/8-inch thick delaminations are also clearly visible. At a depth of 13.5 cm, the top rebar mat appears. Again, the overlapping rebars are clearly displayed at this depth. Finally, at the 15 cm depth, the second layer of rebar appears.

4. CONCLUSIONS

We have provided an overview of a project to develop a prototype bridge deck inspection system which uses MIR technology combined with unique image reconstruction algorithms and described its expected performance as a technology demonstrator. We also presented new experimental results that show that the measurement and processing techniques upon which the prototype are based can be used effectively to detect very thin delamination simulations embedded in concrete. As the project progresses, we expect to perform additional experiments using concrete slabs which contain embedded delaminations generated as a result of rebar corrosion. We will report the results of those experiments in a future publication.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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3. J.E. Mast and E.M. Johansson, "Three-dimensional ground penetrating radar imaging using multi-frequency diffraction tomography," SPIE Vol. 2275, Advanced Microwave and Millimeter Wave Detectors, 25-26 July 1994.

4. 3. E.M. Johansson and J.E. Mast, "Three-dimensional ground penetrating radar imaging using synthetic aperture time-domain focusing," SPIE Vol. 2275, Advanced Microwave and Millimeter Wave Detectors, 25-26 July 1994.

Table 1. MIR module specifications for bridge deck inspection radar

General	
Module configuration	Monostatic, impulse radar
Overall dimensions, weight	5 cm (height), 10 cm (width), 5 cm (depth), < 0.25 kg
Input power	6 to 12 V, < 20 mA
Range (max.)	3 m in air; 0.2 to 0.5 m in concrete (conductivity, dielectric constant, and radar stand-off range dependent)
Transmitter	
Type	Ultra-wide-bandwidth, impulse waveform
Pulse Repetition Frequency	5 MHz
Pulse Rise-time (radiated)	~ 100 psec
Bandwidth	> 3 GHz (from ~ 0.8 to 4.0 GHz)
Radiated power	< 2 W, peak; < 1 mW, average
Antenna	Cavity-backed, monopole with ~ 120° beamwidth
Receiver	
Type	Equivalent-time sampler with sensitivity time control (STC)
Bandwidth	~ 5 GHz
Noise figure	~ 25 dB without low noise amplifier
Overall gain	> 95 dB (with max. STC gain)
STC gain range	0 to 60 dB
Waveform update rate	~ 18,000 records/second (max.)
Analog output voltage	+/- 2 V, max., equivalent time replica spanning 30 μsec (min.)
Antenna	Cavity-backed, monopole with ~ 120° beamwidth

Table 2. Baseline system performance goals

Inspection mode	Maximum speed (mph)	Inspection depth (cm)	Cross-range resolution (mm)	Spatial sampling interval (mm)	Lane-wide storage capacity (m) in 512MB memory	Image reconstruction rate (m/hr)
Quick	35	40	64	64	262	60
Limited Depth	17	16	16	16	131	30
Detailed	9	40	16	16	66	15

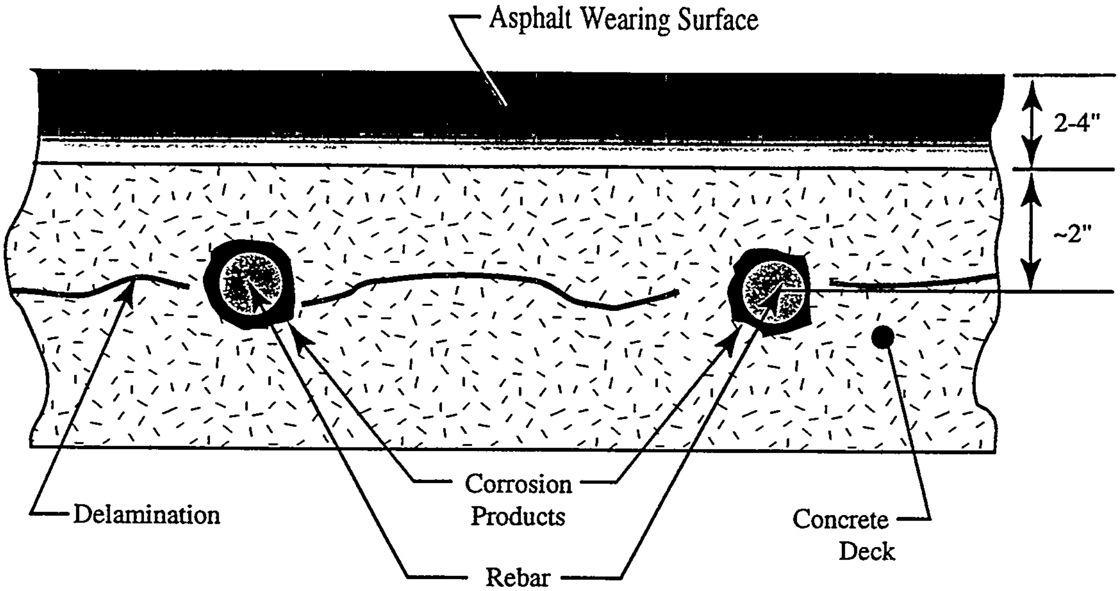


Figure 1. Delamination caused by corrosion of steel reinforcement

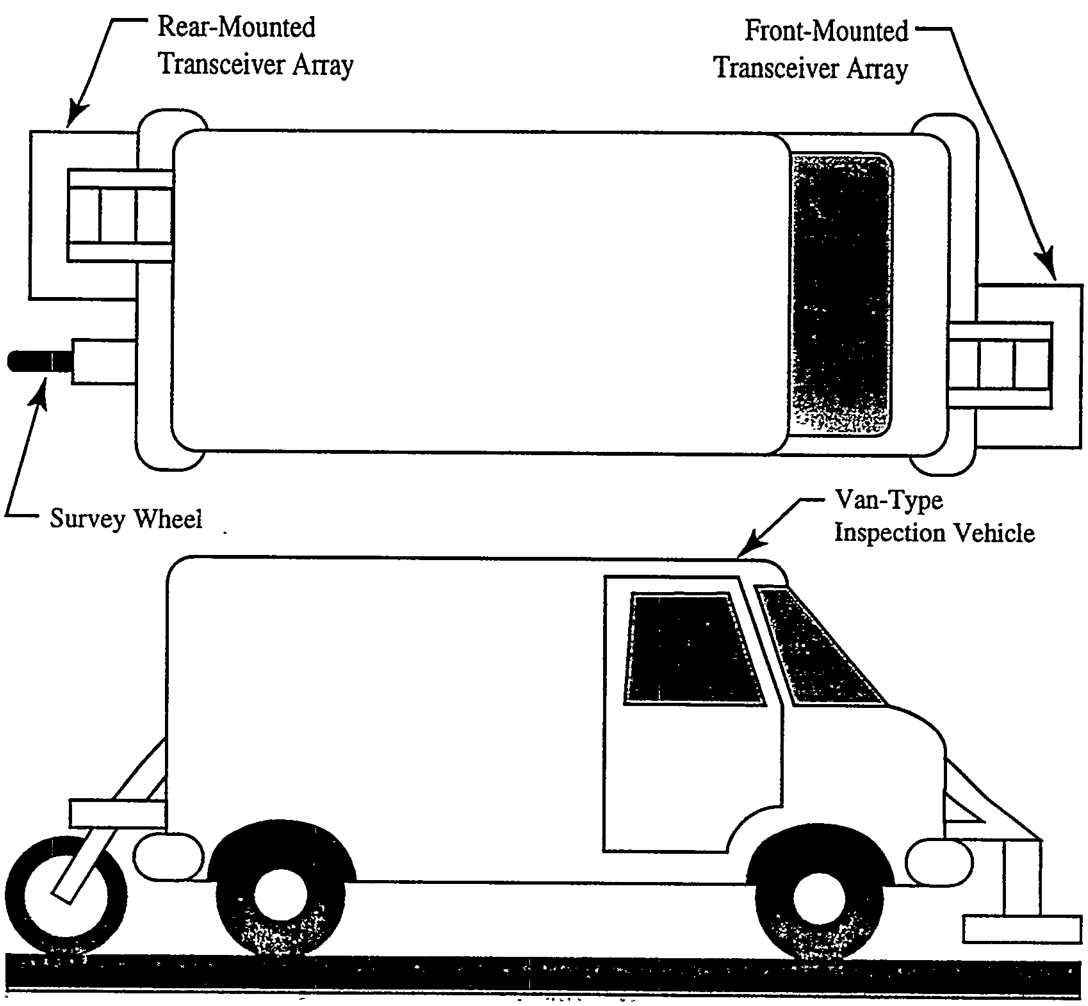


Figure 2. Bridge deck inspection system concept

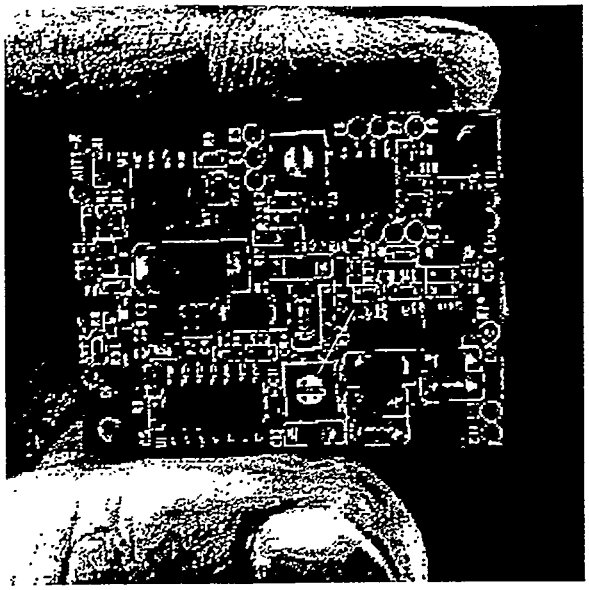


Figure 3. Printed circuit board for a Micropower Impulse Radar motion sensor module.

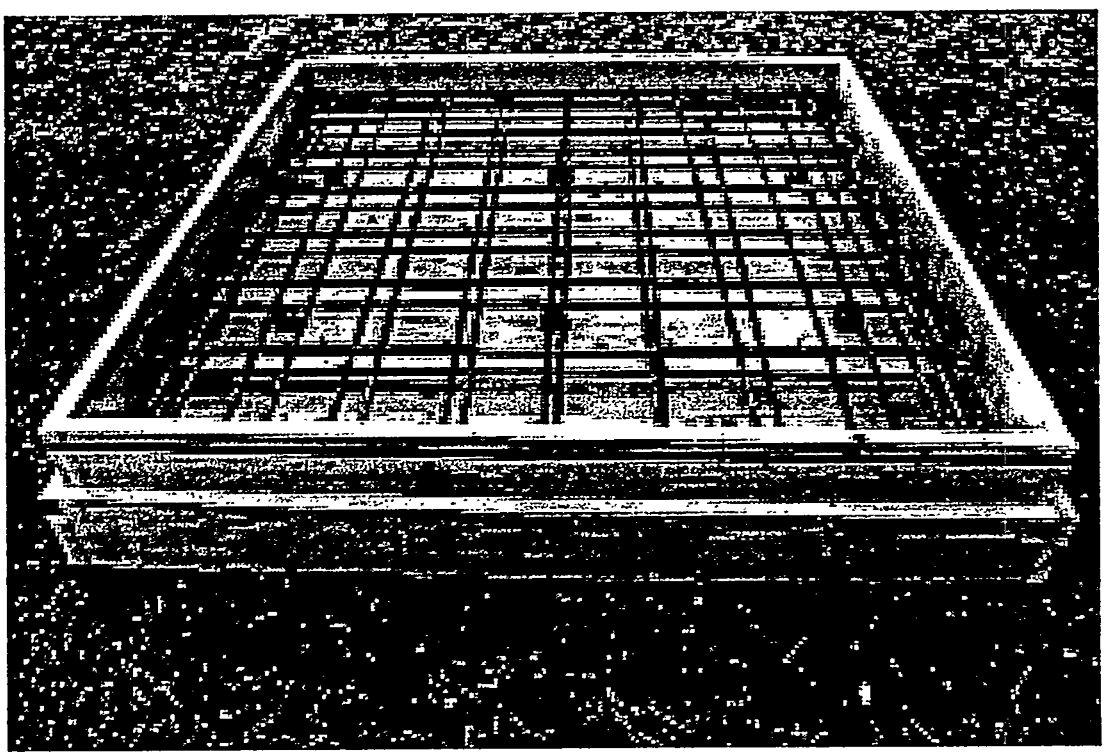


Figure 4. Slab 1 before concrete was poured. Note overlapping rebar pieces in top mat.

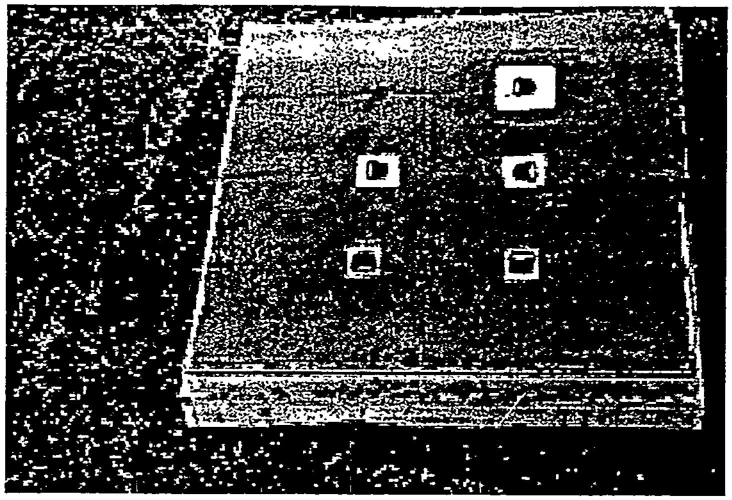


Figure 5. Slab 1 after concrete was poured, with spacer blocks for delamination simulations in place.

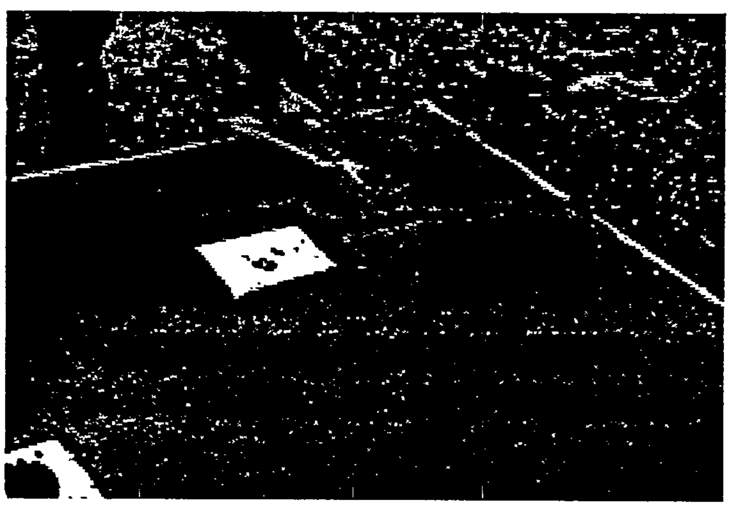
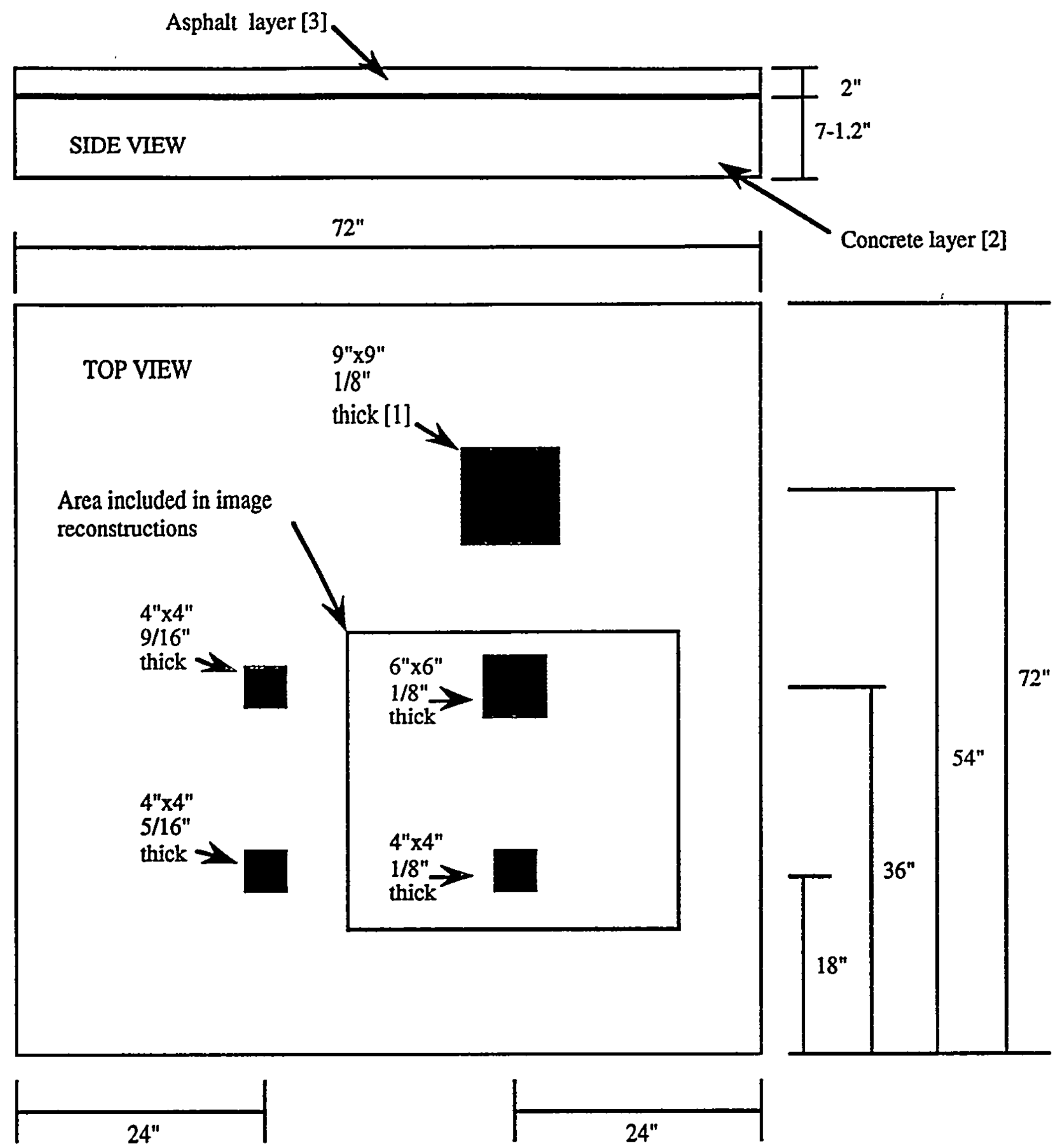
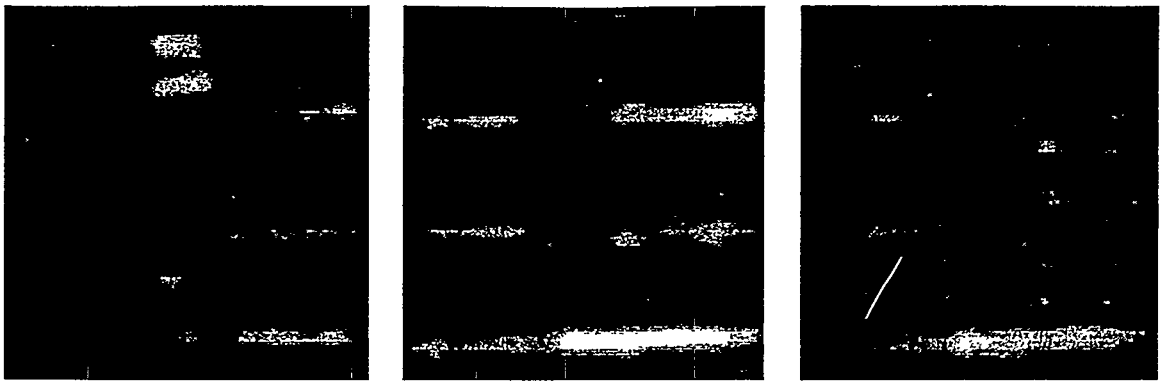


Figure 6. Placement of delamination in Slab 1 after spacer block was removed.



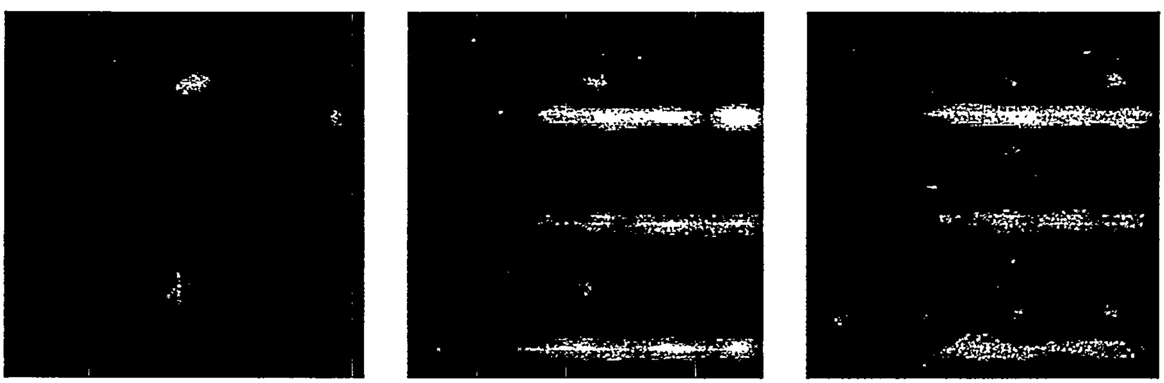
Notes: [1] All delaminations made from styrofoam, placed 2 " below and parallel to top surface.
[2] Rebar grid placed ~2-1/2" below the top surface of concrete.
[3] Asphalt layer not present for slab 1,present for slab 2.

Figure 7. Layout of test slabs (1 and 2) used in experiments.



Depth = 5.5 cm　　Depth = 8.5 cm　　Depth = 10 cm

Figure 8. Two-dimensional planar slices of delaminations and rebars in Slab 1.



Depth = 10.5 cm　　Depth = 13.5 cm　　Depth = 15 cm

Figure 9. Two-dimensional planar slices of delaminations and rebars in Slab 2.