IDEA

Innovations Deserving
Exploratory Analysis Programs

Highway IDEA Program

In-Service Repair of Highway Bridges and Pavements by Internal Time-Release Repair Chemicals

Final Report for Highway IDEA Project 37

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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS
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2.1.2 Acknowledgements

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2.1.4 Executive Summary

The concept is to repair bridges and pavements while in service by the internal time release of repair chemicals. Four specific applications for this concept were investigated in this laboratory and field based research. In frames in the laboratory, it was shown that cracks repaired will cause other areas to crack when stressed thus driving the cracking around the structure, utilizing much of the material strength but preventing catastrophic failure in any one location. In four full scale bridge decks, the chemical releasing tubes were put near the surface to function as creators of automatically fillable control joints. Surface shrinkage cracking acted to pull the brittle tubes apart and the sealant/adhesive flowed to fill the cracks. Thirdly the adhesive filled brittle tubes were placed in the body of the decks to break due to shear cracking and repair these cracks. This type of release not only strengthened the decks in most cases but also drove the expression of strain to new locations for crack formation. Large beams containing adhesive filled tubes were also tested to failure in the lab. These results were rather inconclusive but suggest that some added strength after the adhesive is released may be due to re-bonding of the rebars.

Some of the other accomplishments were to answer questions affirmatively about efficacy of release, survival of filled tubes in the cement mixer, maintenance of a liquid phase of the adhesive, ease of finishing the cement, and demonstration of the concept in three different locations.

The results or products are a video of all aspects of the research, the samples and this report and papers documenting the activity.

2.1.5 Body of the Final Report

The body of the report will be written in four chapters documenting activity on the four different types of structural components and stress type in which internal release was tested.

1) Failure Prevention of Rigid Concrete Frames by Strategic Use of Embedded Self-Repair Adhesives

IDEA Concept and Innovation; Impact of the Investigation

Structural damage in concrete frames causes stresses to be redistributed throughout the frame. This can result in structural failure if the forces are redistributed to inadequate members and connections. In less severe cases, it may lead to unsatisfactory service conditions, such as excessive deflections. Given the brittle nature of concrete, dissipation of dynamic loading is an additional structural challenge. This is a design for the internal release of adhesives within the concrete material as a means of controlled redistribution of forces in order to resist these failures.

In this remedy the location of structural damage in concrete structures is controlled by the strategic release of appropriate internal repair adhesives. High modulus, stiff adhesives released at the structural joints allow damaged joints to regain stiffness, thus preventing future damage at joints and insuring the translation of forces elsewhere. Low modulus adhesives released within the structural members close or seal cracks, but do not increase member stiffness. Thus, these sealed cracks are allowed some movement before additional cracking occurs, which also lends members beneficial damping capabilities. The combination of these adhesives into a single system allows forces in members to be safely transferred through connections to the more flexible members, where failure should occur at ultimate loading. Furthermore, dynamic load energy is dissipated within these structural members while maintaining the critical structural integrity of the connections. Such systems "intelligently" react in the event of excessive damaging forces—by driving forces through the structure to adequate members during the process of structural self-repair.

The self-healing method investigated for this project utilizes the timed release of adhesive into the member at the time of cracking. Chemically inert tubing is cast within the cross section of the member and is then filled with adhesive. At the onset of cracking, the tube wall is fractured, allowing adhesive to exit the tubing and penetrate the developing crack. The adhesive could be placed under pressure in order to produce more effective dispersal of the adhesive into the cracked region.

The experiment was conducted in two parts. The first was intended to identify the characteristics of three different adhesives, by testing each of them separately within a generic, concrete structural model that employed the tube delivery system described previously. The second was meant to examine the feasibility of applying the use of these adhesives to different regions of the same model in order to affect a certain behavior. The model chosen for the experiment was a plane, one-story, rigid portal frame cast monolithically with a concrete base (see Figures 1 and 2).

Part 1: Properties of Frame Repaired Based on Adhesive Type Utilized

For part one of the experiment, several frames were constructed, with glass pipette sections cast continuously through the crossing beam and both beam-column joints. The concrete mix for the frames consisted of 2.25 kg of silica sand, 1.0 kg of type I Portland Cement, and 0.5 kg of water. The samples were poured, allowed to cure for 24 hours inside of the forms, then removed and placed inside a water bath and allowed to continue curing for an additional 28 days. When the samples were removed from the bath, water was forced out of the pipettes with compressed air. The samples were then allowed to dry for 2 weeks before any tests were run.

The tests were performed through the use of a universal testing machine, subjecting the frames to a constant, in-plane, compressive force applied at the beam-column joint, and in a direction parallel to the base (See Figure 3). During the first of two tests, each sample was loaded to a deflection of 5 mm in order to induce minor cracking within the frame. The corresponding resistant force of the frame was recorded, and cracks were clearly marked (see Table 1).

Load was applied in the same manner during the second test 2 weeks later, this time until the sample reached failure (ceased to provide resistance to load). Load and deflection were recorded (Table 1), and the number of cracks located within the area of the adhesive's coverage were observed and identified as either "re-opened" or "new" (see Table 2).

Analysis

The three different adhesives employed were cyanoacrylate adhesive, a two-part epoxy, and a silicon based adhesive. In general, the reaction of the samples due to loading was characterized by a steady rate of deflection and a gradual appearance of cracks in the tension regions of the beam, followed by sudden, sometimes excessive failure at mid-height of the columns due to shear force.

Cyanoacrylate appeared to give the best overall strength improvement for these tests. By examining the data, we note that the cyanoacrylate samples had the highest average ratio of new cracks to reopened cracks (pre-filled: 1.80 ; post-filled: 2.50). This indicates that old cracks sealed by the cyanoacrylate in the first test provided increased strength in the second test, causing redistribution of stress to the uncracked section, where new cracks were formed. All of the other samples had an average new/reopened crack ratio of less than 1.0, indicating that the cracks sealed by the two-part epoxy and silicon adhesives experienced reopening without transferring stress to the uncracked section.

The relative stiffness of each frame was estimated by dividing the amount of load at failure by the final deflection of the sample. The stiffness values obtained from the second test were compared to those of the first, giving a percent change in stiffness from the first test to the second (see Table 1). Here, we note that the cyanoacrylate samples also proved to be the stiffest (pre-filled: 129% ; post-filled: 112%).

Investigation; Results

The most significant discovery of part one of the experiment was that cyanoacrylate increases the stiffness of concrete members weakened by cracking. Visual observations show that after the release of cyanoacrylate into the cracks, stress was redistributed and new cracks were formed, while the sealed cracks remained closed. Therefore, the cyanoacrylate samples were able to derive reserve strength from the uncracked section, while the silicon and epoxy samples experienced failure due to the reopening of old cracks (see Figure 4).

While the silicon adhesive did not appear to cause an increase in member strength, it did seem to exhibit characteristics that could be utilized to provide a damping mechanism within the frame. The flexible nature of hardened silicon based adhesives allows the crack to flex within a reasonable limit, thereby causing a dissipation of resistance energy that would normally be locked within the system and produce further damage. Theoretically, a crack bonded by the silicon based adhesive would recover in the absence of overload, similar to the action of a spring.

Part 2: Frame Repair Systems Integrating Varied Adhesive Types

For part two of the experiment, six new frames were constructed which also incorporated glass pipettes within their cross section. These pipettes were placed separately within each joint of the frame, as well as in the mid-span of the crossing beam and the mid-section of each column (see Figure 5). This allowed adhesive to be selectively administered to specific regions of the test frame, and also reserved the ability to inject different adhesive types into separate regions of the frame. For this part of the experiment, stiffening adhesive was supplied to the joints of all of the experimental samples, and the more flexible adhesives were applied to the beam and column regions of those same samples. The control samples had no adhesive of any type.

The concrete mix and the preparation process of the frames were exactly the same as that used for part one of the experiment, and load was also applied in the same manner as previous testing. These resulting cracks were clearly marked, and adhesive was released into only those areas that were affected by cracking. Cyanoacrylate was released through the pipette delivery system to cracks in the joints, while cracks within the mid-span of the beam and mid-height of the columns had the two additional adhesives (epoxy or silicon).

Two weeks later, observations were made as to whether new cracks were formed or old cracks were re-opened in a second testing of these samples. Again, newly formed cracks had adhesive released into them.

Static load was again applied an additional two weeks later, in test three, in order to examine the performance of the frame after cracking had been developed and sealed by adhesive in each section of the member. Failure modes were checked for each sample to determine whether the frame failed at crack sites sealed by the flexible adhesives or crack sites sealed by cyanoacrylate.

Finally, the frames were subjected to cyclic loading (repetitive static loading, not dynamic) immediately after the third test in order to examine whether or not each experimental adhesive was able to exhibit elastic or inelastic behavior in the frame. Hysteresis graphs were generated based on load and deflection of this fourth test.

Analysis

The amount of adhesive penetration into each crack played a significant part in the overall performance of each sample. Samples that achieved good penetration performed closely to their hypothesized behavior. Cracks in the joints sealed by cyanoacrylate were effectively held closed throughout the tests. This caused most of the stress imposed by successive loading to be carried by cracks within the columns.

The control samples (Sample A and B) experienced crack generation throughout most of the tests, followed by relatively early failure in comparison to the experimental samples. (See Figure 6)

Crack formation in the samples with epoxy in the members and cyanoacrylate in the joints (samples C and D) was slow in the first two tests, beginning on the side nearest the applied load in each column, and continuing steadily through the width of the column. In the final static test, sudden failure occurred at a reopened crack in the column opposite the applied load, while the column adjacent to the load experienced much less damage. This could possibly be due to the less flexible nature of the epoxy, which does not seem to allow ductile behavior.

The samples with silicon in the members and cyanoacrylate in the joints (samples E and F) exhibited a much faster formation of cracks in the third and fourth tests than did the epoxy samples. In the final static test, however, cracking proceeded at approximately the same rate in each column, and a much less dramatic end failure occurred in the column opposite the load. There also appeared to be much less crack generation in the joint areas of the silicon samples than there was in the epoxy samples.

During test two in epoxy sample C, two new cracks were formed in the joint adjacent to the applied load, and one new crack was formed in the opposite joint (see Figures 7 and 8). Likewise, epoxy sample D had a new crack form within the joint adjacent the load in test two (see Figure 7). However, neither silicon sample E nor G experienced new cracking in either joint after cracks were opened in the column and injected with silicon (see Figure 9 and 10). This indicates that while the silicon adhesive was able to dissipate enough energy through crack flexure in the column to prevent further cracking in the joint areas of the frame, the epoxy was not flexible enough, and therefore could not adequately absorb stress from the applied load.

While the intent of tests one to three was to show crack behavior in the presence of flexible and stiffening adhesives, the fourth test was meant to determine the ability of the epoxy and silicon to affect elastic behavior in the system. Results indicated that silicon samples E and G did indeed recover between cycles, experiencing total permanent deformations of 0.15mm, 0.30mm, and 0.10mm respectively. The epoxy samples performed the least favorably overall between cycles 1 and 2, with a permanent deformation of

0.68mm, as compared to 0.15mm for the silicon samples and 0.60mm for the control samples. However, the epoxy samples did out-perform the controls in recovery in the subsequent cycles.

IDEA Product: Technical Progress Made During The Investigation

Conclusions

The ability of cyanoacrylate to seal cracks firmly and prevent reopening was confirmed, and the silicon adhesive was found to exhibit elastic capability. The joints of the frames cracked initially, but after the cyanoacrylate was released, they failed to reopen in the subsequent tests and maintained the ability to transfer loads. Cracks in the mid-span of the columns that were filled with the two more flexible adhesives reopened in the subsequent tests after release.

The primary location of failure was always based in the columns, where the epoxy and silicon were released. This proved one hypothesis of the project, which was that adhesives with higher modulus of elasticity, such as cyanoacrylate, can resist reopening and transfer stress to weaker sections of the member, while lower modulus adhesives will seal cracks, but the section would be flexible and capable of *dissipating* energy. The samples containing silicon displayed elastic behavior after unloading of the cyclic tests, indicating that silicon allows members to recover their original shape better than epoxy.

The results of this experiment show that the timed release of adhesive into cracked regions of rigid concrete frames is a viable form of repair and failure prevention. The location of structural damage can be controlled in conjunction with the repair of damage. Initial damage in critical strength regions can be repaired by high modulus adhesives to prevent future damage in that region, while transferring forces to other portions of the structure. Structural damage, namely cracking, can be directed to the members themselves, where cracks can be repaired by flexible adhesives which allow some flexibility in the members for energy dissipation necessary for resisting dynamic loading failure and recovery from deformation.

TABLE 1
LOAD, DEFLECTION, and STIFFNESS
(Part I: TEST 1, 2)

SAMPLE	LOAD (kN)		DEFLECTION (mm)		STIFFNESS (kN/mm)		% CHANGE
	TEST 1	TEST 2	TEST 1	TEST 2	TEST 1	TEST 2	
Control	0.81	1.18	4.77	7.17	0.170	0.165	97.2
Cyanoacrylate	0.86	1.35	4.88	6.53	0.176	0.207	117.7
Epoxy	0.85	1.32	5.03	7.00	0.169	0.189	111.7
Silicon	0.90	1.28	4.75	5.83	0.189	0.220	116.2

TABLE 2
RE-OPENED vs. NEW CRACKS
(Part I: TEST 1, 2)

SAMPLE	AVG. OLD	AVG. RE-OPEN	AVG. NEW	RATIO (new/re-open)
Control	3.33	3.67	2.0	0.55
Cyanoacrylate-				
	2	1.67	3.0	1.80
	3	0.67	1.67	2.50
	3 4 2	1.67	1.33	0.80
Epoxy				
	2 4 4	2.33	0.33	0.14
	4 4 3	3.0	0.67	0.22
Silicon	3			
	3 4	3.0	0.67	0.22

Table Three
Total Permanent Deformation
Per Cycle
(Test 6)

SAMPLE	DEFORMATION (mm)			
	CYCLE NO.			
	1	2	3	4
A Control	**0.00**	**1.10**	**1.70**	**2.70**
B Control	**0.00**	**0.10**	**1.60**	**2.85**
C Epoxy + Cyano.	**0.00**	**0.60**	**0.75**	**2.00**
D Epoxy + Cyano.	**0.00**	**0.76**	**1.60**	**2.00**
E Silicon + Cyano.	**0.00**	**0.10**	**0.50**	**0.55**
G Silicon + Cyano.	**0.00**	**0.20**	**0.40**	**0.55**

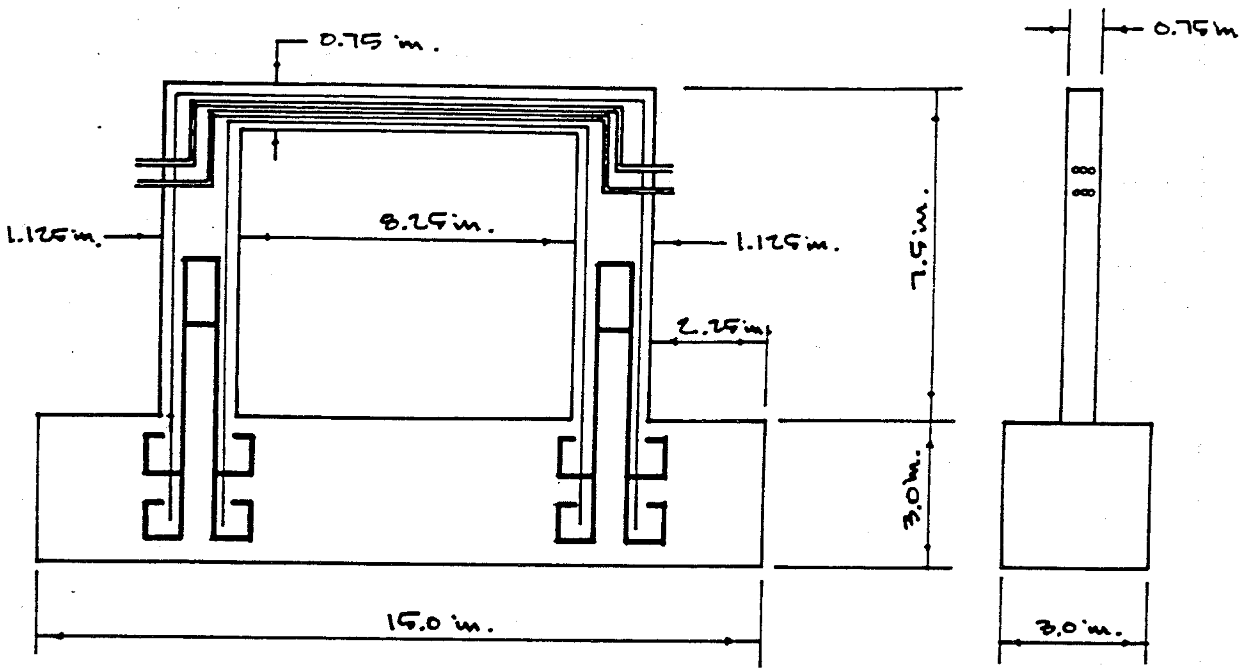

Figure 1. Drawing of sample test frame used in tests 1 and 2.

a. **b.**

Figure 2. Cross section of: (**a**) column, and (**b**) beam.

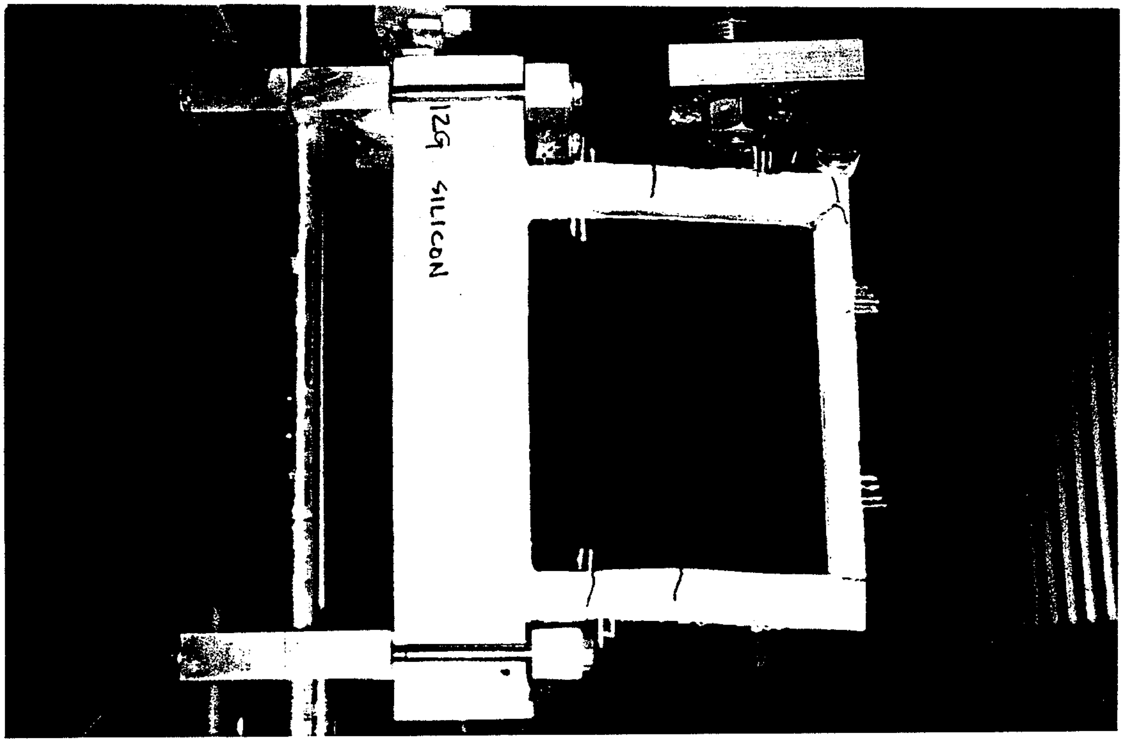

Figure 3. Photograph of typical sample in testing machine.

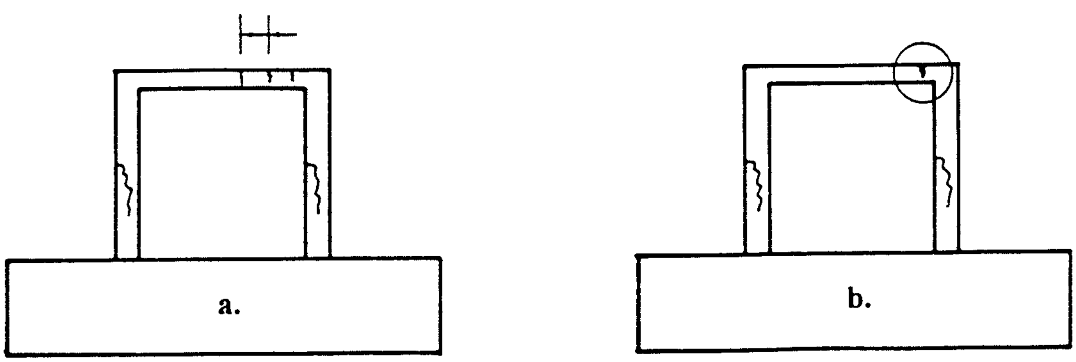

Figure 4. Diagram showing: **a.** stress transfer and new cracking in cyanoacrylate samples and **b.** reopening of old crack in silicon and epoxy samples

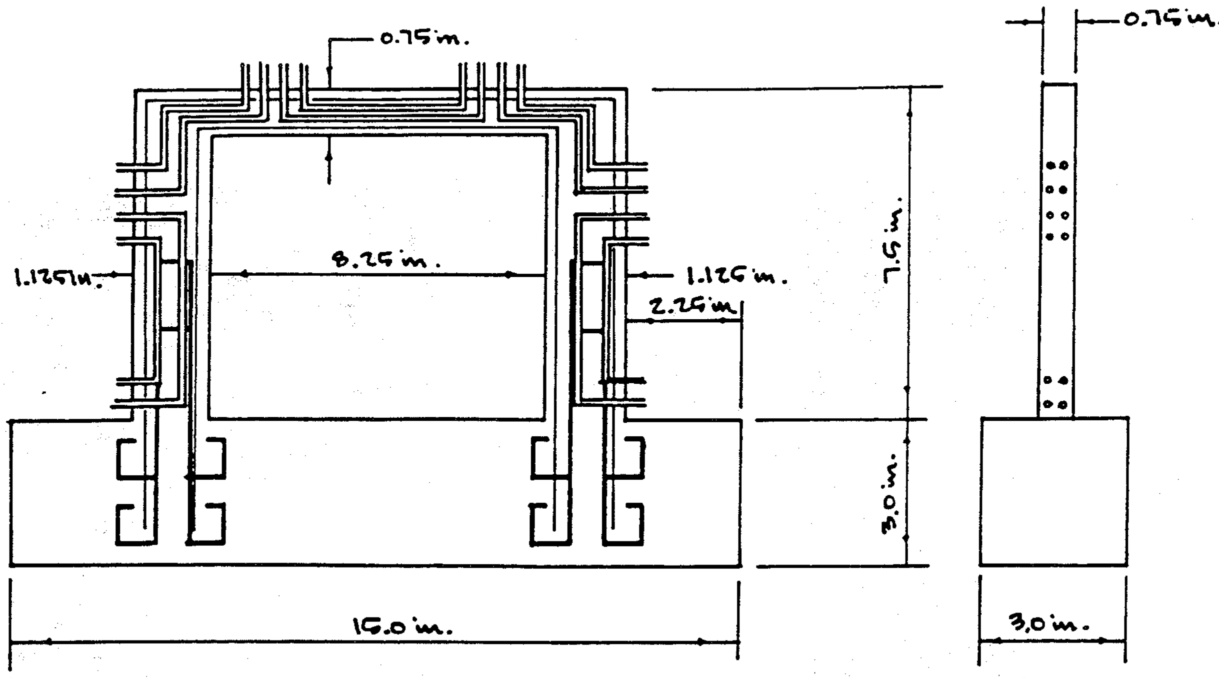

Figure 5. Drawing of sample test frame used in tests 3 to 6.

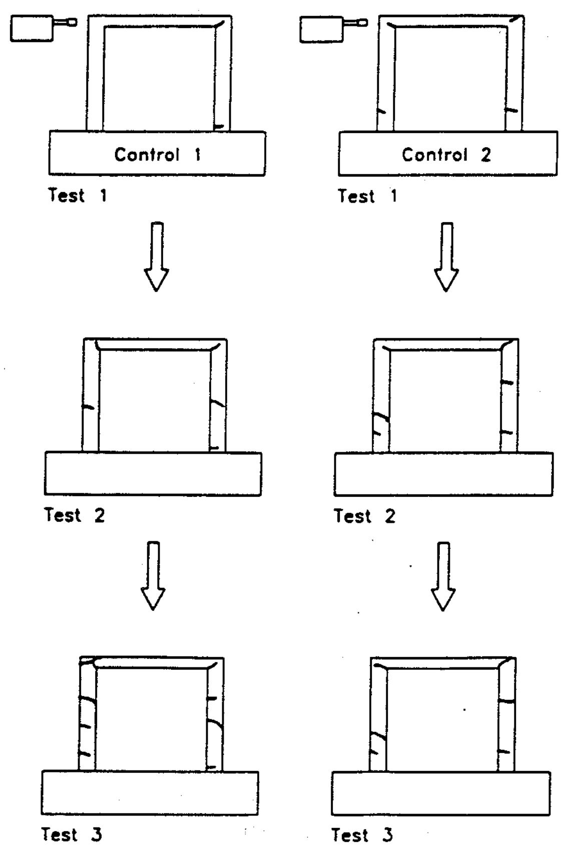

Figure 6. Diagram of control frames (Sample A and B) cracking in three static tests of part II

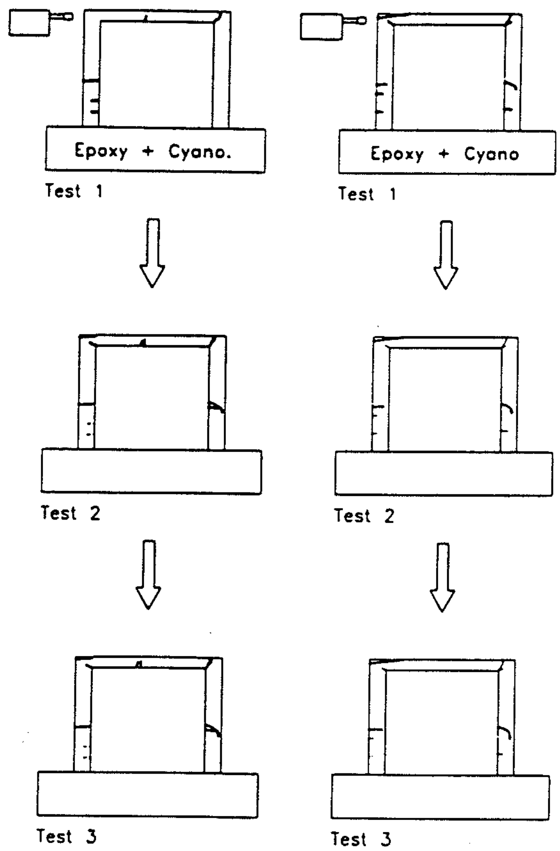

Figure 7. Diagram of epoxy and cyanoacrylate frames (Sample C and D) cracking in three static tests of part II

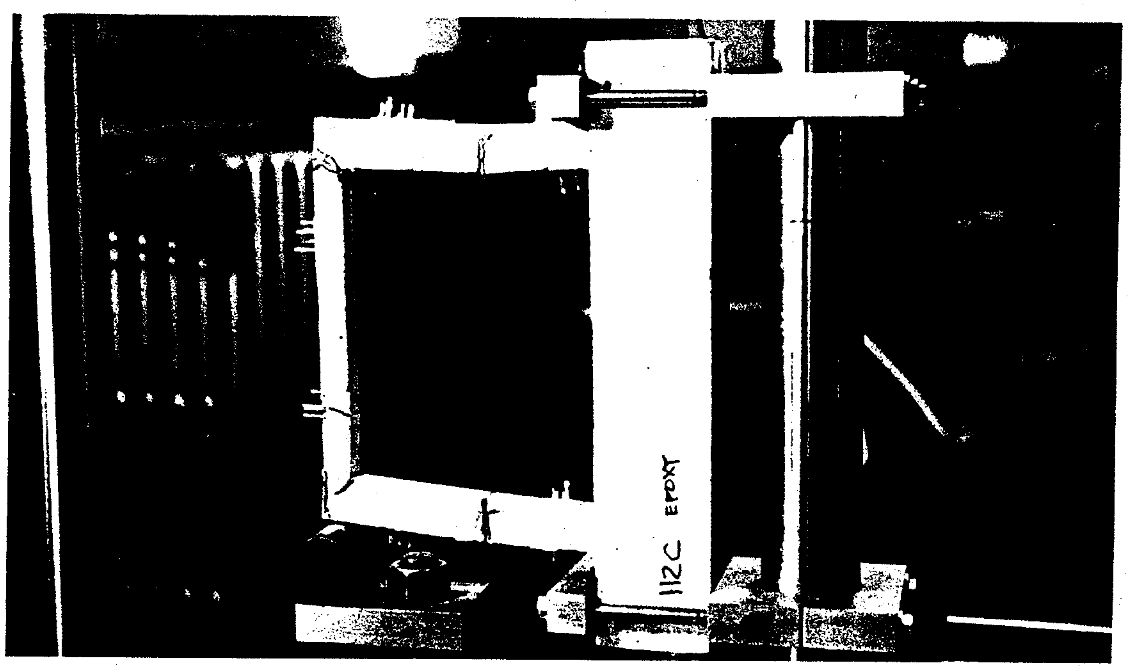

Figure 8 Photo of epoxy and cyanoacrylate frames (SampleC) cracking in the third static test of part II

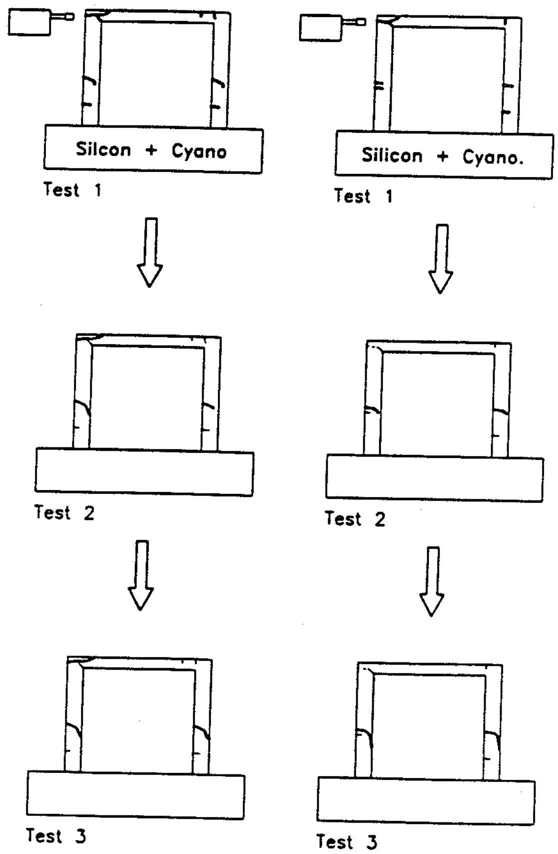

Figure 9. Diagram of silicon and cyanoacrylate frames (Sample E and F) cracking in three of static tests of part II

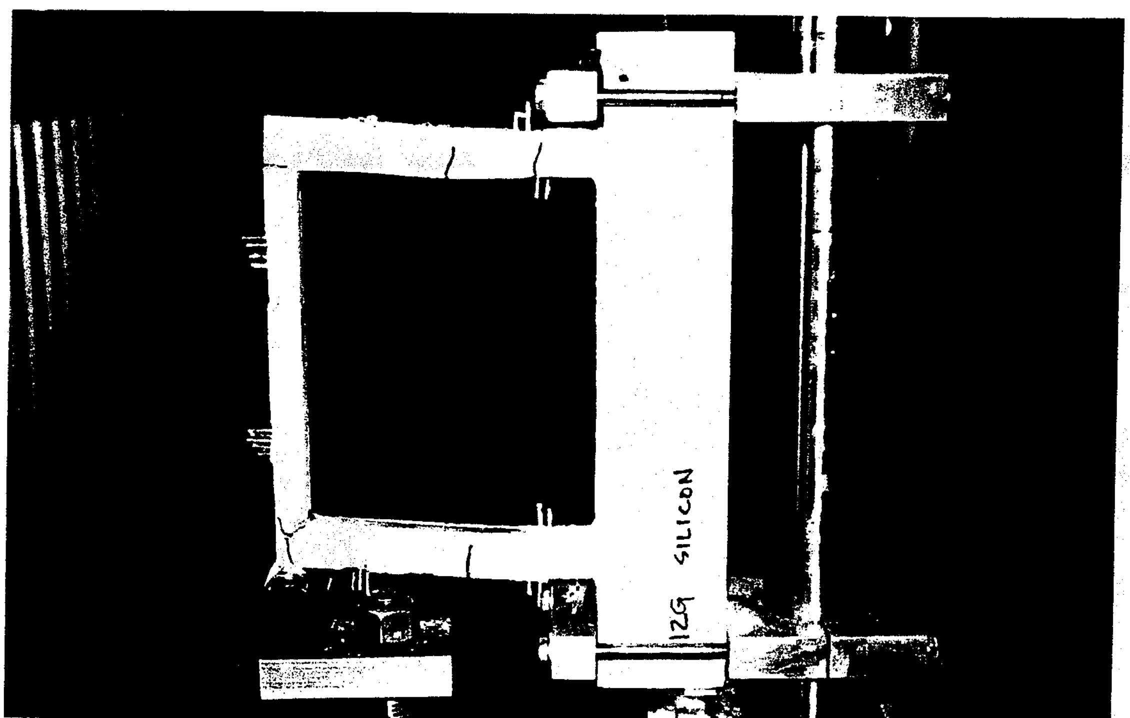

Figure 10 Photo of silicon and cyanoacrylate frames (Sample G) cracking in test two of static tests of part II

II.) Repair and Prevention of Damage Due to Transverse Shrinkage Cracks in Bridge Decks

IDEA Concept and Innovation; Impact of the Investigation

In this research being done at ATREL Lab of the University of Illinois tubes with low modulus adhesive or sealant were placed just beneath the member's top surface, parallel to the longitudinal axis, creating a transverse row that could act as a control joint and a seal in this controlled surface crack. Results from this research proved that the encapsulated repair chemicals were an effective, in-situ means of controlling and repairing transverse shrinkage cracking in bridge decks.

Deck micro-cracking is a critical concern in bridge design; a problem that affects all Departments of Transportation Boards across the Midwest. Transverse shrinkage cracking of bridge decks occurs during and shortly after construction. It allows cracks to form and later allows water and other elements to enter the concrete matrix of the deck and most importantly to fall onto the supporting structure below. This leads to significant structural damage of that support structure. This paper describes a field application of the design for an in-situ means of controlling and repairing transverse shrinkage cracking, by utilizing brittle tubes with sealants in the concrete deck.

This application can be applied to bridge decks specifically to control the location of transverse shrinkage cracks by creating control joints on the surface as a transverse row of sealant-filled tubes. These tubes, which are weaker than the concrete in tension because they are scored, break due to shrinkage strain, thereby focusing the transverse cracks along this line. A sealant adhesive is then released from the tube and seals the cracks in concrete. The repair sealant (which is also an adhesive) has a low modulus of elasticity, thereby allowing future movement to resist stresses and strains in the deck without additional cracks extending from these shrinkage microcracks.

IDEA Product: Technical Progress Made during the Investigation

Four full-scale bridge decks have been fabricated, with repair-sealant tubes embedded at various locations as seen in figure 1. Potential construction problems such as premature release during mixing, difficulty in finishing as well as temperature effects overtime were found not to be problems. Monitoring s ystems were also placed, including optical fibers, ETDR cables, and connection of reinforcing bars for corrosion monitoring.

Results in the first two decks after one month of monitoring showed that repair tubes embedded just under the deck's top indeed ruptured due to surface shrinkage and created repair control joints as designed while repair tubes placed in the deck surface but not totally covered broke after two months while those left totally uncovered did not break. Although these were more exposed to the environment and freezing and thawing weather cycles than the fully embedded ones these environmental forces did not cause breakage. .

Background Work

When initially considering the design for sealant-filled repair tubes embedded in bridge decks, issues of field constructability were to be addressed. These were:.1.Will the mixing action prematurely fracture the brittle fibers?) 2. Will the fibers withstand traditionally finishing methods? 3. Will the changes in temperature affect the release process? 4. Will the adhesives stay fluid in the fibers ?

By using laboratory and full scale field testing, these questions were addressed in the research. The issue raised, regarding the mixing action prematurely fracturing the brittle fibers, was addressed in laboratory research. Previous research done by the principal investigator had shown that brittle filled fibers less than 2-1/2 inches length would survive mixing in standard concrete mixers. The issue regarding quality of the concrete if the adhesive was prematurely release, as in during mixing. was investigated in the laboratory. A set of samples was poured in which the glass fibers were broken by hand during placement and adhesive was released. The concrete was tested for adverse effects and none were found.

Actual field testing was necessary to address if the fibers can withstand traditional finishing methods. As can be seen in figure 2 they did not pose any problem for surface finishing with the small fibers that had been tossed into the mixer. The issues of the affect of changes in temperature, (especially freeze/ thaw cycling) on the release process proved to be not important. The adhesives stayed fluid in the fibers as seen in figure 3. They only solidified, to the low modulus form, after release. In field tests in which these fibers were thrown in the large cement mixer during mixing showed that they will survive such mixing of the concrete slurry as seen in figure 4.

Investigation; Results

Decks 1 and 2

Four continuous bridge deck slabs were fabricated in total. The first two were poured on a cool (50deg. F) overcast day in October, 1997. A local commercial cement company was contracted to deliver an eight bag-mix concrete mix (cement content of about 640 lb./yd^3), using type 1 normal cement with a w/c ratio of 0.38. The entire concrete pour, pipette placement, and finishing process was done with help from a hired laborer, the concrete mix deliverer, and four graduate students and took approximately 2-1/2 hours.

These 4'x20'x3" decks have transverse reinforcing bars at every 8" and four longitudinal bars below these. All bars are 3/8" diameter and located at the deck section mid-height. The decks are composite with 8x10 steel beams, having 3/4" shear studs every 18". These beams are simply supported at either end and at their mid-span, creating a two span deck composite with two steel beams. One of these two decks has adhesive filled fibers placed at right angles along a line above the transverse reinforcing bars, some embedded just below both the top surface of the deck and some exposed on th top surface (see figures 5 and 6). Adhesive filled fibers were also placed randomly in the concrete matrix over the interior support for additional testing of shear crack repair. Additionally, a relatively small number of 2-1/2" long, 100 micron diameter super-glue filled fibers were thrown into the concrete during mixing to test their resistance to breakage during typical mixing conditions. The other bridge deck has no fibers, and serves as a control (see figure 7).

Rebar was left projecting out of the ends of the deck for later corrosion testing; these reinforcing bars are connected with metal wire to permit voltage readings to detect corrosion development at the reinforcing bars. Optical fibers were cast in the deck above each transverse rebar to monitor cracking within the section and on the top surface. Placing uncoated optical fibers inside the decks proved to be very difficult in terms of the logistics of pouring the deck. The fragile fibers were threaded inside hollow pvc pipe which werelocated inside the deck, above the rebars as seen in figure 8. After the concrete was placed but before final finishing the pipes head to be removed so that the fibers would be in contact with the concrete. The pipes left voids so that the concrete had to be vibrated again and then finished.

Assessment

2 ½ inch fibers put in the concrete during mixing remained intact, confirming previous laboratory findings for mixing resistance of filled brittle tubes. Visual assessment was the primary means used for confirming predicted behavior of the sealant filled tubes. These adhesive-filled fibers along the deck surface were monitored for breakage beginning immediately after placement and finishing. The sealant VOC changed color, first to blue and then orange when released into contact with the concrete.

When the deck was being poured, adhesive-filled tubes were placed within the deck's volume at the center portion of the twenty foot length. They were placed after the deck had been quickly leveled, but before it had been finished. Added strength imparted by these tubes will be assessed when the decks are tested in bending at the center portion to test for shear cracking.

Anaylsis

It is evident that tubes in the deck surface broke due to transverse shrinkage strain. Results in the first two decks after one month of monitoring showed that repair tubes embedded just under the deck's top indeed ruptured due to surface shrinkage and created repair control joints as designed while repair tubes placed in the deck surface but not totally covered mostly broke after two months while those left totally uncovered did not break. Although these were more exposed to the environment and freezing and thawing weather cycles than the fully embedded ones, the environmental forces did not cause breakage of the fully exposed tubes. . As seen in figure 9, most of the fully embedded tubes broke by the end of 35 days, the tubes which were not totally embedded broke within the first two months, the typical time dry shrinkage occurs in new concrete and an additional ten percent broke later. The other glass tubes which were not covered account for the approximately twenty percent which did not break at all. These readings were taken usually on a weekly basis although the embedded ones were read only at 35 days. The control joints created by the fully embedded tubes could be seen because the released sealant penetrated up though the concrete and stained it, see figure 10.

During these first several months the decks were subjected to the extremes of freezing and thawing yet those tubes fully exposed and not bonded or covered with concrete did not break. The conclusion is that breakage was due to shrinkage tension from the concrete on the scored brittle tubes which were bonded into the concrete ,not from freeze thaw or weather damage. The result was a transverse line of repaired microcracks, a control joint.

Further testing
Future testing and monitoring is in progress or is planned for additional information acquisition. Corrosion monitoring is currently underway, but no conclusive data has been obtained as of yet. The internal fiber optic devices do not appear to be an adequate sensor, and ETDR cable is to be used in future testing of deck 3 and 4. However, measurement of internal cracking will be attempted using fiber optics embedded. Additionally, salt water will be ponded on the surface, and leaking due to cracking will be assessed. Finally, the middle support of each system will be jacked upward, to load the deck to induce cracking. This loading system actually models different behavior in the deck system. This point loading on a single span (the entire length of the deck) will cause cracking on the top of the deck at mid-span. This will test the effectiveness of the adhesive-filled fibers cast within the mid-span of the deck

Mid-progress Evaluation
The results indicate the significant tube cracking was the result of dry shrinkage and that the self-repair technique was an effective means of controlling the location of and repairing these shrinkage cracks. The four constructability questions were answered with this research. The mixing action will not prematurely fracture the brittle fibers of 2-1/2" long. The fibers can withstand traditional finishing methods. And the adhesives will stay fluid in the fibers. Finally, changes in temperature do not affect the release process.

Field Deck Samples 3 and 4
The second set of decks will be used to confirm these findings from the first phase of this research. Additionally, the affect of sealant type and tube placement along the deck will be investigated. The issue of transverse tensile cracks due to bending along the tops of decks over deck support and at midpoints at the bottom surface of the deck.led to the use of sealant filled tubes over the center line on the top surface as well as placement of ones on the bottom surface at the midpoints. Adhesive-filled tubes at the middle support were again placed for repair of internal shear cracks. The set-time for the repair chemicals and the flexibility or flex resistance of these will be assessed These cracks need to be quickly sealed in bridges, even as traffic continues to pass over these cracks causing continues flexing or pumping. By looking at different adhesive types, this issue will be addressed in the second phase of testing.

These two additional bridge decks were fabricated on a windy, sunny, 60deg. F April afternoon in 1998. Decks 3 and 4 were composite with W16x26 beams and had 1/2" shear studs placed every 12" (see figure 11). VOC and Rotile adhesive filled glass tubes were embedded in the surface along the top and bottom of the deck as shown in figures 12,13,14. Also VOC filled glass tubes were embedded half way into the deck's depth at the midsection of the deck, for repair of shear cracks testing as seen in figure 15.

Rebars for later corrosion testing were again left projecting out of the ends of the deck. Optical fibes were placed on the top of the deck only, and ETDR cables were cast within the section for future measurement of internal shear cracking see figure 16. It is also hoped that a portion of the ETDR, which was placed without its protective jacket, will allow measurement of water intrusion into the deck.

Assessment and analysis
These newly poured decks are being monitored weekly by visual analysis and utilizing internal ETDR cable and for corrosion. It is anticipated that these decks will have similar cracking of embedded tubes due

to shrinkage of the concrete, again creating a control joint. Results from the two decks will be compared with those from the first two weeks.
In this second set of decks, further information is hoped to be gained by looking at embedded fibers in both the top and bottom surfaces of the concrete deck.. The differences in weather conditions, both at the time of the pour and during curing, will also be considered. Using various types of adhesive also allows a comparison of different repair capabilites.

Conclusions

This ongoing research is showing the implementation of a material self-repair system is a promising solution for preventing and repairing shrinkage crack damage in bridge decks. Specifically, these adhesive-filled repair tubes embedded in the concrete surface can create control joints in the deck to control the location of and repair cracks caused by dry shrinkage of concrete. Such dry shrinkage transverse cracks are a common problem in bridge decks. Although these cracks are not in themselves significantly detrimental, they introduce a way for water and other elements to enter the concrete deck, which can lead to more serious deck damage related to lost material integrity, corrosion of reinforcing, and especially damage of the support structure beneath the deck.

This research has potential to repair cracks and prevent damage in concrete bridge decks by using self-repair systems. In addition to repair of shrinkage cracks in the deck surface, these repair adhesives will be investigated to repair bending cracks in deck surfaces and interior bending and shear cracks. This in-situ means of controlling and repairing transverse shrinkage cracking, utilizing brittle tubes with sealants in the concrete deck, is effective a means of repair in actual field testing as predicted by laboratory testing.

References

Krauss, Paul D., and Ernest A. Rogolla, "Transverse Cracking in Newly Constructed Bridge Decks", Report 380, National Cooperative Highway Research Program, Transportation Research Board, National Research Council, National Academy Press, Washington, D.C.,1996

Figure 1) Photo of the four full scale bridge decks which were fabricated at ATREL Laboratory of the University of Illinois

Figure 2) Photo of the finishing process which was not impeded by the fibers in the mixture.

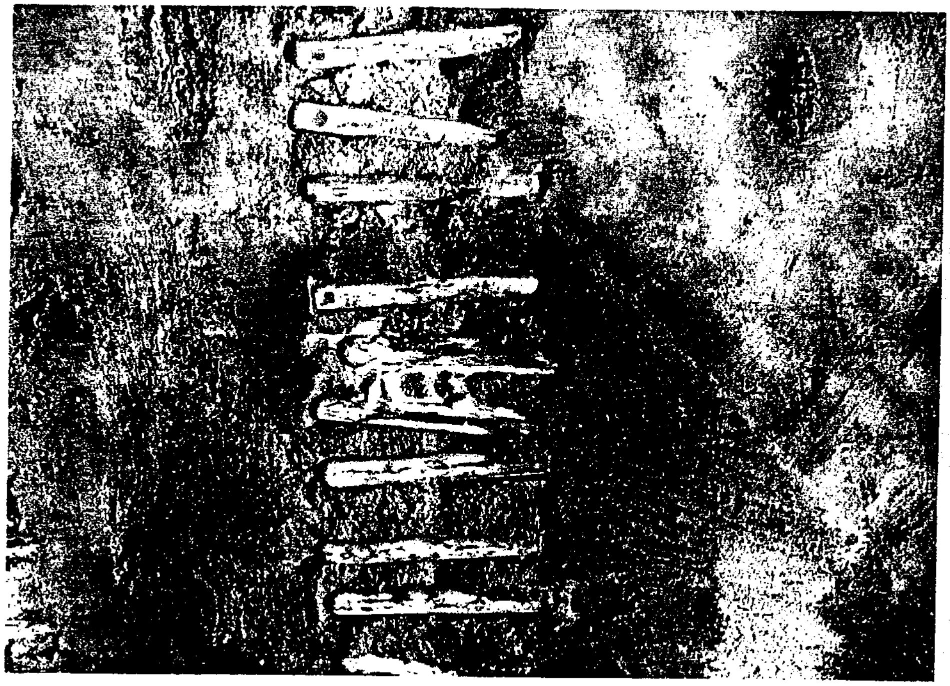

Figure 3) Photo showing the adhesives which stayed fluid in the tubes

Figure 4) Photo showing the 2 ½" long fibers in the concrete , all of which survived the mixing.

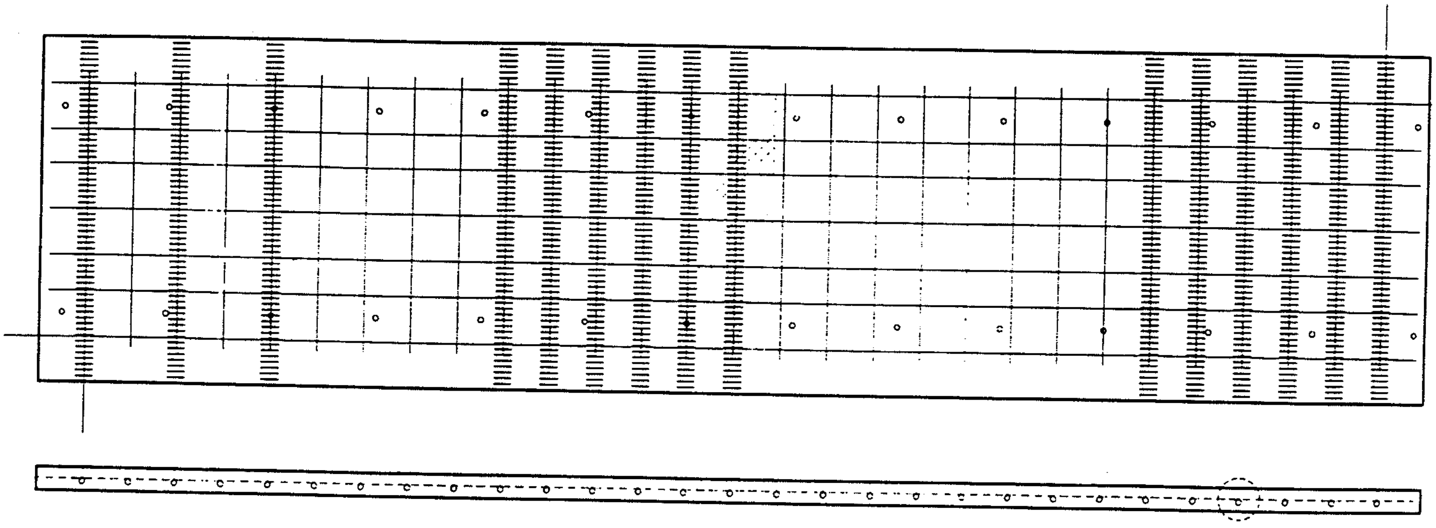

Figure 5) A drawing of the deck containing adhesive filled tubes

Figure6) A photo of the tubes embedded at the top surface of the deck.

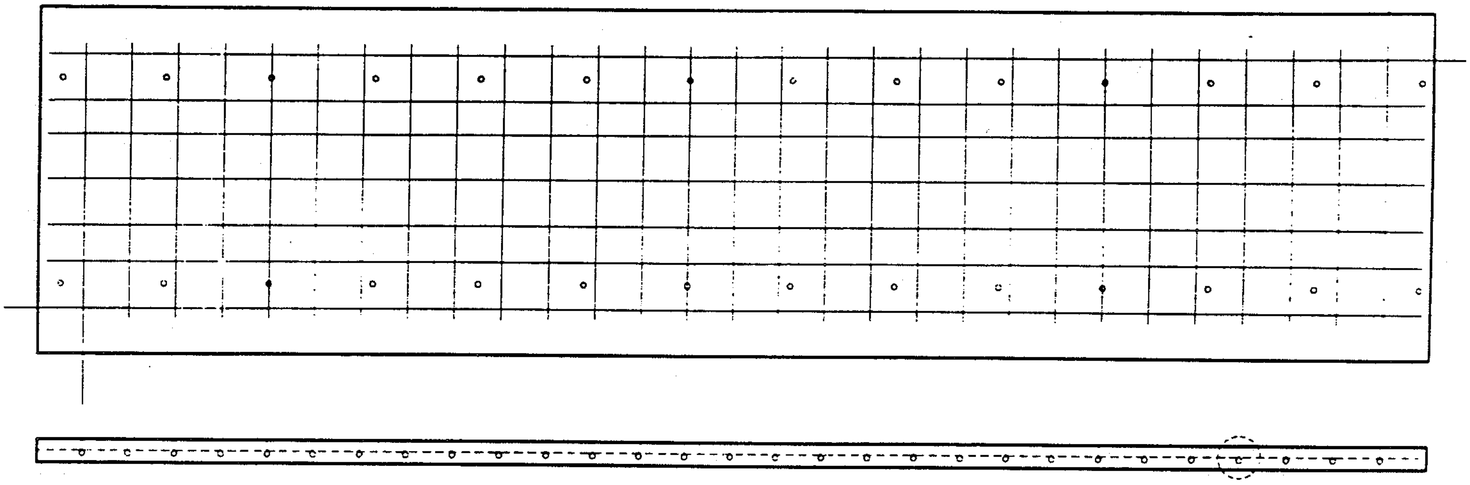

Figure 7) A drawing of the deck without adhesive filled tubes

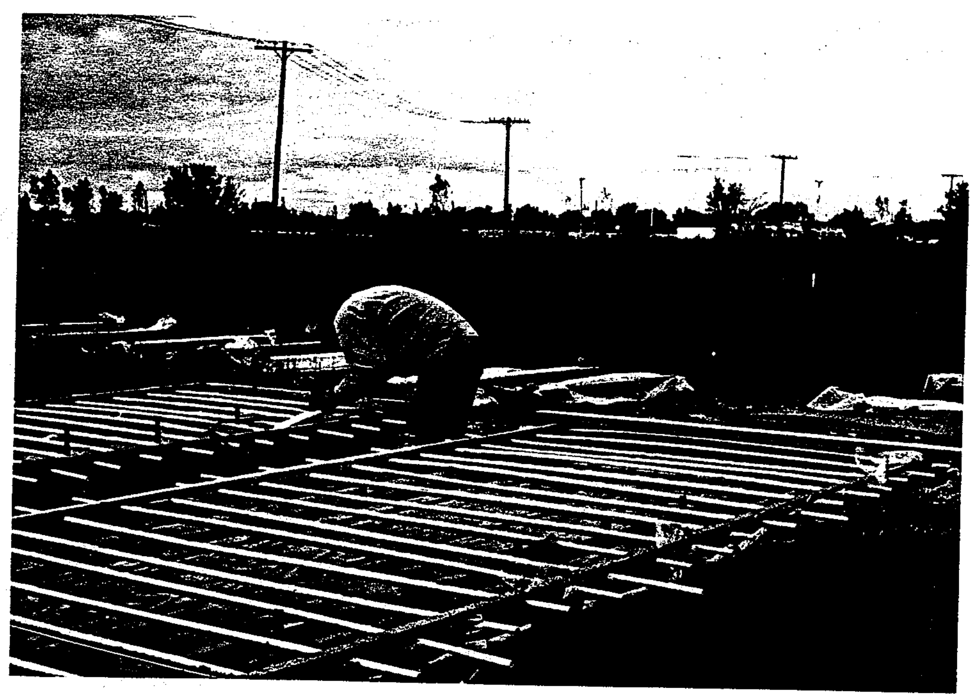

Figure 8) Photo showing the PVC pipe through which optical fibers were threaded

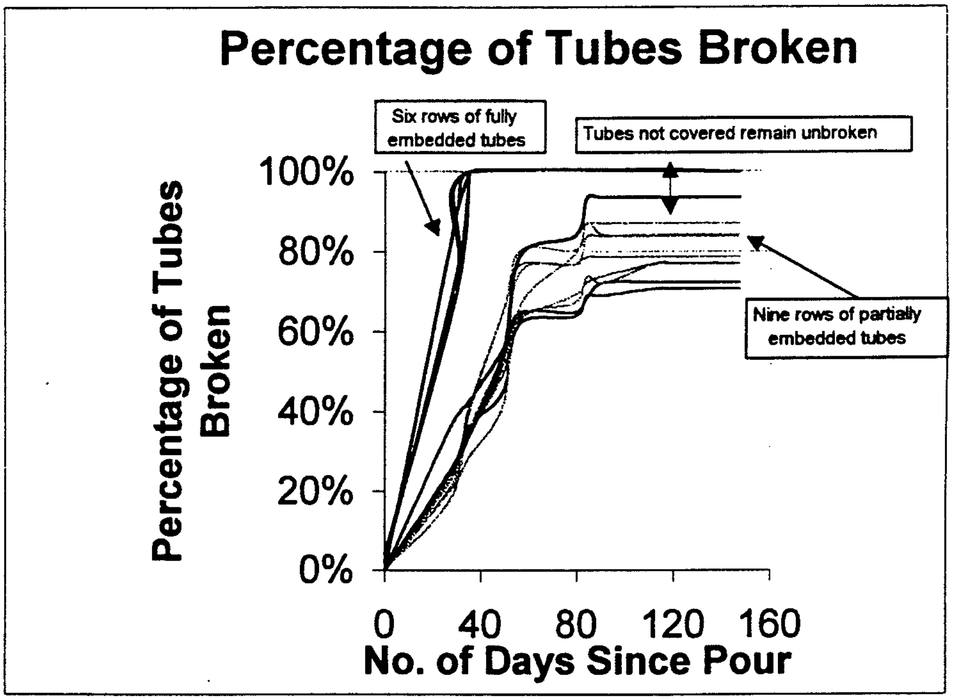

Figure 9) Chart of the percentage of tubes which released sealant over time

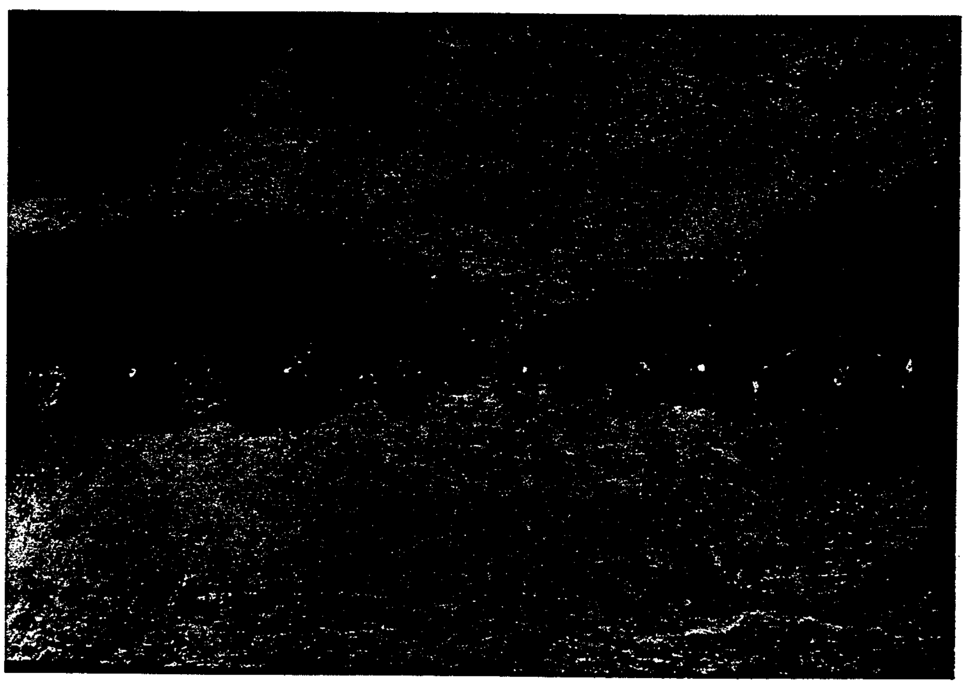

Figure 10) Photo of the control joint line created by the release of sealant from embedded tubes

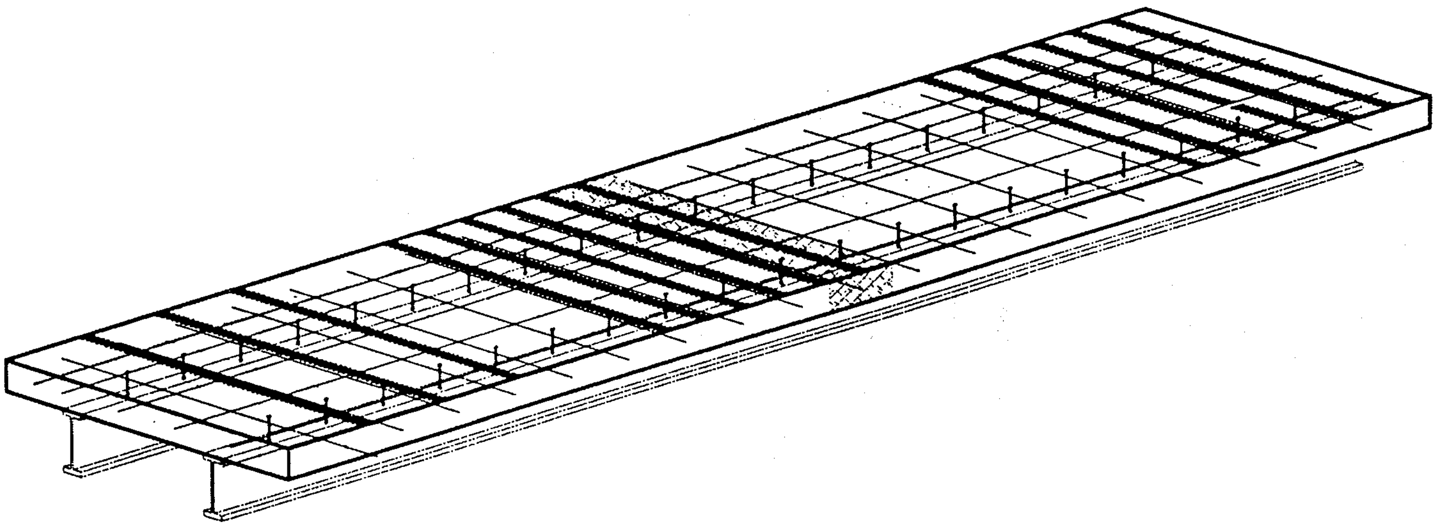

Figure 11) A drawing of the interior structure of decks 1 and 2

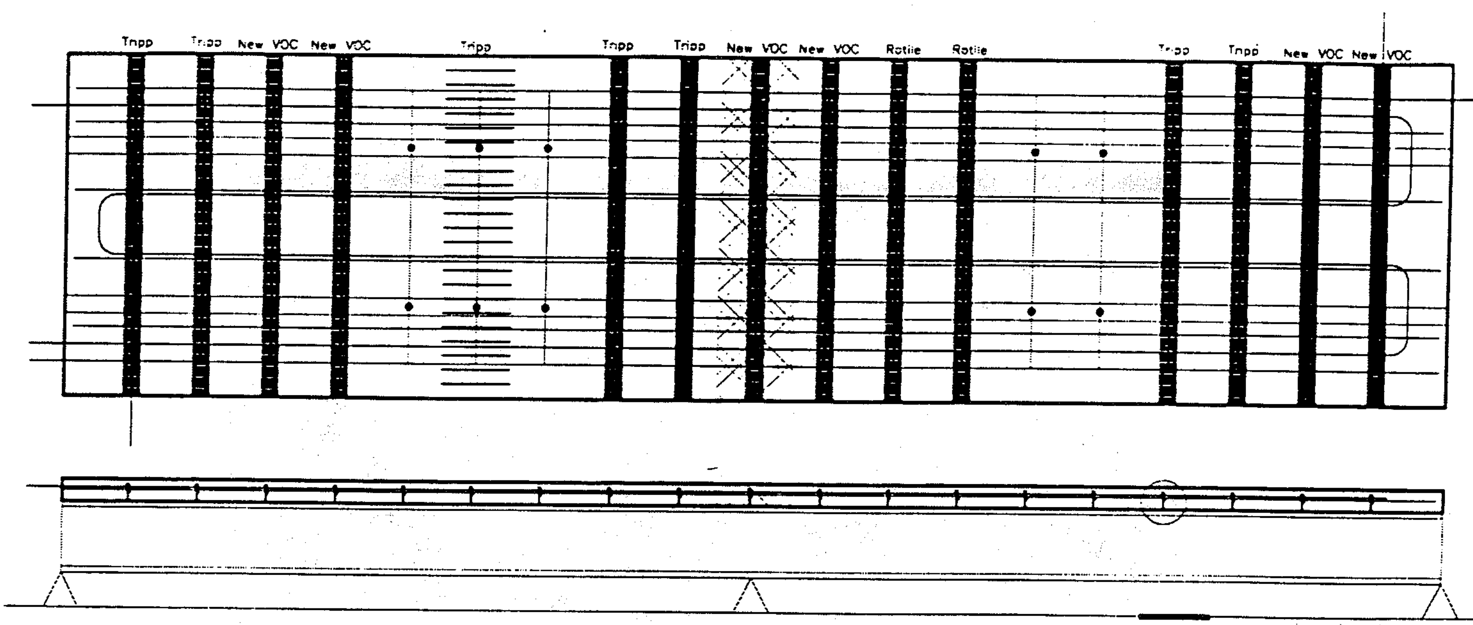

Figure 12) Drawing of the top surface of decks 3 and 4

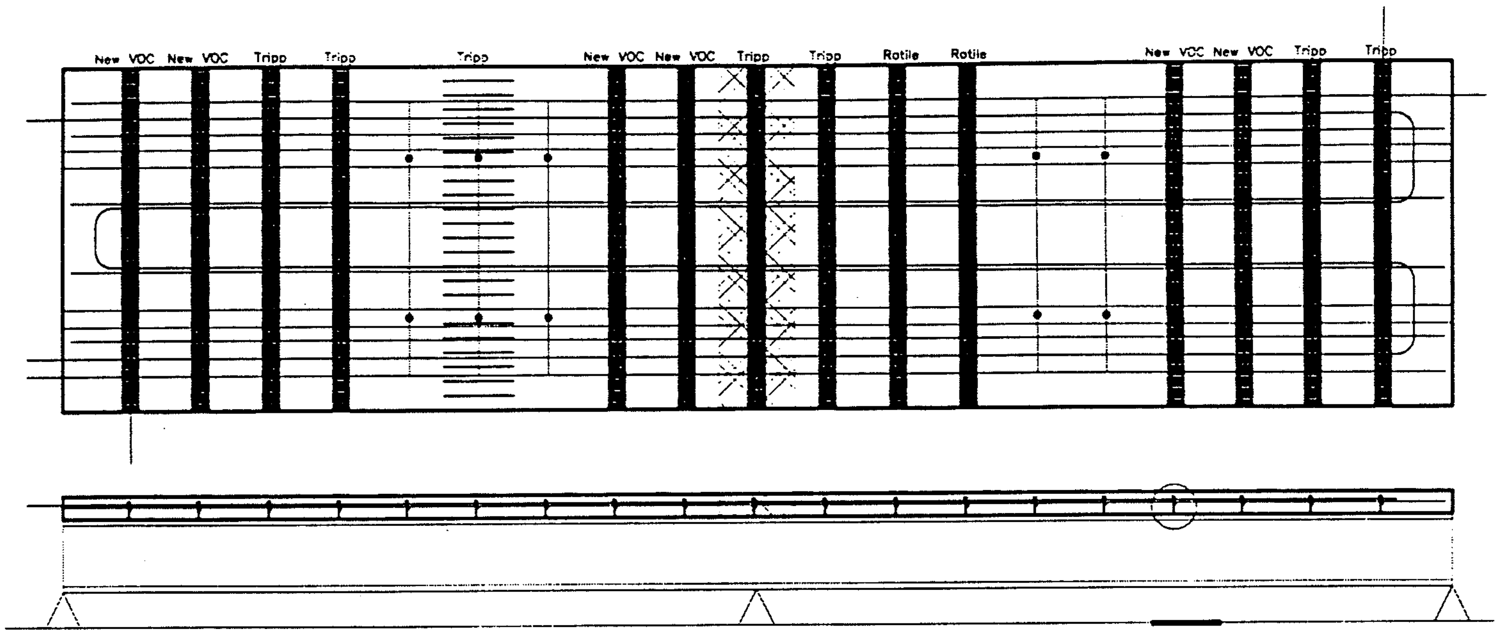

Figure 13) Drawing of the bottom surface of decks 3 and 4

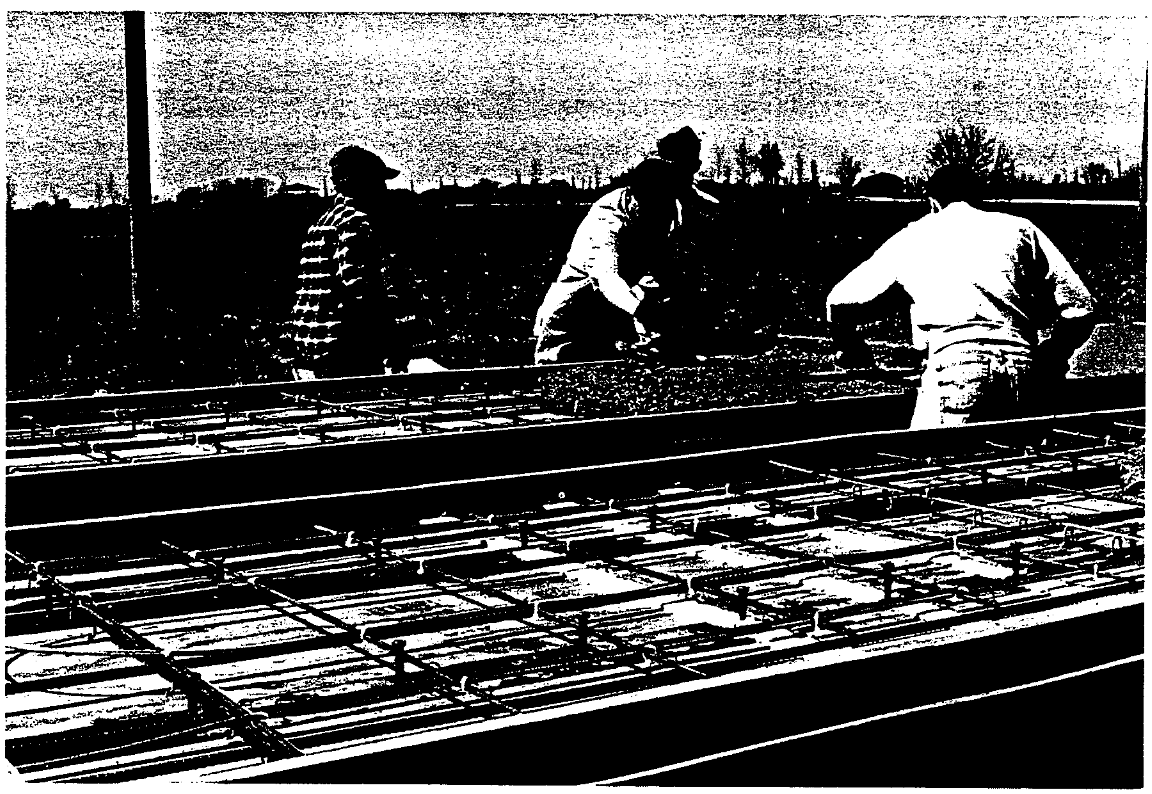

Figure 14) A photo of sealant filled tubes placed in the bottom of the form to be embedded in the bottom surface of decks 3 and 4

Figure 15) A photo of VOC filled tubes ready to be pushed onto the interior of decks 3 and 4 to repair shear cracks

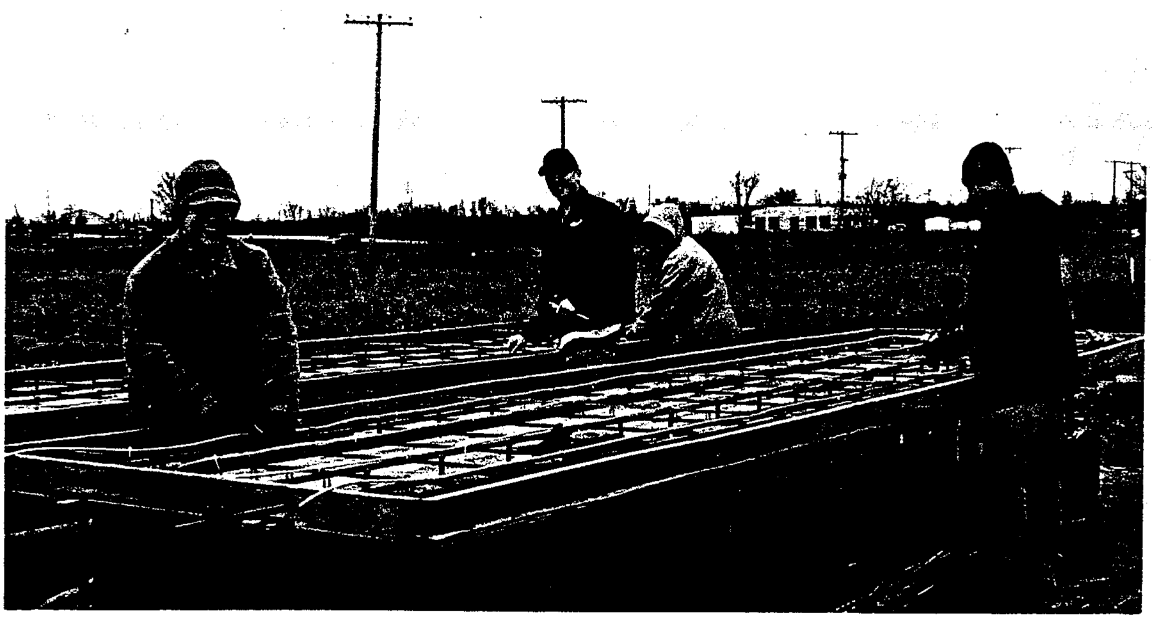

Figure 16) A photo showing ETDR cables which were looped four times through each deck and read as one long continuous cable.

III.) Testing of Full Scale Bridge Decks For Repair of Shear Cracking.
IDEA Product; Concept and Innovation

This research focuses on the repairing of structural load-induced cracks in the four full-scale bridge decks and some structural beams. Capsules containing stronger, high modulus adhesives were placed below the surface in areas of tension caused by bending, for example the top of the section over supports. Structural cracks which were induced by loading were successfully repaired as evidenced by higher strength than a tested control deck without adhesives and by the creation of new cracks in some places where the old repaired cracks had not reopened.
The same four decks that showed the repair system's effectiveness in dry shrinkage crack repair, were loaded in bending to study the repair effectiveness on structural cracking.

The bridge decks were loaded 3 times and the beams were loaded 2 times, allowing time in between tests for the repair adhesives to set. From these test results, the strength gain and/or behavioral changes were able to be assessed.

Methodology - Loading
A simple method was devised to induce structural cracking in the decks. The steel I-beams, which were composite with the deck, were sawed through at mid-span to eliminate the additional strength offered by this composite system. However, the top flange was still embedded in the deck, and would therefore offer significant additional tensile reinforcing at the bottom of the slab, if load was applied at the top of the deck. The load was applied upward at the mid-span of the deck with a pneumatic jack. (See figure 1)

This jack replaced the initial middle support. In most cases, the ends of the deck were tied down to prevent uplift. As seen in figure 1 an 18" long steel, T-shaped steel member was placed transversely at the deck mid-span, with its flange against the deck bottom and its wide web balance on the 1" diameter jack head. The jack supplied an upward load that was measured by the force in the cylindrical base. A 1000 psi pressure converts to 0.785 kips at the deck mid-span.

Methodology - Monitoring
These applied loads were recorded in sequence, as were the resultant upward deflections of the mid-span of the deck. Deck cracking was also monitored visually and measured with a crack caliper. ETDR cables embedded in decks 3 and 4 were used to internally monitor cracking.

Based on the deck dimensions and materials, the following behavior was approximately expected: Initially the deck is only subjected gravity causing bending with tension in the bottom of the deck. The upward jacking force is then applied. Once a jacking force of approximately 0.80 kips (1000 psi) is reached, the deck is in equilibrium (no bending). Any force beyond this, put the deck into the opposite bending, causing tension at the top of the deck. As the concrete can withstand a certain amount of tensile forces before cracking, it is assumed that at jacking force of approximately 1.45 kips (1800 psi) would cause cracking in the top of the deck.

These calculations were based on the assumption of a uniform 3" thick by 4' wide deck of 150pcf concrete. However, these seem to over-estimate the actual strengths which follow (by 20-50% for the cracking strengths and nearly 0% - 40% for their equilibriums). The equipment used for acquiring loads and deflections allow for as much as 10% error in measurement precision. Crack width has similar limitations. The most precise data will be acquired through the ETDR system; it will be correlated with the other results.

Investigation; Results
Testing Results
All four decks were tested three times each in bending. The data is summarized in the table at the end of this paper.

First Break: Deck #3 and #4 June 25 1998

On June 25th the second set of bridge decks (deck #3 and #4) was broken. They had been poured on April 10th and were therefore approximately 2-1/2 months old. The day of the break, it was very humid and hot (about 95°F). The data for this first break of decks #3 and #4 is included in a summary table for all bridge deck break data.

Deck #3

Deck #3 has several hundred TRIPP-filled capsules embedded randomly through a two foot wide section at mid-span of the deck's length. It also has a transverse row of longitudinally aligned capsules with VOC, just beneath the top surface of the decks. These are within the tensile zone during load-induced bending.

The ends of Deck #3 were tied to the ground with a continuous chain before applying the jacking force, and an ETDR reading was taken. The mid-span of the deck was then forced upward. After jacking the mid-span up 1" to a pressure of 1000 (0.785 kips), the deck was held in position for 4 minutes while a second set of ETDR data was taken.

The mid-span was then jacked further, to 1500 psi (1.178 kips), at which point the deck yielded or cracked so that it would no longer take additional loading. The embedded repair adhesive could be seen out through the continuous transverse crack at mid-span on the top of the deck. Circles of it came to the surface at least every ½". The deck was held there for another 4-5 minutes, while a third set of ETDR data was taken.

The deck was then gradually released down to 1100 psi (0.864 kips) and a fourth ETDR reading was taken. More glue released, forming puddles of an average diameter of ½", and dried within 4 minutes. Finally the deck was released of any loading and a final set of ETDR was taken.

Deck #4

While deck #3 contained VOC glue at its surface and through its section, deck #4 had Tripp on its surface and nothing through its section. Deck #4 was tested following the same procedure used in deck #3. After jacking the mid-span up 1" deflection to a pressure of 1000 psi (0.785 kips), ETDR data was taken.

The mid-span was again jacked until a transverse crack (like that seen in deck #3) appeared at 1500 psi (1.178 kips). However, only one half of the transverse crack and another 6" of length on the other end, actually opened enough to visually reveal adhesive released. After taking a second set of ETDR data, the deck was again released to 1100 psi (0.864 kips). The third ETDR reading for this deck was taken. Still, only a slight amount of the glue was visible. The deck was then completely unloaded. Then circles of the repair adhesive began to appear on the surface, coming up from within the deck. However, there was not as much adhesive as in deck #3; the released puddles were about ¼" diameter and continuous.

First Break: Decks 1 and 2 - September 18, 1998

The first set of decks (decks #1 and #2) was broken at a later date, following the same method used on decks #3 and #4. Deck #1 had VOC embedded at its surface, and cyanoacrylate repair capsules through its section. It broke at approximately 1250 psi (0.982 kips), at a deflection of 5/8". Deck #2 was the control deck, and contained no repair adhesives. It broke at approximately 1200 psi (0.942 kips), at a deflection of 1/2". This data for decks #1 and #2 is included in a summary table for all bridge deck break data.

Second Break: Decks 1, 2, 3 and 4 - October 29, 1998

All four bridge decks were loaded again on October 29, 1998. This would test how much effect the repair adhesives and sealants had on the decks for repairing load-induced cracks. Two of these decks had been poured over one year ago; the other two were over 6 months old. All four decks had been loaded to failure previously: decks 1 and 2 on September 18th, 1998 (2 months previously), and decks 3 and 4 on June 25th (4 months previously). One concern with these repair chemicals in the field was their longevity, however even after as long as one year, there was still liquid adhesive released during this second loading.

Deck #1

Deck #1 originally broke at 1250 psi (0.982 kips). The crack from the first loading remained closed under this second loading until 900 psi (0.707 kips). At that time, only the eastern 2/3 of the original transverse crack reopened to 0.007 inches, and glue was released. However, the western 1/3 of the original crack, where adhesive had been released during the first test, remained closed. A slight increase to 1000 psi (0.785 kips) widened the eastern 2/3 of the original crack to 0.010 inches, while a secondary parallel crack (0.007 inches) opened 7 inches offset form the 1/3 of the original crack that remained repaired.

This correlates with results from earlier loading. At that time, glue was seen as it released in the western 1/3 of the transverse crack at mid-span. This glue repaired the original crack in this region, allowing it to gain strength beyond the rest of the concrete matrix. Under a second loading, this repaired portion did not reopen. In fact it remained closed as the failure was actually diverted to a previously intact portion of the deck.

In the reopened crack, visibly more repair adhesive was released. The new offset cracks showed slight signs of adhesive release.

Deck #2

Deck #2 was the control, and therefore had no strength gain, as anticipated. After failure from the first loading, additional loading was unable to be held. Whereas deck #1 was able to reach 1000 psi (0.785 kips) before cracks reopened or new ones were formed, cracks in deck #2 reopened as soon as the dead load of the deck was overcome by mid-span upward loading. By a loading of 800 psi (0.628 kips) the crack widths were about 0.010 inches.

Deck #3

This deck, with VOC at the surface and Tripp through the section, did not appear to repair as well as Deck #1; no portion of the crack remained closed or was diverted under secondary loading. The original transverse crack did not reopen until a load of 1000 psi (0.785 kips), at which time it was measured at 0.010 inches. The crack continued to widen under loading.

No apparent crack repair occurred in this deck. The re-opened crack did again release VOC under this second loading as it had under its first loading as seen in figure 2. Therefore, it seems that the VOC releases as necessary, but does not supply desired strength gain properties.

Deck #4

Deck #4, which had Tripp repair adhesive embedded just below its surface and nothing through its section, showed more successful signs of structural crack repair than deck #3. The original crack remained closed under this second loading until a load of 1100 psi (0.864 kips). At this time, the outside 16" of the transverse crack reopened to a width of 0.004 inches; a new 0.007 inch crack opened 6" offset from the original crack in the middle 28" of the transverse crack. A slight load increase to 1200 psi (0.942 kips) caused the original crack to then reopen in this middle section, to 0.004 inches, while the new crack widened to 0.007 inches. At this load, the outside edges of the original crack were opened to approximately 0.0101 inches.

Third Break: Decks 1, 2, 3 and 4 - November 20, 1998

Just three weeks later, all four bridge decks were loaded for a third time, to test the effectiveness of the repair adhesives in repetitively repairing load-induced cracks.

Deck#1

Deck #1 held its strength, much like the previous re-loading. At the east end, the primary crack reopened and released glue. On the west end, the primary crack reopened, but the secondary crack remained closed through most of the loading. This seems to indicated that the secondary crack (approximately 7" offset from the primary crack), was repaired by the cyanoacrylate embedded in a 2 foot section of the bridge deck.

There was a decrease in the overall load capacity from the first and second loadings (1250 psi or 0.982 kips) to 1100 psi (0.864 kips).

Deck #2
Under this third testing, the control deck behaved the same way it had under the second loading. This is as expected.

Deck #3
Bridge deck #3 released a modest amount of new adhesive (dots 1/16"in diameter). This was concentrated in the western 18" of the transverse width. There was a decrease in the overall load capacity from the first and second loadings (1500 psi or 1.178 kips) to 1200 psi (0.785 kips).

Deck #4
Deck #4 released adhesive all along its transverse length in this third loading. The primary crack in the middle of the transverse length opened first. The rest of the primary crack and the entire secondary crack re-opened under additional loading. Larger amounts of adhesive (1/4"-1/2" diameter dots) appeared along the primary transverse crack, with most of it outside the middle third of the crack's length.

There was a slight decrease in the load capacity from the first loading (1500 psi or 1.178 kips) and second loadings (1800 psi or 1.414 kips) to 1700 psi (1.335 kips).

IDEA Product: Technical Progress Made During the Investigation
Assessment of Results and Conclusions
1. Crack Diversion
The most successful evidence of the structural crack repair capabilities of this system are the diverted cracks in the second loadings of decks #1 and #4. In both cases, original cracks from the first loading were repaired; secondary cracks opened, at least in portions, during the second loadings before the primary cracks did reopen.

In both cases, the secondary cracks were offset 7" from the original cracks. Based on calculations: the tensile forces at the centerline of the deck centerline are about 125% of those just 7" from the when cracking is expected in the deck. This calculation was done assuming that cracks occur at approximately 350 psi tension in the concrete. When the centerline is under 350 psi, only 280 psi is acting just 7" over. However, no cracking occurred at the centerline then. By the time 7" offset region reaches 350 psi, the centerline is at 437 psi. Although these calculations overestimate the actual values at which the concrete cracks opened, the proportions between the forces at the centerline and 7" offset are still viable.

Therefore, the repaired cracks must have been strengthened to nearly 125% of their original concrete strength, in order to remain closed and cause the crack to be diverted.

Since decks #1 and #4 contained different repair adhesives, both of their repair systems must be considered. Deck #1 had VOC at its surface and cyanoacrylate through its section. As the VOC of deck #3 did not cause any cracks to be diverted, the crack diversion in deck #1 can be attributed to the cyanoacrylate throughout the section. Deck #4 had only Tripp on its surface, no other embedded adhesives, which can be credited with diverting a portion of its structural crack under second loading. In the third loadings of these decks, no new cracks were formed; however the secondary cracks showed signs of repair as they re-opened after the primary cracks re-opened under this third loading.

Where secondary cracks did not form, the original cracks re-opened to a width equal to the sum of the primary and secondary cracks in the repaired regions.

2. Strength Gain
Compared to the second and third loadings of the control deck, #2, which contained no repair adhesives, decks #1, #3, and #4 all showed signs of bending strength re-gain in their later tests. Deck #1 reached its initial load capacity (1250 psi or 0.942 kips) during the second loading. However, during its third loading, it reached only 88% of that capacity (1100 psi or 0.864 kips).

Deck #3, which had no signs of structural crack repair through crack diversion, did seem to regain all if its initial bending strength during its second loading (1500 psi or 1.178 kips). It reached 80% of its initial strength during its third loading (1200 psi or 0.942 kips). Deck #4 exceeded its initial bending strength (1500 psi or 1.178 kips) in both the second and third loading, by 20% and 13% respectively at 1800 psi (1.414 kips) and 1700 psi (1.335 kips).

Failure- final
mode load

Strength Increase

Deck #	1st Load (kips)	2nd Load (kips)	% change	3rd Load (kips)	% change
1	1250	1250	0%	1100	-12%
2	1200	800	-33%	800	-33%
3	1500	1500	0%	1200	-20%
4	1500	1800	20%	1700	13%

Micro- .007
crack

Strength Increase – crack width = 0.007"

Deck #	1st Load (kips)	2nd Load (kips)	% change	3rd Load (kips)	% change
1	1250	900	-33%	700	-25%
2	1200	750	-37%	800	5%
3	1500	1100	0%	900	-25%
4	1500	1200	20%	1200	0%

Macro- .012
crack

Strength Increase – crack width = 0.007"

Deck #	1st Load (kips)	2nd Load (kips)	% change	3rd Load (kips)	% change
1	1250	900	-33%	700	-25%
2	1200	750	-37%	800	5%
3	1500	1100	0%	900	-25%
4	1500	1200	20%	1200	0%

Failure

Strength Increase – crack width = 0.007"	Between Not done	2nd and 3rd loads			
Deck #	1st Load (kips)	2nd Load (kips)	% change	3rd Load (kips)	% change
1	1250	900	-33%	700	-25%
2	1200	750	-37%	800	5%
3	1500	1100	0%	900	-25%
4	1500	1200	20%	1200	0%

These strength gains might be attributed to sealing the cracks and increasing the concrete's tensile capacity significantly, or more likely, improving the bond between the concrete and the embedded reinforcing steel. The means utilized to measure these load capacities are inexact, with 10% margin of error possible. However, it is evident, especially between the decks #1 and #2, which were poured at the same time and were identical except for the repair adhesives in deck #1, that strengths were higher in later testing when compared to the control.

The presence of glass tubes within the concrete does not seem to adversely affect the strength of the decks. As evidence, decks #1 and #2 failed under virtually the same load during their first loading. Another note regarding the cracking in the deck is the additive properties where two cracks occur. As the two cracks' widths add up to the total width of the crack where only one crack occurs in the same deck. This is the evidence that these crack widths are not arbitrary, but the reflection of structural loads (and failure) of the deck.

3. Re-release of repair adhesives in second and third loadings

In all of the decks containing repair adhesives, subsequent loadings revealed additional adhesive release all along the re-opened crack. These adhesives survived for over 1 year in field conditions ranging from below freezing to over 100°F. The adhesives in all three decks released during loading under varied temperatures up to three separate times. Decks #3 and #4 were particularly successful in re-releasing glue.

There are two possibilities. The first is that as the tubes cracks, it releases enough of its adhesive to seal the crack, and then reseals the tube, protecting the remainder of the unreleased adhesive. If this is true than the number of times each tube can repair cracks can be assumed as follows:

$$\text{Number of Times to Repair} = \frac{\text{Total Volume of Glue in Tube}}{\text{Total Volume of Repaired Crack}}$$

The second possible explanation is that only some of the tubes break during each loading, leaving additional unbroken tubes for later crack repair. In any case the cracks were able to be repaired multiple times with this system by excess adhesive available in all sorts of field conditions.

4. Size of Structural Cracks

The size of cracks (length and depth) is a critical factor for the volume of adhesive necessary for repair to be effective; but the force, time and size of crack re-opening is also important. The distance from the repair adhesive source is also important since the adhesive must move from the encapsulator to the crack. These structural surface cracks, which were up to 0.050 inches wide, were able to be sealed and repaired by adhesive. Only a small volume of adhesive was needed to fill the crack. Furthermore, this small distance was capable of being bridged by the adhesive in its liquid state without extensive adhesive loss through leaking and dripping.

Regarding the location of the embedded tube in relation to the crack, decks #1, #3, and #4 should again be noted. The cyanoacrylate embedded in #1 deck section was able to repair structural cracks, which obviously begin to open and are widest at the top, but do continue down into the section. However, Tripp at the surface of deck #4 was effective in structural crack repair, but it was not effective when embedded through the section of deck #3. Tripp is not as strong as cyanoacrylate. Tripp was effective when optimally placed for repairing these structural bending cracks where they open first and widest, at the deck's tension surface. Cyanoacrylate was strong enough and fluid enough to permeate and repair these cracks from within the deck section, while Tripp was either not strong enough or too viscous to permeate upward in to repair these cracks.

The effectiveness of the crack repair system for a particular crack is a function of crack volume both depth and length (Vc), location of repair adhesive source (distance from mouth of crack)(Dc), viscosity of the repair adhesive compared to water and therefore ease of flow(p), volume of embedded repair adhesive remaining (Vr), and the dynamics of crack opening (F) including vacuum force, time, and size or width of crack opened

$$\text{Effectiveness of filling a particular crack with adhesive} = \frac{(Vr)}{Vc * Dc * p * F}$$

The size of the crack seems to dictate the amount of adhesive released in another way. Adhesives appeared first in the largest cracks. These largest cracks tended to have opened first also. Therefore, the larger cracks had more size, time and vacuum force to pull adhesive in for repair.

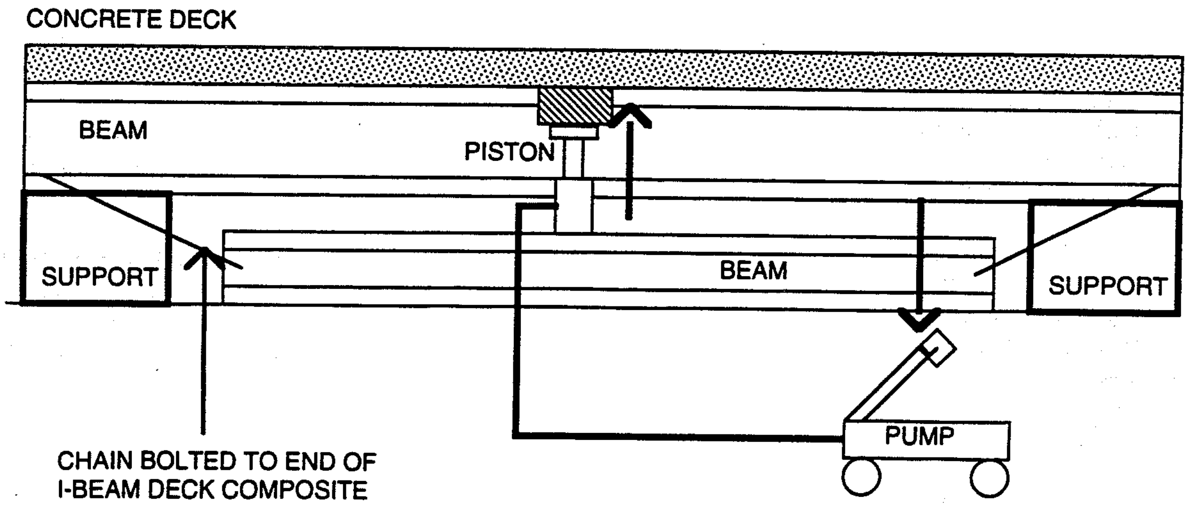

Figure 1) drawing of experimental testing test set-up to test concrete decks in bending

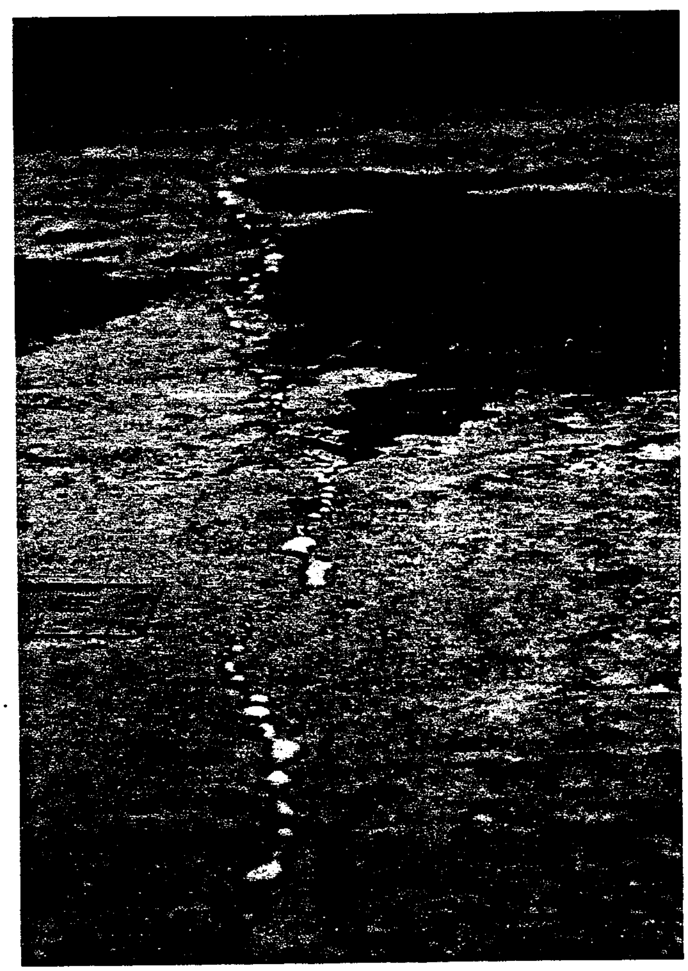

Figure 2) photo of release of adhesive into crack on second testing for release of adhesive when subjected to upward bending, deck #3 with VOC embedded

IV) Testing of Large-Scale Beam Samples in Bending

IDEA Concept and Innovation; Impact of the Investigation

Methodology

A set of ten beams was loaded in bending on full-scale test apparatus

Ten 6"x6"x6'-0" concrete beams were tested as another means of determining the structural crack repair capabilities of this system of embedded repair adhesives. Two #2 smooth reinforcing bars were embedded in the bottom half of these member section. Empty glass tubes were also embedded in the bottom half of most of these members. The ends of these tubes were open to allow filling with crack repair adhesive either before or after loading. The on site casting of these beams can be seen in figure 1.

Each beam was placed in three point bending over a 5 foot span. Each member was loaded in bending until its structural crack passed nearly through its section. Any introduced repair adhesives were then allowed to set ups and the beams were tested again under three point bending for comparison.

Testing Results

The following table summarizes the repair adhesive content, testing, and behavior of these 10 beams. Graphs offer additional means for comparison of their behaviors.

		1st Test	2nd Test
Beam #1:	**Control** No glass, no adhesive	11/10/98	11/24/98
Beam #2:	**Control** No glass, no adhesive	11/10/98	11/24/98
Beam #3:	**Tripp** – Filled 11/9/98 streamed out 1st test	11/10/98	11/24/98
Beam #4:	**Cyanoacrylate**- 10/19/98 only in 2 of 3 tubes,	09/22/98	11/10/98
Beam #5:	**Control** Glass tubes, no adhesive	11/10/98	11/24/98
Beam #6:	**Elmers glue** – 10/19/98 only in 2 of 3 tubes, hard to fill	09/08/98	11/10/98
Beam #7:	**VOC** – Filled 10/19/98 in 3 glass tubes	09/22/98	11/10/98
Beam #8:	**VOC** – Filled 11/09/98 in 3 glass tubes	11/10/98	11/24/98
Beam #9:	**Control** Glass tubes, no adhesive	09/08/98	11/10/98
Beam #10:	**Tripp** – filled 11/09/98 in 5 glass tubes	11/10/98	11/24/98

Beam #1

Beam #1 was a control and behaved as expected. There was no strength gain or crack repair between first and second loadings.

During the first loading, the beam sustained loads to 8000 lbs (8 kips), before experiencing a capacity loss. This sudden drop-off coincides with the point where the steel yielded or the bond between the concrete and steel failed. Under continued loading, the beam actually reached a maximum of 9000 lbs; but it was unable to hold this load as its already large deflection continued to increase.

The second loading showed no initial strength. Only under significant, and growing, deflections was it able to reach just over 8 kips.

Beam #7
Beam #7 showed the most significant signs of strength re-gain between its first and second loadings of any of the beams.

During the first loading, the beam sustained loads to nearly 9000 lbs (9 kips), before experiencing a capacity loss. Under second loading, the beam actually reached a maximum of 9000 lbs again, and with little more deflection than in the first test. The steep slope of the graph, nearly parallel with the first loading, indicate a study rise in capacity with little deflection. However, once the load reached just over 9000 lbs, the beam was unable to hold this load as its deflection increased indefinitely at this load.

Beam #10
Beam #1also showed signs of strength regain, especially in behavior under second loading. During the first loading, the beam sustained loads to nearly 9000 lbs (9 kips), before experiencing a capacity loss. Under continued loading, it did again reach over 10,000 lbs (10 kips) in capacity, but only under indefinite deflections.

In the second loading, the beam actually reached nearly 14000 lbs (14 kips) again, where it then experienced some capacity loss like that seen in the first loading of all of the beams. This indicates a possible loss in the bond between the steel and concrete again. This indicates that this bond would have been repaired between tests, since it had already been failed under the first loading. The slope of the graph was also shallower however, and at 13,000 lbs. (13 kips) large deflections increased indefinitely.

Assessment of Results
Most of these beams did not show significant signs of structural crack repair or strength gain for one primary reason. The first loadings allowed the beams to fail, then continue to deflect under sustained load, creating large structural cracks. Some of these cracks reached 1/3" in width. None of the repair adhesives were capable of bridging such distance, as most adhesive would leak out such cracks before drying or setting.

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Conclusions

Most of these beams did not show significant signs of structural crack repair or strength gain for one primary reason. The first loadings allowed the beams to fail, then continue to deflect under sustained load, creating large structural cracks. Some of these cracks reached 1/3" in width. None of the repair adhesives were capable of bridging such distance, as most adhesive would leak out such cracks before drying or setting. The initial cracking up to failure were smaller. These may have been repairable. But once the sudden structural failure occurs, the beam continues to deflect and cracks grow under the sustained loading, creating unrepairable cracks.

However it is interesting to note that a few of the beams did show some signs of strength regain. Under its second loading beam #7, which contained VOC, showed a steeper initial slope than the most of the other beams, indicating that it not deflecting as much under increased loadings b. **As these structural cracks were too large to be repaired, the repair adhesive must have been aiding in the bond between the concrete and the embedded reinforcing steel (rebar).**

Beam #10, which contained Tripp, the second loading actually reached a higher capacity, and showed a peak with a drop off. This also indicates a possible improvement, and then eventual failure, in the concrete and reinforcing steel bond.

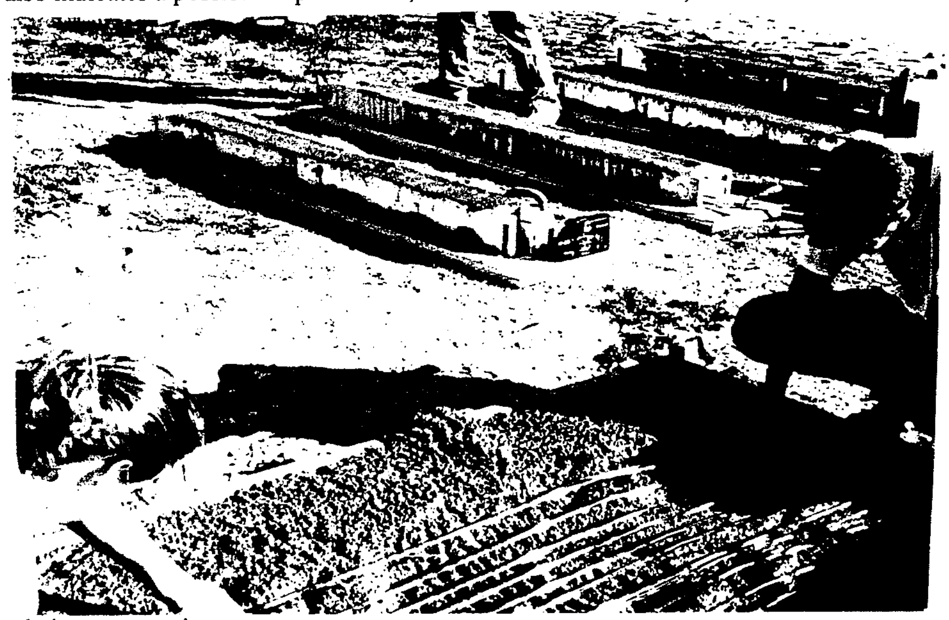

Figure1) Photo of the beams being cast on site

2.1.6 Conclusions

The concept is to repair bridges and pavements while in service by the internal time release of repair chemicals. Four specific applications for this concept were investigated in this laboratory and field based research. In frames in the laboratory, it was shown that cracks repaired will cause other areas to crack when stressed thus driving the cracking around the structure, utilizing much of the material strength but preventing catastrophic failure in any one location. In four full-scale bridge decks, the chemical releasing tubes were put near the surface to function as creators of automatically fillable control joints. Surface shrinkage cracking acted to pull the brittle tubes apart and the sealant/adhesive flowed to fill the cracks. Thirdly the adhesive filled brittle tubes were placed in the body of the decks to break due to shear cracking and repair these cracks. This type of release not only strengthened the decks in most cases but also drove the expression of strain to new locations for crack formation. Large beams containing adhesive filled tubes were also tested to failure in the lab. These results were rather inconclusive but suggest that some added strength after the adhesive is released may be due to re-bonding of the rebars.

Some of the other accomplishments were to answer questions affirmatively about efficacy of release, survival of filled tubes in the cement mixer, maintenance of a liquid phase of the adhesive, ease of finishing the cement, and demonstration of the concept in three different locations.

2.1.7 Investigator Profile

Work by the Principal Investigator, Dr. Carolyn Dry, on Self Healing Materials

1)Honors, Awards for research on self healing materials

University Fellow, Oak Ridge National Laboratory, Metals and Ceramics Division, Summer 1987
Faculty Achievement Award, College of Fine and Applied Arts, UIUC, 1991
P/A Award for Architectural Research, *Progressive Architecture*, 1995
Research work on time release of chemicals filmed by PBS, 1994;

2)Invited Lectures and Invited Conference Presentations on self healing

Seminar Leader, "Research on Timed Release of Chemicals into Cement," National Science Foundation, National Advanced Cement Based Materials Center, Northwestern University, Evanston, Illinois, 1993
Taught short session on "Timed-Release Smart Materials," University of Strathclyde, Glasgow, Scotland, 1994
Lecturer on Research, "Timed-Release of Adhesives for Cement Repair," W. R. Grace, Co., Cambridge, Massachusetts, 1994
Lecturer on Research, "Repair of Polymers by Internal Time Release of Adhesives," B. F. Goodrich Co., Cleveland, Ohio, 1994
Keynote Speaker, "Smart Materials," Region 8 Concrete Pavement Conference, North Dakota Department of Transportation, Bismark, North Dakota, 1995
Invited speaker, Fiberoptics Workshop, Newark, NJ, May 1998
Invited speaker, workshop on High Performance Concrete, Mongolia, July, 1998
Invited participant, Gordon Conference on Biomineralization, New England College, August, 1998

3)Grants Received on self healing

Principal Investigator, Virginia Polytechnic Institute and State University, Core Research, Economic Development & Product Center, "Encapsulation of Material Properties in Structural Matrices Using Afrons (biliquid foams)," 1985-86,
Co-Principal Investigator with R. Donahey, "Internal Release in Concrete of Sealant Materials from Fibers," University of Illinois Research Board, 1989-90,
Co-Principal Investigator with V. Li, "Passive Smart Cementitious Composite for Dynamic Control Structures: Internal Timed Release of Chemicals for Self-Repair of Crack Damage," submitted to National Science Foundation/Strategic Highway Research Program in response to Program Initiative on Structural Control Research and done as subcontract to U. of M, 1992-96,
Principal Investigator, "Liquid Core Fibers for Crack Detection in Polymer and Concrete Matrices," National Science Foundation, 1995-96,
Principal Investigator, "In-Service Repair of Highway Bridges and Pavements by Time Release of Repair Chemicals," Transportation Research Board, National Academy of Science, 1996-97,
Principal Investigator, "A Cementitious Material which Forms a Densified, Strong, Protective

Surface National Science Foundation 1998,

Principal Investigator, "Rebonding of Prestressed Tendons in Concrete by Internally Released Adhesives," National Science Foundation, submitted, 1999

4)Chapters in Books on self healing

"Timed Release of Chemicals into Hardened Matrices Cementitious for Crack Repair, Rebonding Fibers, and Increasing Flexural Toughening," Fracture Mechanics, 25th Volume, ASTM STP 1220, F. Erdrogan, editor, pp. 268-282, American Society for Testing and Materials, Philadelphia, PA, 1995

"Monitoring and Repair by Release of Chemicals in Response to Damage," Intelligent Civil Engineering Materials & Structure, an ASCE special publication, 1997 (in press)

"Liquid Core Optical Fibers for Crack Detection and Repairs in Concrete Matrices," Special Technical Publication of Workshop on Fiber Optics, Newark, NJ (in press)

5)Articles in Journals on self healing

"Passive Tuneable Fibers and Matrices," International Journal of Modern Physics B, Vol. 6, Nos. 15 & 16, pp. 2763-2771, World Scientific Publishing Co., Rivers Edge, New Jersey, 1992

"Passive Smart Materials for Sensing and Actuation," Journal of Intelligent Material Systems and Structures, Vol. 4, no. 3, pp. 415-418, Blacksburg, Virginia, July 1993 * "

"Matrix Cracking Repair and Filling Using Active and Passive Modes for Smart Timed Release of Chemicals From Fibers Into Matrices," Journal of Smart Materials and Structure, Vol. 3, no. 2, pp. 118-123, June 1994

"Smart Concrete," Progressive Architecture, July 1995, pp. 92, 93

"Three Part Methylmethacrylate Adhesion System as an Internal Delivery System for Smart Responsive Concretes," Smart Materials and Structures, 1996, pp. 297-300

"Smart Fibers that Sense and Repair Damage in Concrete Materials," Materials Technology, Vol. 11, no. 2, March/April 1996, pp. 52-54

"Procedures Developed for Self-Repair of Polymer Matrix Composite Materials," Composite Structures, 35, Paisley, UK, 1996, pp. 263-269

"Building Materials That Self-Repair," Architectural Science Review, Vol. 40, Melbourne, Australia, June 1997, pp. 45-48

"A Novel Method to Detect Crack Location and Volume in Opaque and Semi-Opaque Brittle Materials," Journal of Smart Material and Structures, Vol. 6, 1997, pp. 35-39

"Crack Healing in Epoxy Matrix Composite Materials by the Internal Time Release of Adhesives," Polymers (resubmittal)

"A Time Release Technique for Corrosion Prevention," Journal of Cement and Concrete, with Melinda Corsaw ,1998

"Two Self-Forming and Self-Repairing Polymer Cementitious Composites," Journal of Intelligent Materials Systems and Structures (resubmittal)

"A Comparison Between Adhesive and Steel Reinforced Concrete in Bending," Journal of Cement and Concrete (in review)

"Detection of Crack Location and Volume in Brittle Opaque Matrix Composites (Using Liquid Released Internally from Hollow Optical Fibers)," Experimental Techniques (resubmittal)

"Self-Repair of Polymer Matrix Composite Materials," Materials Technology, Summer 1998

"Design of Inexpensive Self-growing, Self-repairing Building Construction Materials Which Perhaps Improve the Environment," special issue of the Electronic Green Journal (submitted)

6)Bulletins, Reports, or Conference Proceedings on self healing

Kroner, W., B. Givoni, and C. M. Dry, "Changeable Properties of the Building Envelope--Adaptability to Changing Performance Requirements." Proceedings of the 3rd International

Congress on Building Energy Management, Vol. IV, Lucerne, Switzerland, September 28-October 2, 1987, pp. 101-108

Dry, C. M., B. Givoni, and W. Kroner, "Encapsulation Technology and Building Materials: Enhancing of Adaption to Environmental Change in Aiding the Process of Building." Proceedings of the 3rd International Congress on Building Energy Management, Vol. IV, Lucerne, Switzerland, September 28-October 2, 1987, pp. 117-122

Dry, C. M., "Building Materials, Which Evolve and Adapt Over Time--Use of Encapsulation Technology and Delayed Reactions." University of Illinois, Proceedings of the 1st International Architectural Research Centers Consortium Conference/ARCC '88, Urbana-Champaign, Illinois, November 13-15, 1988, pp. 6-11

Dry, C. M., "Building Materials Which Evolve and Adapt Over Time; Use of Encapsulation Technology and Delayed Reactions." Proceedings of the Conference of International Council for Building Research, Studies and Documentation (CIB), Paris, France, June 19-23, 1989, pp. 391-399

Dry, C. M., "Alteration of Matrix Permeability, Pore and Crack Structure by the Time Release of Internal Chemicals." Proceedings ACS/NIST Conference on Advances in Cementitious Materials, edited by S. Mindess, American Ceramic Society, Inc., co-sponsored by National Institute of Standards and Technology, Gaithersburg, Maryland. Meeting held July 22-26, 1990, Elsevier Publisher, pp. 729-768

Dry, C. M., "Passive Tuneable Fibers and Matrices." Proceedings of the International Conference on Electrorheological Fluids, edited by R. Tao, Southern Illinois University, October 14-15, 1991, Carbondale, Illinois, World Scientific Publishing, Singapore, pp. 494-498

Dry, C. M., "Smart Materials for Sensing and/or Remedial Action to Reduce Damage to Materials." Proceedings of ADPA/AIAA/ASME/SPIE Conference on Active Materials and Adaptive Structures, edited by Gareth Knowles, November 4-8, Alexandria, Virginia, 1991, Institute of Physics, Publishing, London, Great Britian, pp. 191-194

Dry, C. M., "Passive Smart Materials for Sensing and Actuation." Proceedings: Conference on Recent Advances in Adaptive and Sensory Materials and Their Applications, edited by C. A. Rogers and R. C. Rogers, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, April 27-29, 1992, Technomic Publishers, Lancaster, England, pp. 207-223

Dry, C. M., "Smart Building Materials Which Prevent Damage or Repair Themselves." Material Research Society Symposium Proceedings on Smart Materials Fabrication & Materials for Micro-Electrical-Mechanical Systems, Vol. 276, editors A. P. Jardine, et al., San Francisco, California, April 28-30, 1992, Materials Research Society Publishers, Pittsburg, Pennsylvania, pp. 311-314

Dry, C. M., "Smart Materials Which Sense, Activate and Repair Damage; Hollow Porous Fibers in Composites Release Chemicals from Fibers for Self-Healing Damage Prevention, and/or Dynamic Control," Proceedings on First European Conference on Smart Structures and Materials, edited by B. Culshaw, et al., Glasgow, Scotland, May 12-14, 1992, SPIE Volume 1777, Institute of Physics Publishing, Bristol, England, and EOS/SPIE and IOP, EUROPTO Series Publishing Ltd., pp. 367-371

Dry, C. M. and N. Sottos, "Passive Smart Self-Repair in Polymer Matrix Composite Materials," in Smart Structures and Materials 1993: Smart Materials, Proceedings, SPIE 1916, V. K. Varadan, Editor, 1993, pp. 438-444

Dry, C. M., "Time Release of Polymers Inside Concrete to Reduce Permeability," American Concrete Institute Annual Meeting, Minneapolis, Minnesota, November 8-12, 1993

Dry, C. M., "Structural Control During and After Seismic Events by Timed Release of Chemicals for Damage Repair in Composites Made of Concrete or Polymers, First World Conference on Structural Control, Proceedings, Volume 2, edited by G. W. Housner, S. F. Masri, A. G. Orassia, International Assoc. for Structural Control, Los Angeles, California, August 3-5, 1994, pp. TAI-60 - TAI-65

Dry, C. M., "Release of Repair Chemicals from Fibers In Response to Damage in Polymer Composites, Proceedings of First International Conference on Composites Engineering, edited by D. Hui, New Orleans, Louisiana, August 28-31, 1994, pp. 1061-1062

Dry, C. M., "Smart Multiphase Composite Materials Which Repair Themselves by a Release of Liquids Which Become Solids," in Smart Structures and Materials 1994: Smart Materials, Proceedings SPIE 2189, V. K. Varadan, Editor, 1994, pp. 62-70

Dry, C. M., "Adhesive Liquid Core Optical Fibers for Crack Detection and Repairs in Polymer and Concrete Matrices," in Smart Structures and Materials 1995: Smart Sensing, Processing and Instrumentation, Proceedings SPIE 2444, W. B. Spillman, Jr., Editor, 1995, pp. 410-413

Dry, C., "Pavements Which are Self-Healing by the Release of Repair Chemicals Upon Demand," Smart Pavement Conference, Dallas, Texas, December 5, 1995, pp. 52-56

Dry, C. M., "Crack and Damage Assessment in Concrete and Polymer Matrices Using Liquids Released Internally from Hollow Optical Fibers," Smart Sense Processing, Symposium on Smart Materials and Structures '96, Proceedings of SPIE's Smart Structures and Materials Conference, San Diego, CA, February 1996, pp. 448-451

Dry, C. M., "Smart Bridge and Building Materials in Which Cyclic Motion is Controlled by Internally Released Adhesives," Smart Systems for Bridges, Highways, and Structures, Symposium on Smart Materials and Structures '96, Proceedings of SPIE's Smart Structures and Materials Conference, San Diego, CA, February 1996

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Dry, C. M., "Smart Material Which Senses and Repairs Damage in Concrete Materials," Research in Architecture and Planning, Spring '97 Research Conference, Architectural Research Centers Consortium, Atlanta, Georgia, April 24-26, 1997

Dry, C. M., "Improvement in Reinforcing Bond Strength in Reinforced Concrete with Self-Repairing Chemical Adhesives," Smart Systems for Bridges, Structures, and Highways, Proceedings of SPIE's Smart Structures and Materials Conference, 1997, pp. 44-50

Dry, C. M., "X-ray and Fiber Optic Detection of Cracks in Concrete Using Adhesive Released from Glass Fibers," Smart Sensing, Processing, and Instrumentation, Proceedings of SPIE's Smart Structures and Materials Conference, 1997

Dry, C. M., "Damage Assessment Using Liquid Filled Fiber Optic Systems," Proceedings of the Advanced Composites Conference, SPIE, Bangalore, India, 1998

Dry, C. M., "Release of Smart Chemicals for the In-Service Repair of Bridges and Roadways," Proceedings of the Advanced Composites Conference, SPIE, Bangalore, India, 1998

Dry, C. M., "Event Initiated Adhesive Release System to Control Cracking and Repair the Concrete Matrix," Proceedings of the Iyer Conference, Bangalore, India, 1997-98

Dry, C. M. and J. Unzicker, "Preserving Performance of Concrete Members Under Seismic Loading Conditions," Smart Systems for Bridges, Structures, and Highways, Proceedings of SPIE's Smart Structures and Materials Conference, San Diego, March 1-5, 1998

Dry, C. M., "Self Repair of Polymer Matrix Composites for Use as Infrastructure Materials," Proceedings of the International Conference on Composites in Infrastructure," Tucson, Arizona, January 5-9, 1998

Dry, C. M., "Repair of Highway Bridges by Internal Time-Release of Repair Chemicals," Proceedings of Engineering Mechanics: A Force for the 21st Century, La Jolla, California, May 17-20, 1998

7)Abstracts on self healing

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"Encapsulated Water Used to Hydrate Cement," Architectural Research Centers Consortium Directory of Current Research Efforts, M. Kihl, editor, Spring, 1989, p. 23

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"Use of Filtration Fibers for Time Release of Chemicals into Concrete to Promote Durability," American Filtration Society Spring Seminar and Exposition, Rosemont (Chicago), Illinois, May 10-14, 1992, p. 542

"Method of Corrosion Resistance Using Time Release of Chemicals From Fibers into Cement Matrices," Annual Meeting of the American Society of Civil Engineering, Dallas, Texas, October 25-28, 1993

"Time Release of Chemicals From Fibers in Hardened Matrices to Adapt to Changes in Environment," Eighth International Cimtec Conference, Forum on New Materials, Symposium on Smart Materials and Systems, Florence, Italy, July 1-4, 1994

"Time Release of Chemicals From Fibers in Hardened Matrices to Adapt to Changes in Environment," Eighth International Cimtec Conference, Forum on New Materials, Symposium on Smart Materials and Systems, Florence, Italy, July 1-4, 1994

"Smart Earthquake Resistant Materials (Using Time Released Adhesives for Damping, Stiffening, and Deflection Control)," 3rd International Conference on Intelligent Materials, Lyon, France, June 3-5, 1996

Conference on Smart Materials, Barcelona, Spain, May 1996

"Engineering of Polymer Composites for Self-Repair," Fourth International Conference on Composites Engineering, July 6-11, 1997, Kahala Coast, Hawaii

"Special Fibers That Sense and Repair Damage in Concrete Polymer Materials," International Symposium on Intelligent/Smart Materials II, July 14-17, 1997, Gold Coast Queensland, Australia

"Damping of Brittle Matures by Movement and Changes of Electrorheological Fluids Contained in Hollow Fibers," International Conference on ER Fluids, MP Suspension, and Their Applications, Yoweyawa, Japan, July 22-25, 1997

"Self-Repair of Polymer Matrix Composite Materials," 5th Japan International SAMPE Symposium Exhibition, Tokyo, Japan, October 28-31, 1997

. 8)Papers Delivered at National/International Conferences on the topic of self healing

"Low-weight-to Strength Ratio Ceramic Materials for Construction," 90th Annual Meeting and Convention, Canadian Ceramic Society, Toronto, Ontario, Canada, February, 1992

"Timed Release of Chemicals from Hollow Porous Fibers in Cement and Polymer Materials," 24th Annual Meeting of the Fine Particle Society, Chicago, Illinois, August, 1993

"Method of Corrosion Resistance Using Time Release of Chemicals From Fibers Into Cement Matrices," Annual Meeting of the American Society of Civil Engineering, Dallas, Texas, October, 1993

"High Performance Concretes for Tall Buildings," International Conferences on Tall Buildings, Rio de Janeiro, Brazil, May, 1993

"Passive Smart Cementitious Composites Using Time Release of Chemical to Repair Cracks and Rebond Fibers," ARCC Spring 1994 Conference on Contemporary Themes in Architectural Research, School of Architecture and Planning, Howard University, Washington, DC, April, 1994

"The Self Forming Organization of a New Type of Bone-like Biomimetic Material," Symposium on Smart Materials and Structures '96, San Diego, CA, February 1996

"Self-Repairing of Composites by Internal Release of Chemicals," 42nd International SAMPE Symposium, 1997

"Two Self-Forming and Self-Repairing Polymer Cementitious Composites," SPIE Smart Structures & Materials Conference on Biology and Materials, San Diego, CA, February 1996

"Event Initiated Adhesive Release Systems to Control Cracking and Repair the Concrete Matrix," ASCE Conference on Smart Materials, Washington, DC, 1997

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Andrew Pollack, The Age of Smart Materials, "Someday Bridges May Have Feelings Too," *New York Times*, February 16, 1992, p. 6

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