IDEA

Innovations Deserving Exploratory Analysis Programs

Highway Program

Adhesion Tool for Overcoating Risk-Reduction Analysis

Final Report for Highway-IDEA Project 74

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INNOVATIONS DESERVING EXPLORATORY ANALYSIS (IDEA) PROGRAMS
MANAGED BY THE TRANSPORTATION RESEARCH BOARD (TRB)

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TABLE OF CONTENTS

LIST OF FIGURES

BACKGROUND

Overcoating an existing bridge coating system can be an economical solution to maintain bridges. Overcoating eliminates the costs for coating removal of old, often hazardous paint systems that may have been applied decades ago. When applied to a properly prepared bridge, overcoating can extend the time between maintenance painting.

Primarily because of reduced cost and lower impact on the travelling public, overcoating is an attractive option compared to other maintenance painting techniques. However, it is not always the most cost-effective option. This technique requires that the existing coating is well adherent – coating with inadequate adhesion must be removed. Unfortunately, the determination of a well-adherent coating is not an exact science. The mechanisms to evaluate a bridge for overcoating have been developed over many years, but do not always suffice to ensure adequate adhesion.

Disbondment mechanisms in an overcoating project usually appear within one to two years after completion. These are often associated with a rapid change in temperature or are a side effect of the curing of the overcoating paint system. It has been theorized that shear stresses (stresses acting tangential to the coating film) cause the disbondment of the existing coating from the bridge substrate. An investigation of these stresses as a result of overcoating paint system cure was the focus of this research program.

Objectives

The specific objectives of this project were:

1. Identify the stress levels imparted during cure of overcoating systems.

2. Develop a device capable of evaluating coating adhesion using the stress levels identified.

3. Evaluate this device in a laboratory setting.

4. Recommend how to implement the successful device as a standardized adhesion test tool.

CONCLUSIONS

The work performed under this program lends itself to the following conclusions.

1. Shear stress transferred to the substrate can be induced during coating cure. This stress is a measurable phenomenon. The measurement technique is sensitive and easily influenced by external factors. The stresses measured during this program were found to be as high as 9 MPa (1305 psi), the same magnitude as cure stresses measured by other researchers.

2. Conceptually, several devices can be developed using available materials of construction to create stresses in an existing aged coating system. Yet obstacles remain to apply the desired forces to a coating to simulate overcoating stress. Working with a manufacturer of elastomers, adhesion testers and coating inspectors, the development of such devices is possible.

   This project looked in depth at several devices, which were able to impart stresses on coating systems applied to steel substrates. The most promising was an elastomeric device capable of producing stresses above 10 MPa on shim stock, resulting in adhesive failure of the coatings.

   The elastomeric device was not capable of producing 10 MPa stresses over test panels representative of an existing structure. This device was capable of maintaining a near constant level of stress on these panels throughout the monitoring period (as long as 225-minutes). This is the only technique evaluated that is suitable for time-dependent failure evaluation (i.e., is capable of maintaining a constant load over a period of time).

3. The devices evaluated in Stage II of this program have shown promise as tools for evaluating an existing coating for overcoat maintenance coating. Each has technical details requiring further development. The next step towards development of a new adhesion test method should include evaluation of prototype equipment by coating inspectors and researchers.

RECOMMENDATIONS

The following recommendations are made based on the results of this program.

1. *Time-Dependent Failure Evaluation of Elastomeric Device.* In addition to simulating the stress development during overcoating cure, the elastomeric device is also capable of maintaining a stress load over a time period (current testing was limited to a monitoring period of 225-minutes). The development of a near constant load over a time period is unique for this device, as no other method (currently commercially available or evaluated in this program) is capable of such. This method, while not able to induce an immediate failure, may have a time dependent failure window, where exposure for some duration will result in the complete disbondment of the original coating material. Further evaluation of this time-dependent failure device should be conducted to determine the load/time-to-failure relationship.

2. *Refinement and Development of Adhesion Techniques.* The techniques evaluated exhibited promise in simulating the adhesive failure of an overcoating system. Although all devices did not induce failure, their ability to simulate a stress and/or failure of a coating system was observed. Further development (including field application) of this device is necessary to develop a formal adhesion test procedure and apparatus.

THEORETICAL DISCUSSION

The overcoating process is widely accepted and implemented in the United States. The fundamentals of this process and theories on failure mechanisms are discussed below.

Overcoating Process

A bridge (or other structure) is selected for overcoating based on its current condition (typically physical appearance), coating age (from date of last application or maintenance painting) and an assessment of the existing coating integrity. This assessment typically includes measurements of coating adhesion (tensile and cross-cut) along with thickness, general appearance and observations of deterioration. Table 1 highlights some of the more common test techniques used.

Table 1 – Common Tests For Evaluating Coating Adhesion

Test	Specification	Description
Tensile Adhesion	ASTM D4541	Measure of coating strength when a normal (perpendicular) load is applied, strength and failure location determined.
Cross-Cut Adhesion	ASTM D3359	Measure of resistance to shear stress imparted by adhesive backed tape applied over intentionally damaged area.
Coating Thickness	ASTM E376	Measure of intact thickness using magnetic or eddy current gages.
General Deterioration	Varies Rust – ASTM D610 Blistering – ASTM D714 General Appearance – ASTM D1654 Chalking – ASTM D4214 Cracking – ASTM D661 Checking – ASTM D660	Obvious signs of visible degradation of the coating material and/or evidence of substrate corrosion.

Based on the limited data obtained from one or more of these tests, the maintenance painting strategy is determined for a bridge (or its individual sections). However, there is no *consensus* on interpreting the data to determine if an existing coating system is acceptable for overcoating. Reliance on this technical data has not proven adequate to prevent overcoating failure via complete system delamination.

Overcoating Failures

Overcoating failures are observed when large sections of the coating system (including the existing paint) disbond from the bridge substrate. This typically occurs within a few months to a few years after an overcoating project. It has been speculated that this disbondment is associated with the stresses imparted due to thermal cycling of the coated steel substrate, curing stresses or structure vibration. Figure 1 shows an example of a failed overcoating project.

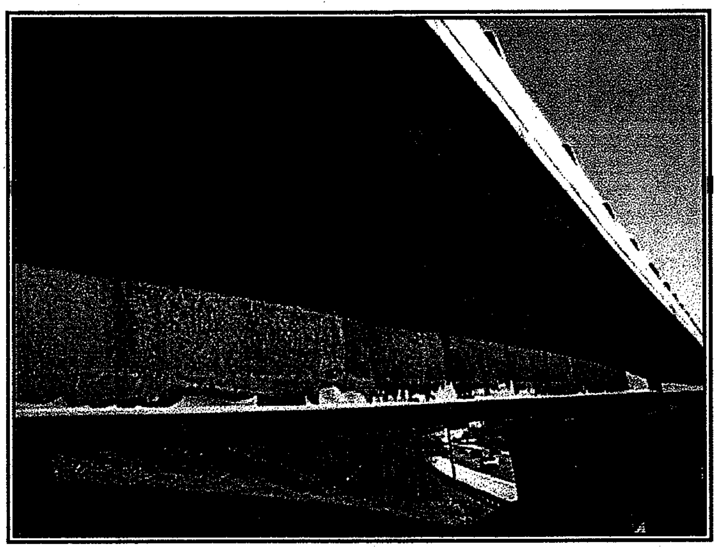


Figure 1. Example of Failed Overcoating Project.

Delamination of the Overcoating

Most of the mechanisms speculated to contribute to the delamination of an overcoating system have a common theme – shear development in the over coating system puts undue stress on an existing, aged coating, resulting in loss of adhesion and eventual delamination. This work focused on measuring the level of shear stress that the existing system can withstand as a decision tool for overcoating.

This project focussed, in particular, on the development of shear stresses during the cure process. S. G. Croll stated, *"Strains are produced in coatings because of shrinkage, due either to solvent evaporation or the chemical changes of crosslinking."*[1] During the cure process, solvents and other volatile materials "flash-off" leaving behind a solid, cured film. During the solidification process, the coating film changes in volume. It is this coating solidification process that causes the coating to "pull-back" on itself and effectively shrink. This can cause thin spots on edges or sharp corners and can induce shear stresses. Figure 2 shows this schematically.

CURE PROCESS

Coating is applied to the existing aged material as a liquid.

Coating cures, creating a solidified film that develops internal stresses.

The aged system (less adherent to the substrate) disbonds under the heightened stress conditions.

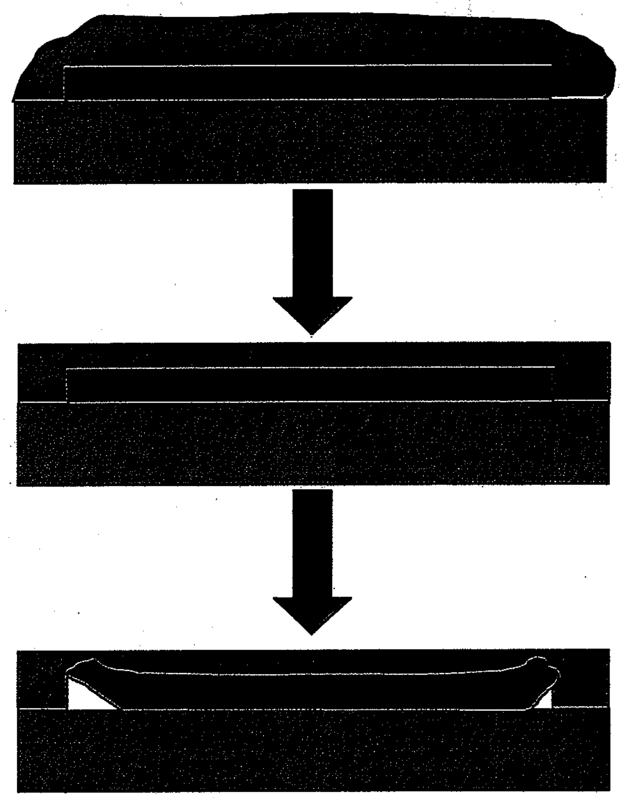
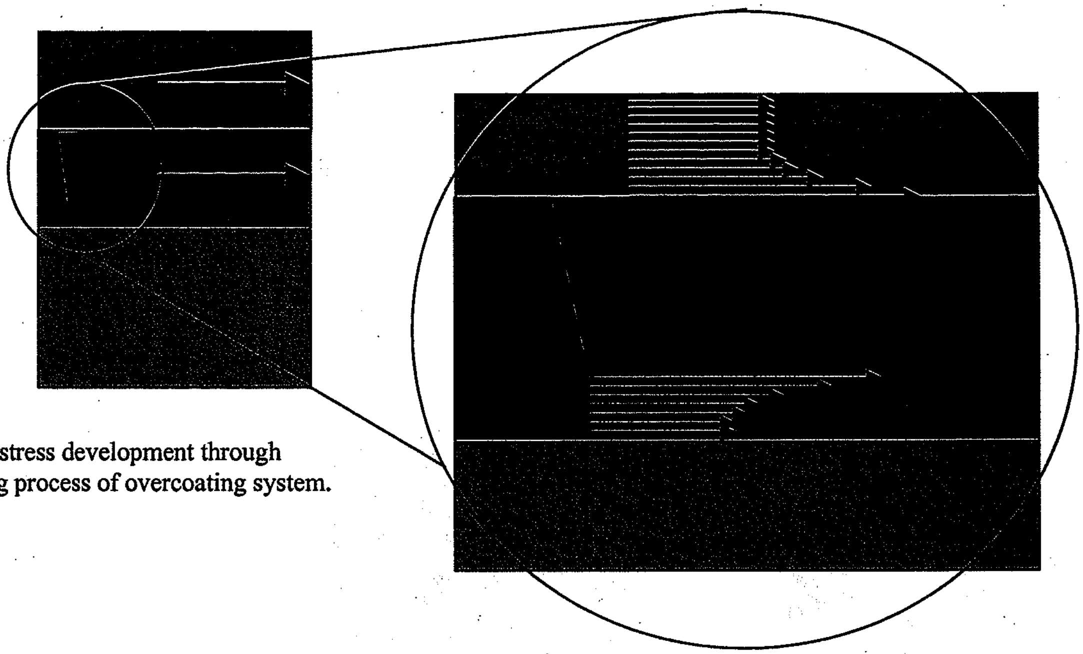


Figure 2. Shrinkage of an Overcoat System.

As additional coats are added, the total shear force acting on the coating is increased. *"...internal strain can have a large and detrimental effect on the adhesion of coatings. Energy stored in a coating by virtue of its internal strain increases as the coating thickness increases and, at a particular thickness, becomes sufficient to overcome the work of adhesion at the interface so that the coating spontaneously peels off."*[2] Although delamination is often not observed immediately after overcoating, prolonged exposure and/or exposure to other stress inducing phenomenon (i.e., weather events and structure vibrations) can cause the early onset of this type of coating failure. A system targeted to last 15+ years may fail within the first few years of service, with no warning signs. Thermal or vibratory stresses are assumed to be additive to the stress developed by the coating cure.

Once stresses are developed in an overcoating material, they are transmitted through to the existing, aged system. Years of exposure to the natural elements can cause embrittlement of the coating and crack development (among other phenomenon). When the stresses developed are transmitted to this brittle coating they form stress risers at existing cracks. Crack propagation to the substrate can eventually result in delamination of the brittle coating. Figure 3 shows a sketch of a stress riser acting on an aged, cracked coating.



Bulk stress development through curing process of overcoating system.

At crack locations stress concentrations (raisers) develop at the crack initiation points, promoting propagation. Once such cracks reach the substrate, stresses become concentrated at the coating/substrate interface causing rapid loss of adhesion of the existing, brittle coating.

Figure 3. Crack Growth Mechanisms.

Previous work with automotive clearcoats [3] was done to evaluate micro-cracking, which changed their physical appearance (loss of gloss). This work evaluated the spontaneous development of such crack by measuring fracture energies of newly formed and aged coating systems. This work has shown that crack propagation energy can decrease from 1/2 to 1/6 of its original value after 3,000 hours accelerated weathering for well adherent coatings. Most overcoating projects have coating systems that are over a decade old, where further decreases in fracture energy may have occurred. Such a reduction in fracture energy would make existing coatings more susceptible to crack formation and growth.

Measurement Tools for Evaluating Shear Stress – Conceptual Design

The stress acting on these aged systems is tangential to the plane of the coating material, which is shear in nature. A measurement tool that could simulate such stresses would be useful in determining the adhesive properties of an existing coating at candidate overcoating locations. The development of such a tool would minimize the risk associated with overcoating projects, improving success rates and making this a viable option for additional structures. During this project we investigated several concepts for simulating and measuring shear stress development in a coating. The following discussion focuses on concepts that showed the most promise:

Concept 1 – Torque Dolly

A "torque dolly" was developed to evaluate the adhesion of an existing coating system. This dolly was similar to those used in current pull-off adhesion tests; however, a torque would be used in place of a tensile force to induce coating disbondment. Figure 5 shows a sketch of the first version of this device.

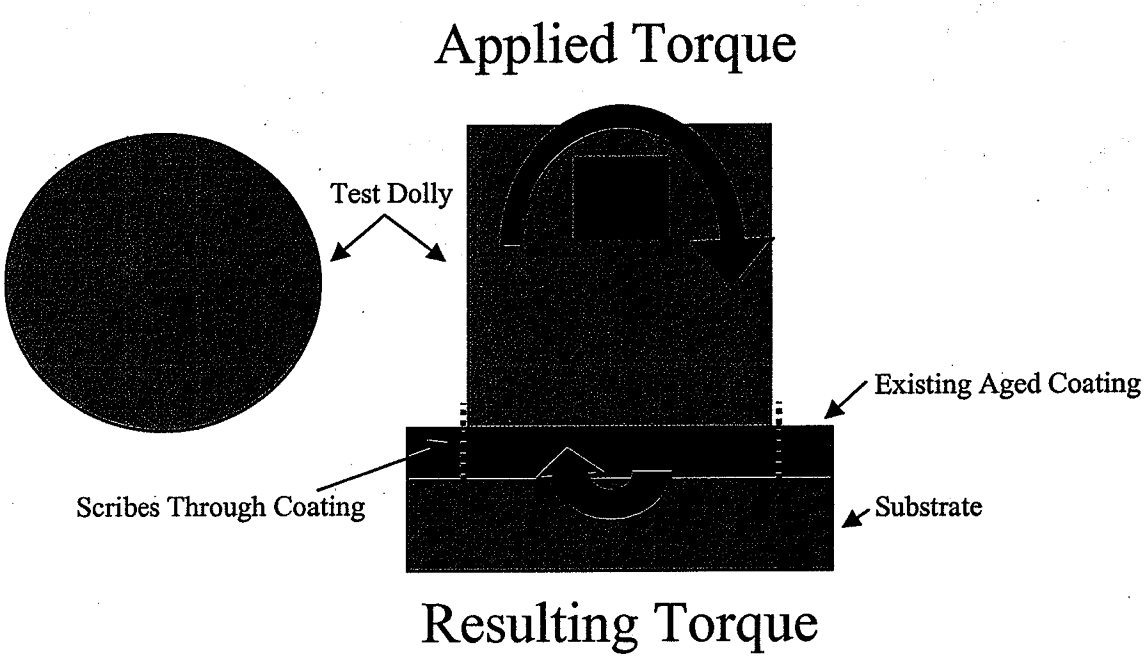


Figure 4. Conceptual Design 1.

Stress development using this device is calculated using the Flexure Formula [5], based on the cross-sectional area of the device. The moment applied to this device develops two unique stress distributions, acting in shear and normal to the substrate. Figure 6 shows this schematically. Immediately upon applying torque, the forces are all normal to the coated surface. As the dolly rotates, the normal component of stress decreases and the shear component increases. Since the coating fails when the dolly has passed through a very small angle of rotation, the shear component of force never becomes significant. This limitation precluded it from further evaluation.

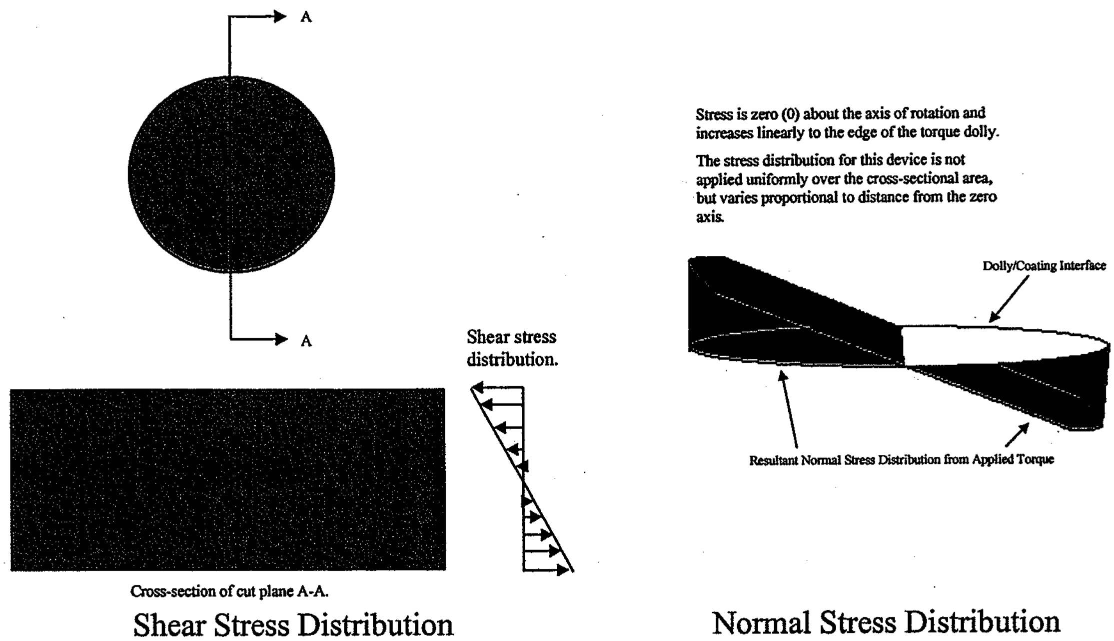


Figure 5. Sketch of Stress Distribution from Torque Dolly (Version 1).

Concept 2 – Torque Dolly

Using the same dolly geometry described above, a torque was applied such that it acted around the central axis of the dolly (figure 7). This twisting force (moment) would cause the stresses to act tangential to the plane of the coating/substrate interface (acting in true shear). This is more representative of the stresses developed during coating cure than concept 1.

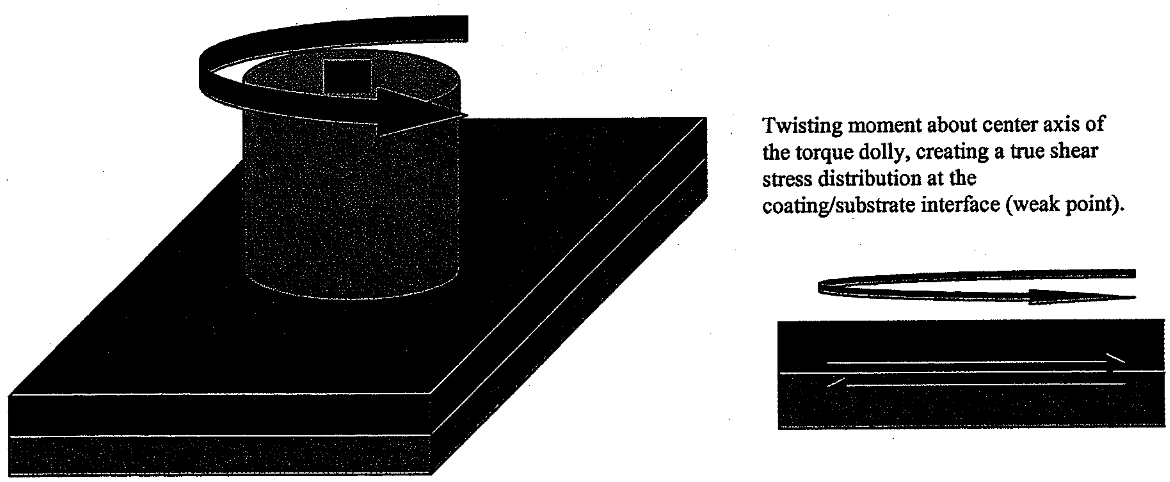


Figure 6. Alternative Torque Dolly.

Stress development in this device is similar to a cylindrical shaft with a fixed or constrained end and is a function of the radius of the torque dolly. The stress distribution can be calculated from the Torsion Formula[5]:

$$\tau = \frac{Tr}{I_p \times 10^6}, \text{ where:} \qquad \text{(eq. 1)}$$

τ = stress, MPa
T = applied Torque, N•m
r = radium, m
I_p = moment of the cross-section area, m^4

Use of this formula shows that the maximum stress occurs at the outer edge of the circular cross-section and varies linearly inward (figure 8 shows a sketch of this distribution). These stresses are present throughout the dolly, adhesive and coating materials (which are bonded together). Cutting through the coating to the substrate along the outside radius of the dolly allows the coating and adhesive to act as part of the cylindrical shaft. Since this is a laminated shaft, failure would occur at the point in this system where the shear stresses overcome the material stress limit or bond strength between materials. For a poorly adherent, aged coating, this would be the coating/substrate interface.

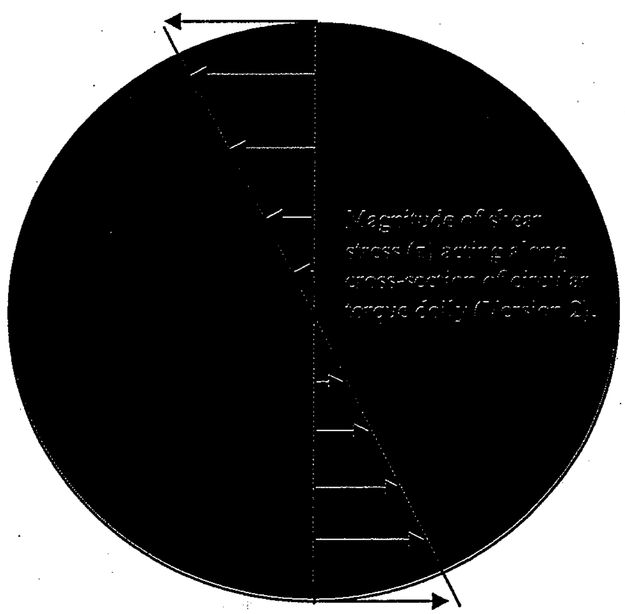


Figure 7. Shear Stress Distribution Schematic for Torque Dolly (Version 2).

This technique is not subject to the multiple stress distributions or loading as observed in concept 1. This device was evaluated as a method to evaluate coating adhesion of an existing coating when subjected to shear stress levels during cure.

Concept 3 – Elastomeric Material

The third concept was to use an elastomeric material to simulate the stresses imparted on the existing coating surface, which cause disbondment. This device would be constructed of synthetic rubber or other elastomeric sheet material, which can be stretched to a pre-stressed condition and adhered to the existing coating to simulate an overcoating system. Figure 9 shows a sketch of this conceptual device.

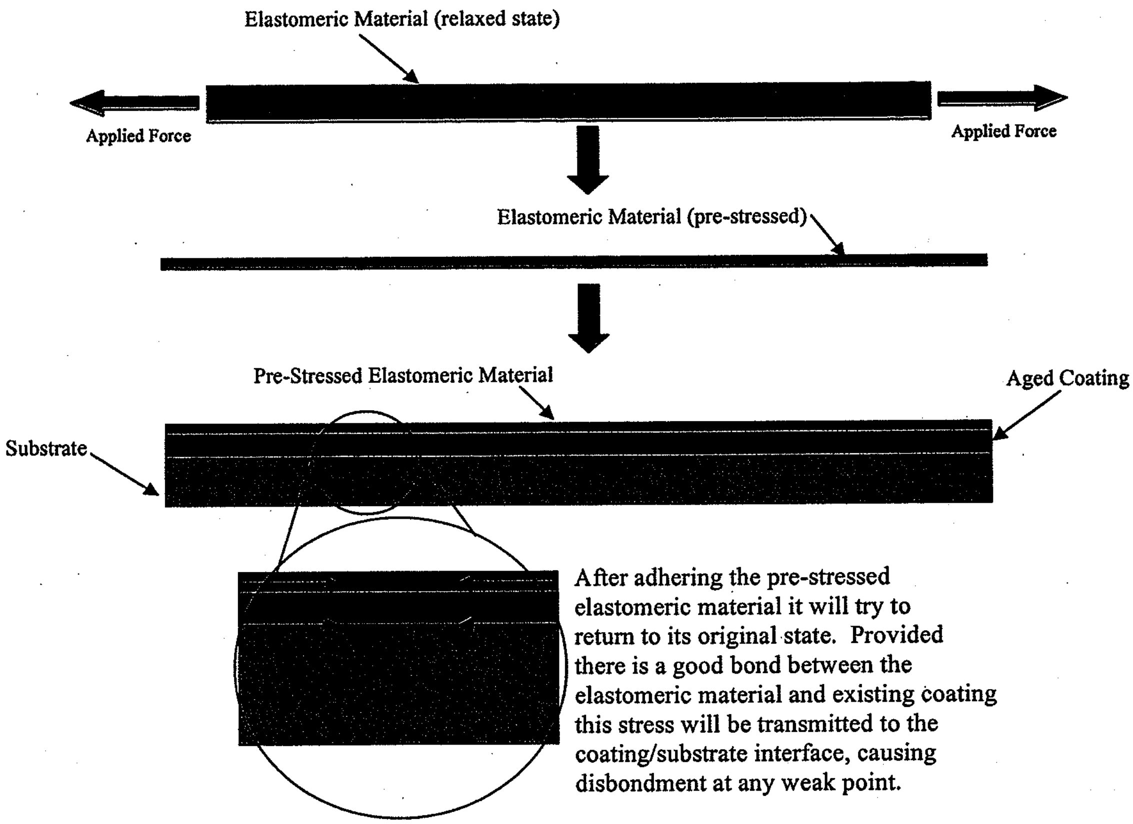


Figure 8. Conceptual Design 3, Elastomeric Material.

This device simulates "shrinking", which occurs during the coating cure process and results in the development of shear stresses. Stretching the material by some defection, results in a pre-stressed condition. The elastomer is then bonded to the existing, aged coating and disbondment can occur from the natural relaxation of this material, depending on adhesion to the substrate (i.e., how well adhered the existing coating is to the substrate).

Key factors to implementation of this device include stretching an elastomeric material (which can be uniformly and repeatedly pre-stressed within its elastic region) selecting an adhesive that successfully bonds the elastomer to the coating surface and devising a reproducible and repeatable procedure to load (pre-stress) the material. Such a device was developed during this program, although some of these issues remain unresolved and require further development work.

TECHNICAL APPROACH

The technical approach section of this project was divided into two stages. Stage I characterized stress development during the cure process. Stage II evaluated various overcoating risk reduction tool designs in a laboratory setting. The technical approach for each stage is discussed below.

Stage I – Characterization of Shear Induced During Coating Cure

The shear forces created during curing of a coating system can be significant. For aged coatings, which are brittle and inelastic, this can cause cracking and disbondment of the existing system from the substrate, although this may not be visible (i.e., the overcoating may not show signs of such cracking or delamination). During Stage I, measurements were attempted to determine the shear stresses developed during the cure process of four (4) overcoating materials. These were:

1. Alkyd,
2. Acrylic,
3. Moisture Cure Urethane and
4. Epoxy.

Technique 1 – Deflection Measurements to Calculate Shear Stress

Measurement technique 1 attempted to determine the deflection of a thin gage steel shim by measuring capacitance. This technique has been used by other researchers and was suggested as an accurate means for determining small deflections, which may be unobservable to the naked eye.

During this test, thin steel shims (0.006-inch thick) were painted with a two-part epoxy coating, mounted vertically and continually monitored for deflection. The non-contact capacitance probe had a working range of 0 to 0.050-inch, requiring close proximity to the test sample. An adjustable sled was used to manually position the probe into close proximity of the sample.

The deflection of the steel shim (as a result of stress during the cure process) was continually measured with the capacitance probe. From deflection, the applied shear stress was calculated from the equation:

$\sigma = (DEd^3)/3\delta l^2(d+\delta)(1-\nu)$, where: (eq. 2)

σ = internal stress, MPa
D = deflection, mm
E = substrate modulus of elasticity, MPa
d = substrate thickness, mm
δ = coating thickness, mm
l = length of panel
ν = substrate Poisson ratio

Technique 2 – Optical Strain Gage Measurements

Optical strain gages were used to measure strain (related to stress by a material's modulus of elasticity) at the steel shim/coating interface. The gages used were fiberoptic sensors capable of detecting small changes in strain. From these changes in strain the stress can be computed, using the stress-strain relationship of the material from the equation:

$\sigma = E\varepsilon$, where: (eq. 3)

σ = internal stress, MPa
E = substrate modulus of elasticity, MPa
ε = strain

During this test each of the four (4) overcoating materials were applied to similar steel shims as above. Prior to coating application, a strain gage transducer was mounted to the steel substrate. Coatings were applied under ambient conditions and allowed to cure. During the initial cure process the strain was continually monitored.

This technique proved to be the best method available to measure quantities related to shear stress at the coating/shim interface. Although other non-contact measurement techniques may be available, the data obtained confirmed what was reported in the literature and appeared sufficient for purposes of proceeding with Stage II.

Stage II – Development of an Overcoating Adhesion Tool

During Stage I, measurements of the overcoating cure-induced stress were made. These were similar in magnitude as stress levels reported by other researchers. Having identified the stress levels, adhesion tool development (Stage II) proceeded.

During this development period prototype tools were developed for Concepts 2 and 3 discussed above. Evaluation of the adhesion test devices was performed on both newly applied materials as well as an aged coating system. The newly applied coating was a two-part polyamide epoxy covered under specification MIL-P-24441 for a type III coating. This was applied over a well prepared (grit blast using aluminum oxide to an SSPC SP-10, *Near White Metal Blast* condition with 2-3 mil profile) and minimally prepared (wire wheel to bright metal, with a negligible profile) substrates. The aged coating system was an epoxy primer used for non-skid on US Navy ships (covered under MIL-PRF-24467). This system was applied over a rotopeened substrate (similar to the wire wheel substrate above) and tested for 2000-hours in a prohesion cabinet.

Data collected during Stage I and experience from Stage II are discussed below.

RESULTS AND DISCUSSION

The testing and theoretical analysis performed during this program suggests that an overcoating adhesion risk reduction analysis tool can be developed and implemented on bridge and highway structures. Although a tool was not fully developed, the theory behind its development has been explored and demonstrated in the laboratory. Continued development work should be able to produce prototype devices for field demonstration and evaluation.

The data and results from Stages I and II are discussed below.

Stage I – Characterization of Shear Induced During Coating Cure

During Stage I testing, data was collected on the stress development during coating cure. Work by others had shown that these values can be as high as 2.0 to 3.5 MPa for an epoxy coating.[4] From our testing we observed stresses as high as 9 MPa. Based on this and work by other researchers (evaluating both cure and environmentally induced stresses)[1, 2, 4], a shear stress value of 10-MPa was chosen for development of the overcoating adhesion tool. This value represented an extreme, worst-case stress level that would be an appropriate target for the prototype test apparatus. Appendix A presents the details of the Stage I testing.

Stage II – Development of an Overcoating Adhesion Tool

Tool development focussed on two of the original concepts. These were the Torque Dolly and Elastomeric Material devices. The development of these devices is discussed below.

Concept 2 – Torque Dolly

The second version of the Torque Dolly device uses an applied torque about the central axis of the cylindrical torque dolly. This produces a stress that acts along the cross-section of the dolly (i.e., is shear in nature). From the applied torque, the maximum shear stress was calculated using the Torsion Formula. Figure 9 shows the maximum shear stress developed during this test.

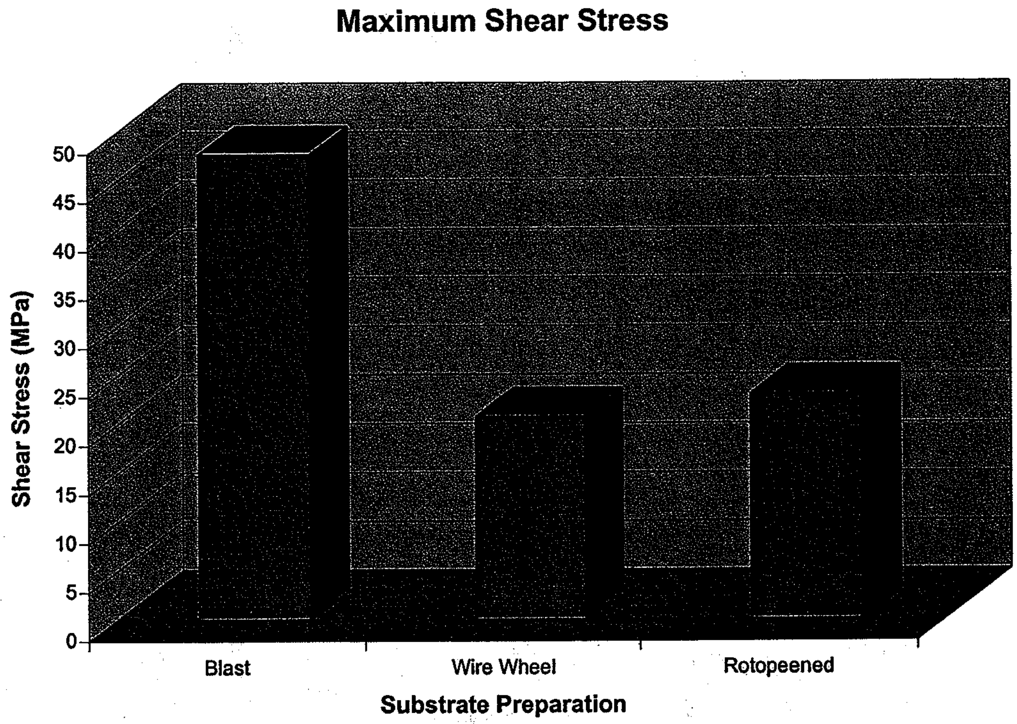


Figure 9. Maximum Shear Stress, Torque Dolly Version 2.

Figure 9 shows that the well prepared substrate had the highest stress. The stresses developed for the wire wheel and rotopeened substrates were similar, with the rotopeened being marginally higher. However, these stresses only represent the mechanical forces imparted on the sample, they do not show the weak point in the system (where failure would occur).

The failure mode for the newly applied coatings was at the adhesive/dolly interface, demonstrating that the coating/substrate adhesion could withstand the shear stresses developed during testing. However, the aged coating failed at the coating/substrate interface, demonstrating that the adhesive bond of the coating was not capable of withstanding the stresses developed. Figure 10, 11 and 12 show the samples after testing for the grit blast, wire wheel and rotopeened substrates, respectively.

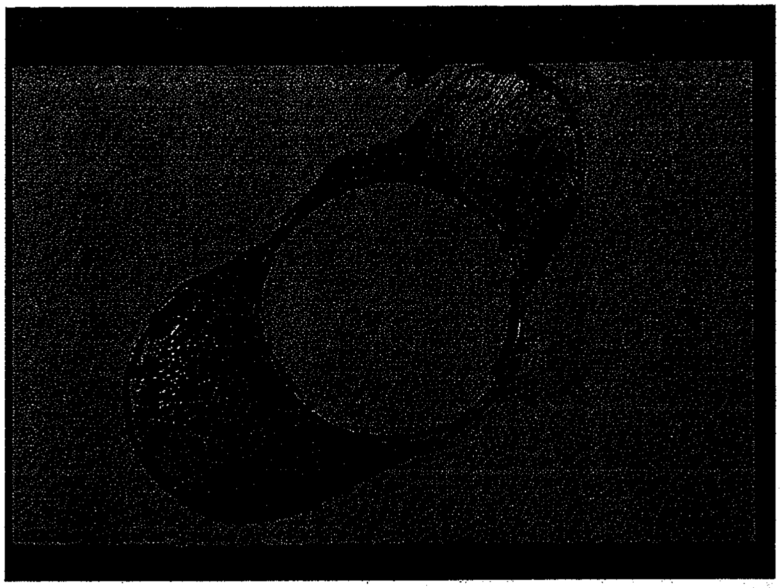


Figure 10. Grit Blast Panel after Torque Testing.

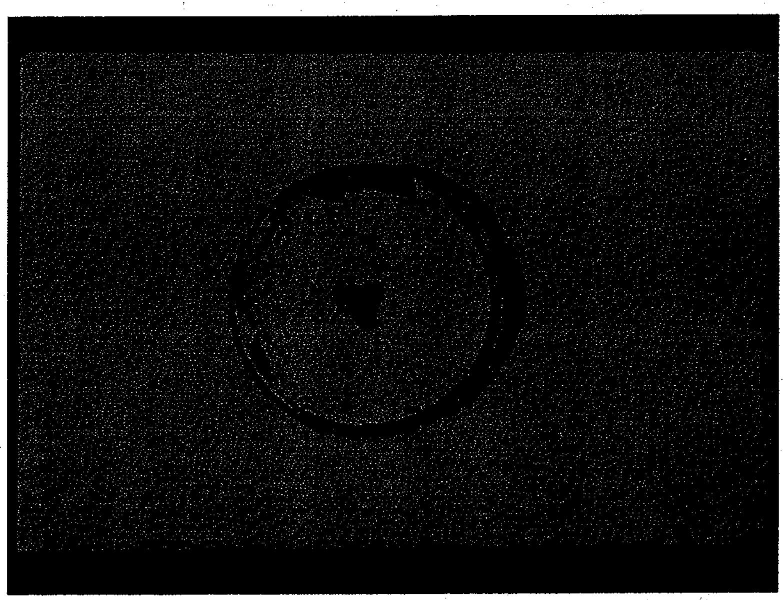


Figure 11. Wire Wheel Panels After Torque Testing.

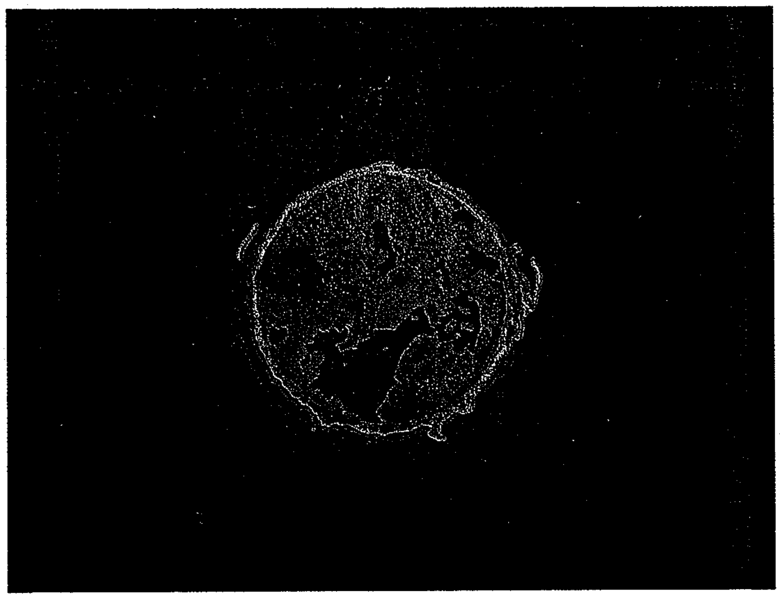


Figure 12. Rotopeened Panels After Torque Testing.

Although this device was capable of imparting a shear stress above the desired 10 MPa level and did result in disbondment of the coating, further development work is necessary before it can be used as an adhesion test tool. This includes:

- Evaluating the natural stress distribution of this device – Is disbondment directly proportional to maximum stress? Is there some critical stress/area relationship above which disbondment occurs?
- Variation of results due to loading – Do changes in torque rate affect adhesion test results? Does the method chosen for torque application result in other loading, possibly affecting test results?
- Repeatability/reproducibility of results – Are similar results obtained for similar samples (age, coating and surface preparation methods)? Are the results valid for multiple coating materials, ages and substrate preparation methods (i.e., can it be used for any structure)?

Concept 3 – Elastomeric Material

The use of an elastomeric material to simulate curing stresses provided the best opportunity to accurately simulate the cure of an overcoating material. The concept was to pre-stress a material (by initial deformation) and adhere it to the existing coating surface. Provided the material is "stretched" to a deformation within its elastic region, when unloaded it will attempt to return to its original shape. Bonding this material to the coating (while pre-stressed) will allow for the development of shear stresses similar to those incurred during the shrinkage of an overcoating system during cure.

Several vendors of rubbers and other elastomeric materials were contacted. Stripalastic manufactured by Fulflex, Inc. was ultimately chosen because of its reported yield stress of 1,800-psi (12.4 MPa) and minimum elongation of 600%. This material had a thickness of 25-mils (0.025-inch).

Having chosen a material of manufacture, a method of uniformly stretching this material was needed. Initial development of this device suggested that a circular cross-sectional area, providing a uniform stress distribution along the surface acting radially inwards would best simulate the "shrinkage" of a curing overcoating system. During initial testing a 500% elongation (corresponding to a 10.5 MPa stress) was attempted. Uniform deformation of a circular cross-section was not easily achieved so a rectangular cross-section was evaluated. The rectangular geometry has the disadvantage of providing significant stress in only one direction; however, it was considerably easier to attached to the surface for demonstration.

A 500% elongation was still desired to obtain a stress of 10.5 MPa. This was attempted on the first linear sample, however, failure of the elastomeric material occurred before this elongation was achieved. The practically achievable range of elongation was 125% to 190% (corresponding to stresses of 2.6 to 4.0 MPa) and was used for all further tests. Although this elongation may be less than desired, testing was performed as a proof-of-concept.

Shim Stock Evaluations

Evaluations were performed to determine the stress induced by the elastomeric material. This testing used the shim samples previously prepared for Stage I strain testing. The elastomer was cut into 1-inch wide by 6-inch long pieces, pre-stressed and adhered to the existing coatings on these samples and the strain response was monitored. This strain is measured at the coating/substrate interface of the overcoating materials.

The measured strain can be used to determine the resultant stress on the steel substrate using the stress/strain relationship (equation 3). This stress will be proportional to the actual stress of the elastomer. In its simplest form, stress is a function of force over area ($\sigma = F/A$)[5]. For a constant force, as the area decreases, the strain increases (and vice-versa).

Assuming that 100% of the force creating the stress in the elastomer is transferred to the steel, stress is inversely proportional to the cross-sectional area of the material. In this test, the elastomer had a cross-sectional area of 0.025-in^2 (1-inch by 0.025-inch) and the steel shims had a cross-sectional area of 0.003-in^2 (0.5-inch by 0.006-inch). These areas are approximately one (1) order of magnitude (10^1) different. Therefore, the stress in the steel shim would be approximately one (1) order magnitude higher than the stress in the elastomer. Figure 13 shows the stress (calculated from strain) in a steel shim when tested using the elastomer.

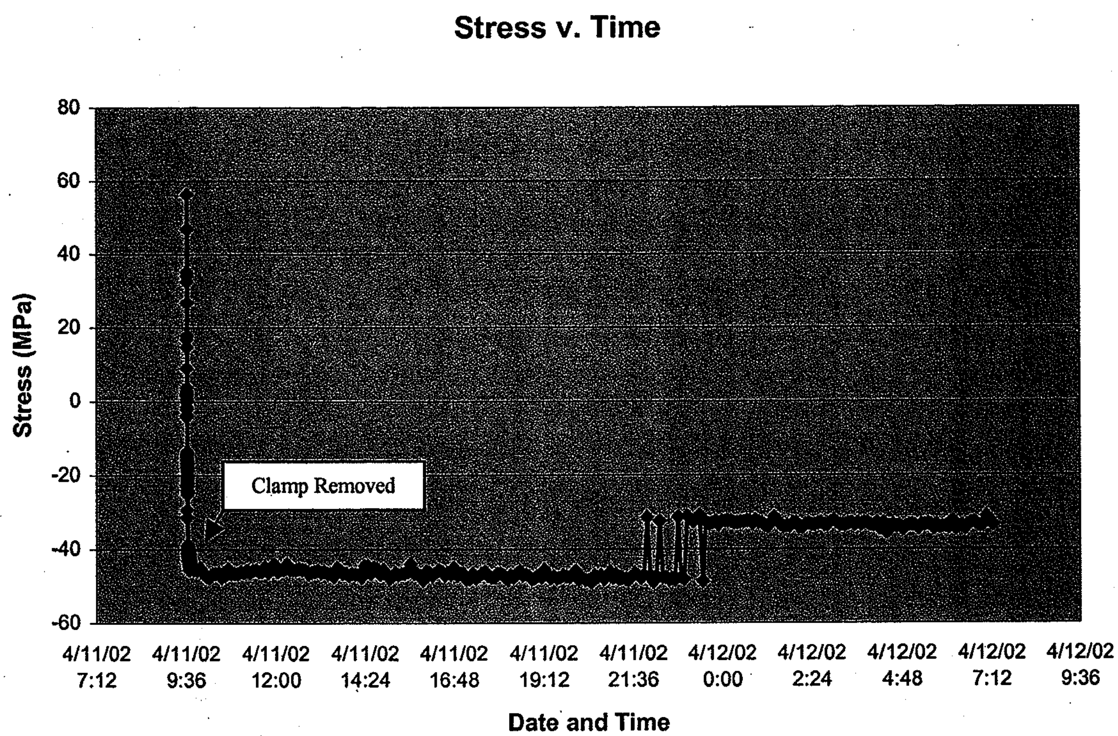


Figure 13. Stress v. Time, Elastomer Test over Shim Stock.

Figure 13 shows that the stress on the steel shim was between 49 and 32 MPa when under test by the elastomer. This corresponds to an elastomer stress of 3 to 5 MPa, based on the above area ratio. This is similar to the theoretical stress derived from stretching of the elastomer. Figure 14 shows a representative picture of a sample after testing.

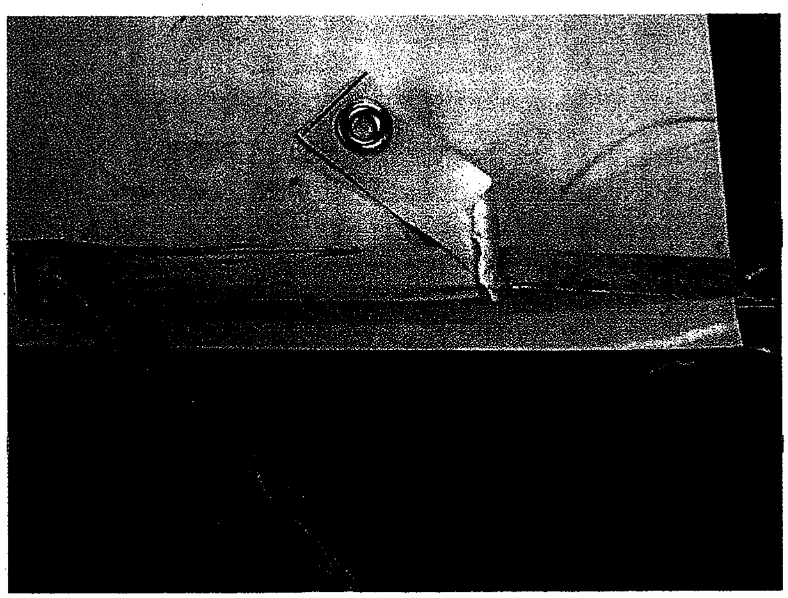


Figure 14. Test Sample, Elastomer over Shim Stock.

In addition to stressing the substrate, some disbondment of the coating did occur. This shows that the elastomer is capable of causing an adhesive failure of a coating over a minimally prepared substrate (the shim stock was prepared by light abrading using 120-grit sandpaper only). During these tests, both ends of the shim were constrained to represent adhesion testing on an actual structure. Figure 15 shows a similar test sample once the clamps were removed and the stresses allowed to freely act on the elastomer, coating and shim. When left unconstrained, the elastomer caused the shim to curl as a result of the applied stress. This further shows that residual stress remains in the elastomer.

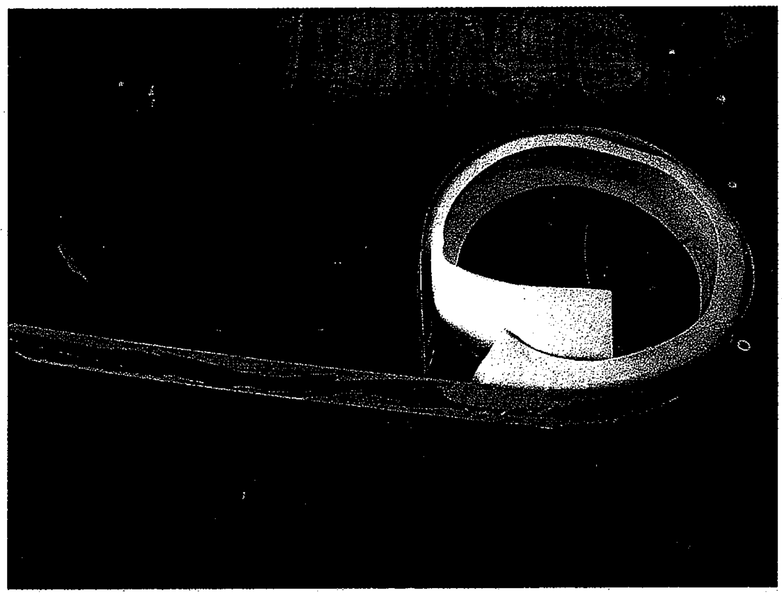
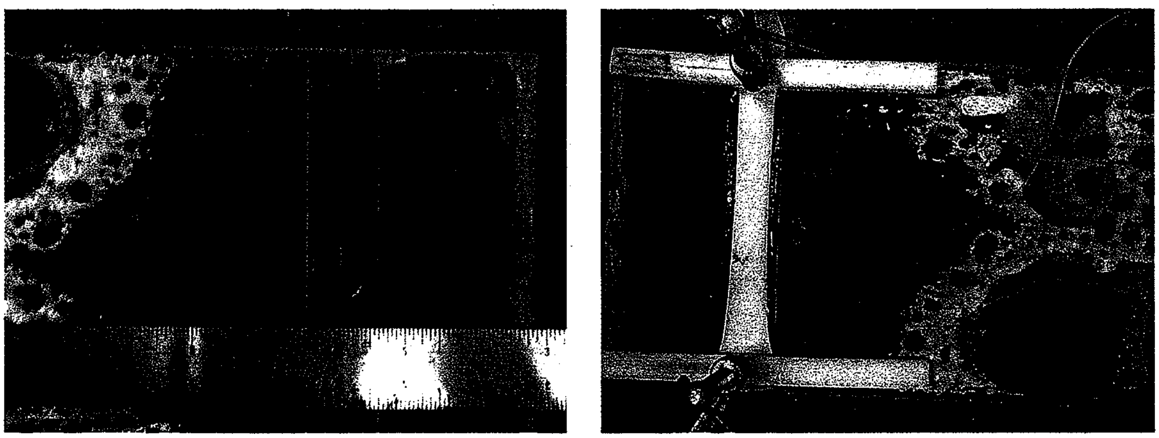


Figure 15. Elastomer over Shim Stock, Unconstrained.

Test Panel Evaluations

The elastomeric material was also used to measure the adhesion of a coating to a panel substrate (simulating use on a painted structure). A 1-inch wide by 4-inch long piece of elastomeric material was adhered to a newly applied coating over a well prepared and minimally prepared substrate along with an aged coating system (know poor performer). Prior to adhering the elastomer, a strain gage was mounted to the coating, monitoring strain at the elastomeric material/coating interface. The elastomer was pre-stressed and adhered using a cyanoacrylate adhesive. While the adhesive cured, the elastomer was kept in a pre-stressed state. After cure the perimeter around this material was scribed to the substrate using a razor knife. Figure 16 shows the strain gage and elastomer adhered to the aged test panel.



Strain Gage. Adhered Elastomer

Figure 16. Pre-Stressed Elastomer Adhered to Aged Coating System.

During this test, none of the stresses applied were near the 10 MPa value desired and none of the coating systems failed. A theoretical stress of 2.6 to 4.0 MPa was developed in the elastomer. The strain gage response was negligible, likely due to the manner in which the gage length was affixed to the coating. An improved measurement techniques need to be developed to confirm the magnitude of stresses transferred to the coating.

However, this technique was capable of produce a constant stress level at the coating interface for up to 225 minutes (the longest monitoring period for these samples). This technique would be well suited for the evaluation of time-dependent failures by maintaining a constant load over a given duration.

Adhesion testing under a prolonged constant load does not currently exist in commercially available field techniques for evaluating overcoating systems. Current systems use a gradient or stepwise loading to failure strength. The use of constant loading over a given time period may prove to best simulate the failures typically observed during overcoating projects (typical failures occur within two-years of an overcoating project, but are not immediately observable).

The successful development of stresses on the shim stock and disbondment of coatings applied to these devices shows that this technique is capable of producing adhesive failure of a coating. Further development work would allow for the production of a field adhesion test device for overcoating projects.

REFERENCES

[1] S.G. Croll, *Journal of Coatings Technology, Volume 53, No. 672,* Residual Strain Due to Solvent Loss From a Crosslinked Coating, January 1981, pp. 85-92.

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[3] M. E. Nichols, *Journal of Coatings Technology, Volume 74, No. 924,* Anticipating Paint Cracking: The Application of Fracture Mechanics to the Study of Paint Weathering, January 2002, pp. 39-45.

[4] O. Negele and W. Funke, *Progress in Organic Coatings, Volume 28,* Internal Stress and Wet Adhesion of Organic Coatings, 1996, pp. 285-289.

[5] J. M. Gere and S. P. Timonshenko, *Mechanics of Materials, Third Edition,* 1990, p. 260.

APPENDIX A – STAGE 1 REPORT

Appendix A contains an abbreviated version of the Stage 1 report submitted to NCHRP in July 2001. Specifically, the manufacturer's data sheets and manuals have been eliminated from this report for brevity. These items can be found in the original Stage 1 report submitted to NCHRP.

Stage 1 Report

NCHRP-IDEA Project,
Contract No. NCHRP-74

Adhesion Tool for Overcoating Risk-Reduction Analysis

Submitted by

Corrpro Companies, Inc.
1235 Jefferson Davies Hwy, Suite 500
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July 3, 2001

Table of Contents

Stage 1 Report
NCHRP-IDEA Project, Contract No. NCHRP-74

Adhesion Tool for Overcoating Risk-Reduction Analysis

Introduction

The ultimate objective of the proposed IDEA program is to design and demonstrate an innovative field adhesion test device. The intent is to provide bridge owners with a process that will effectively evaluate one aspect of an existing coating to determine its overcoat feasibility. Briefly, the overcoating adhesion tester will measure the existing coatings reaction to in-plane stress and its inherent ability to adhere to the substrate. The test gauge will replicate the stresses imparted from a new coating to the old coating in a worst-case scenario. Specifically, the gage will simulate the stress incurred during the curing and mechanical movement of the new coating. The results will show quantitatively if the existing system may be overcoatable or not from this point of view.

In order to achieve the above objective, the following work will be undertaken:

1. Demonstrate the mechanical forces created in different overcoating processes,
2. Determine the mechanical force needed to disbond an aged, lead-based paint, and
3. Develop a field-applicable technique for assessing the impact of this force on existing bridge coatings. This will provide an engineering basis for the overcoat decision.

As per contract stipulation the project will be performed in two contingent stages.

<u>Stage 1:</u> Work in this stage will involve development of laboratory test procedures for measuring coating stresses. Testing parameters will be defined and evaluated and suitable overcoat materials will be examined for residual stress. The data will be discussed with a panel of regional experts and modifications to the test procedures will be made based on panel's recommendations.

<u>Stage 2:</u> Work in this stage will design and assemble prototype field testers. Following laboratory tests and necessary refinements, the most promising testers will be further evaluated in the field. The tests will be conducted over bridge structures coated with lead-based paint and the results will be compared with those obtained by standard ASTM tests. The data will be discussed with the expert panel. Test specifications and use guidelines will be developed.

The IDEA Program must approve satisfactory performance of each stage before the next stage of project activity can commence.

Another stipulation of the project contract is that in addition to the Technical Project Advisor nominated by the IDEA Program, the investigator is to select and establish a panel of experts (3-6 experts). This expert panel should preferably be from state transportation agencies and the user community in the region in which the investigation is carried out or the product may be applied. The purpose of the panel is to make site visits and provide guidance to the investigator for the IDEA product development and transfer of results to practice.

During the first quarter a brief literature review was conducted to identify the types of stresses that may be involved in overcoating failures and ways to measure them in the laboratory. Further information was gathered to identify potential coating stress simulation and measurement devices, and to evaluate and develop appropriate laboratory methodology to measure stresses in organic coatings. Alternative overcoat materials were identified for testing. Finally an expert panel was suggested by the project team and duly approved by the IDEA program office.

Work Accomplished in Stage 1

Work in Stage 1 primarily involved examining and evaluating some laboratory test procedures for measuring internal coating stresses. Two methods were eventually tried: (1) deflection measurements using a capacitive sensor and (2) direct measurements using a miniature surface mounted fiber optic (FO) strain gage. The fundamental bases for these two techniques are given in Appendix 1. Off the shelf commercial devices were available for both techniques. The operating principles and product literature for the two devices used in the test program are provided in Appendix 1.

Several different overcoating materials were tested and these included a poly silicone alkyd, an acrylic, a moisture-cured urethane, and two different epoxies. Particulars about the coating systems are provided in Table 1 of Appendix 2. Manufacturers' specification sheets for these coatings are also included in Appendix 2.

Details about the test procedures and the data obtained are presented below.

Stress Measurements Utilizing Deflection

Experimental Approach

The test specimen consisted of 0.006-inch thick steel (feeler gage) shim as the substrate on which the selected coating was applied at a thickness of about 5 mils (wet film thickness). This type of specimen has been found to be ideal for determining internal coating stress in the laboratory[1],[2]. During coating application and curing, environmental conditions (wet and dry bulb temperature) were monitored allowing for the calculation of relative humidity and dew point. Testing was conducted to identify the

[1] S.C. Croll, J.Oil Color Chem. Assoc., 63, (1980), 271.
[2] S.C. Croll, private communication (2001)

appropriate method for coating application on the shim material. Two methods were tried, brush application and drawdown blade. The latter was found to provide the most consistent wet film thickness as indicated by the data in Table 1 of Appendix 3. Coating stress was determined from the deflection of the test specimen as measured with a capacitive sensor (transducer) manufactured by Capacitec, Inc. (model HPC-75 coupled to a 4100 series amplifier). A brief description of capacitive sensors as well as some product literature for the Capacitec devices is provided in Appendix 1. The calibration curve for the capacitive sensor used in the present testing program is shown in Figure 1 of Appendix 3. Figure 2 of Appendix 3 shows the experimental set up used for deflection (and hence coating internal stress) measurements.

Immediately following application of the coating, the steel shim was oriented horizontally in the test rig. A piece of release paper was positioned below the shim preventing bonding of the coating system to the plastic surface. The capacitance probe was then positioned between 5 and 10-mils away from the steel shim. The potential output of the probe was monitored to determine a change in distance between the steel shim and probe. Based on the deflection of the shim the stress generated by the coating material during the curing process can be calculated using equations given in Appendix 1.

Results

Testing was performed using MIL-P-24441 Type IV, a two-part epoxy. Following application of the coating material the shim was placed in the test rig to monitor displacement. This displacement was monitored during the cure of the coating system.

During the first 2 minutes of testing the potential quickly decreased (indicating a decrease in distance between the probe and steel shim). This decrease continued until approximately 4-minutes after testing began. The measured voltage then began to increase indicating that the distance between the probe and shim was increasing. However, after approximately 18-hours of testing this voltage was still 200 mV less than the original (indicating an overall decrease in the distance between the probe and steel shim. Figure 3 of Appendix 2 shows a plot of the displacement of the shim while Figure 4 shows the calculated stress in the coating material. Based on these plots it appears that the greatest stresses are induced during the first few minutes of cure (corresponding to the greatest displacement). Following this initial period the level of stress decreased, but there were still residual stresses on the steel shim.

Conclusions

Based on this testing the following conclusions were made.

- This test apparatus does appear valid to measure deflection of the test sample during cure.
- Additional testing is warranted to determine if variables (like static electricity) has any impact on the experiments.

- Drawbacks to this system include operator variability and the ability to only test one sample at a time (each sample requires approximately 24-hours to complete testing). However, Capacitec does manufacture more expensive devices for monitoring multiple specimens.

Because of the drawbacks mentioned above and additionally because direct measurements with miniature FO strain gages (discussed below) gave more reliable data, further testing with the deflection device was not conducted.

Stress Measurements Utilizing Miniature Fiber Optic Strain Gages

Experimental Approach

Coating induced stresses (during cure) were measured using miniature fiber optic (FO) strain gages (manufactured by Luna Innovations of Blacksburg, VA) attached to the steel shim stock. Operating principles of the FO gages as well as specifications are provided in Appendix 1. The gages were oriented along the longitudinal axis of a 0.5-inch by 12-inch by 0.006-inch steel shim as shown in Figure 2 of Appendix 1.

The FO strain gages were bonded to the specimen surface (after recommended surface preparation) using an M-Bond 200 adhesive (commercially available epoxy adhesive designed for strain gage applications). Following application and complete cure of the adhesive, a coating film was applied over the entire length of the shim material and allowed to cure while oriented vertically. This was done to minimize the effects gravity would have on strain reading, allowing for the measurement of the true strain induced by the coating material. Throughout cure discrete measurements of the strain were recorded to determine stress as a function of time.

Results

The MIL-P-24441 epoxy tested with the deflection method (discussed above) was tested using the FO strain gage technique to compare the data obtained with the deflection technique. The other four coatings listed in Table 1 of Appendix 2 were also evaluated for cure-induced stress with the FO technique. These latter coatings represent the chemistries of the most popular bridge overcoat materials used today.

Immediately following coating application, the sample was oriented horizontally and connected to the strain gage meter. This meter gave a direct reading of the strain observed by the gage throughout cure. Figure 5 (a through c) show the laboratory set up used for the FO strain gage measurements. Discrete measurements of the strain were made. From these the curing stress developed by the coating material was calculated using the equation $\sigma = E\varepsilon$, where σ is stress (MPa), E is the modulus of elasticity (190,000 to 210,000 MPa for steel) and ε is strain.

The results obtained with the MIL-P-24441 epoxy are shown in Figure 6 of Appendix 3, which also shows a plot of the relative humidity and temperature during the test. It can be seen that the measured stress decreased slightly during the first 2 to 3 hours and then showed a steady increase for the next several hours before leveling out at about 5 MPa after about 8 hours. It may be noted that the coating stress observed using the capacitive transducer apparatus presented earlier, was much lower than expected for such a coating during cure. The FO strain gage data is more representative of what has been reported by researchers in this field. This data is also similar to that was observed with the other epoxy system evaluated in this program (see later).

For the four overcoat systems, duplicate tests were conducted but at different time periods (during February through June). It was noted that although the room temperature remained more or less constant to within a few degrees of 20° C, the ambient relative humidity (RH) changed significantly during the different time periods (from as low as 10% in February to over 60% in early June). No attempts were made to control the relative humidity in the room. Hence the data are represented in four sets to reflect this variability in RH. In the first set (Set-1, conducted in February/March) the four coating systems were tested for 24 to 48 hours (except for the epoxy, which was tested for about 7 hours). The second set (Set-2, conducted in early April/May) was a repeat of the 1st set but all 4 systems were tested for at least 20 hours. The third set (Set-3, conducted in early May and early June) involved gathering longer-term data (up to about 1200 hours) for the Set-1 specimens. The fourth set (Set-4, conducted in early June) involved longer-term data acquisition for the specimens from Set-2. Figures 7 through 10 of Appendix 3 show plots of the stresses for each coating system for the first set of specimens (Set-1). Figures 11 through 14 represent data from Set-2 specimens while Figures 15 and 16 show longer-term coating stress data for Set-3 for the urethane and epoxy systems respectively. (**Note**: Data could not be obtained for the alkyd and acrylic systems since the FO strain gages attached to the specimens were damaged during handling). Figures 17 through 20 represent the long-term data from Set-4.

Figures 7 through 14 show the variation of the curing stress for the four coating materials during the first 24-48 hours after application. It is important to note the difference in stress patterns displayed by the coatings depending on the ambient relative humidity. The Set-1 specimens, which were tested when the RH was in the range of 10-25%, developed expansive (positive) stresses to varying magnitudes (see Figures 7 through 10). This implies that the coating is applying a compressive stress on the substrate (i.e. undercoat material) which may not be detrimental. The Set-2 specimens, where the RH was in the range of 40-45%, showed quite different behavior particularly the acrylic and urethane which developed significantly large shrinking (negative) stresses (see Figures 12 and 13 of Appendix-3). The alkyd and epoxy however, still showed expansive (positive) stresses. Shrinking (negative) stresses imply that the coating is imparting a tensile (curling) stress to the substrate. If this curling stress exceeds the adhesive strength between the coating and the undercoat, then the coating material could be disbonded from the undercoat. Additionally, if the curling stress exceeds the adhesive strength of undercoating material, then the undercoat could disbond from the substrate.

Data from the long term tests (Figures 15-20) where the RH increased to over 65% showed that shrinking (negative) stresses developed by the acrylic and urethane coatings at lower RH values became less negative but still remained in negative territory. On the other hand the expansive (positive) stresses displayed by the alkyd and epoxy became less positive and crossed over to slightly negative values with an increase in RH.

Conclusions

Based on this testing the following conclusions were made:

- The foregoing data demonstrates that the ambient RH has a significant effect on the type and magnitude of stresses developed by different types of coatings during curing and aging.
- It is anticipated that the ambient temperature may have a similar effect though this aspect was not investigated because of time and budgetary constraints.
- Under certain relative RH and temperature conditions, some types of coatings may develop sufficient shrinking stresses to cause disbondment of the undercoat as is sometimes encountered in the field on painted bridge components.

Summary of Stage 1 Work

1. Two methods of measuring cured-induced stresses in coatings were examined: (a) deflection measurements using a capacitive transducer and (b) direct measurements using a miniature surface mounted fiber optic (FO) strain gage.
2. Because of certain drawbacks and additionally because direct measurements with miniature FO strain gages gave more reliable data, further testing with the deflection device was not conducted.
3. The miniature fiber optic strain gages provide an elegant method of determining internal coating stress.
4. The ambient RH has a significant effect on the type and magnitude of stresses developed by different types of coatings during curing and aging.
5. Under certain relative RH and temperature conditions, some types of coatings may develop sufficient shrinking stresses to cause disbondment of the undercoat as is sometimes encountered in the field on painted bridge components.

Work Plan for Stage 2

As mentioned earlier in this report, work in Stage 2 will involve designing, assembling, and testing prototype field testers. Two concepts will be attempted which are discussed below. It may be mentioned here that other field tester concepts were suggested in the proposal submitted to NCHRP. However, these were discarded after subsequent technical considerations.

Concept 1: Pre-stressed Elastic Material Adhesion Tester

In order to provide the in-plane stress that represents an overcoat material, an elastic material (i.e., rubber or similar) will be pre-stressed and bonded to the old coating (see Figure 21 of Appendix 3). The amount of deformation of the elastic material will correlate to a predetermined in-plane stress. The material will be stressed to varying degrees and then applied to the old coating. A scribe will be made around the test material to represent an existing crack or weak point(s) in the coating. We will monitor the test material for disbonding of the old coating from the substrate.

The purpose is to have a simulation of an actual coating stressing the old coating in a similar manner. This is analogous to a test patch of the coating applied to the old coating, but this would be:

- Accelerated
- Repeatable
- Quantifiable

It should be relatively easy to have the stress of the material simulate the coating stress. The equation would be: $F=k*X$, where k=spring constant of the material and X= displaced distance of the material. This force would be imparted in same in-plane manner as a coating that cures. The force must be matched to the proper size (area) of the patch.

For the actual test apparatus, frames can be manufactured at set sizes that correspond to certain stresses. The elastomeric material should be tested to make sure the spring constant is consistent over the distance that it will be stressed and for the length of time that the material can be stressed and not have significant change in spring constant (relaxation.) The stresses will be relatively small so it may be possible to pre-stretch the material in the field before applying to the bridge coating. An adhesive will have to be applied to the material to ensure transfer of stress to the bridge coating. When testing, several stresses should be used to quantify the actual adhesion of the old coating.

Concept 2: Mechanical Shear Stress Adhesion Tester

This design is similar to the aluminum dollies currently used for pull-off adhesion testing. This test method uses a moment, imparted on the existing coating, to impart shear stress. In its simplest form, a shear stress is a result of a moment applied to a material. The flexure formula[3] shows that a shear stress a given point from the principal plane of a structure is determined from the moment acting on that structure and the geometry of the cross-section (see Figure 22 of Appendix 3).

The flexure formula is:

$$\sigma_x = \frac{M_z y}{I_z}$$

Where:

σ_x = internal stress, Mpa
M_z = the moment about the z-axis, N-m
y = the distance from the principle plane where the stress is acting
I_z = the moment of inertia about the area of a centroid, kg-m^2

Using this principle, shear stress can be applied by imparting a moment on the existing coating system. Knowing the thickness of the coating and the base length of the cross-section, the stress resulting from this applied moment can be easily calculated.

The conceptual design would be an aluminum dolly with a square face measuring 1-inch by 1-inch. The height of this dolly would be approximately ½ to ¾-inch, with a square hole approximately 1/8-inch from the top. This hole would allow for the use of a moment device similar to a torque wrench used by mechanics. Figure 23 of Appendix 3 shows a sketch of the test dolly. This device would differ from a traditional torque wrench in that it would register the maximum moment applied and keep that reading until reset by the user. A special square-head bit would fit into the square hole at the top of the dolly to impart a moment on the dolly, which is attached to the existing coating.

Testing of this device would differ from the previous test method in that the coating is tested to failure. The moment causing this failure can then be used to determine the shear stress imparted on the existing coating. Substituting in the dimensions of the test dolly and coating film, the flexure formula can be re-written to determine the stress acting on the existing coating material.

This equation is:

$\sigma_x = \frac{6M_z}{t^2}$, where:

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[3] J. M. Gere and S. P. Timoshenko, Mechanics of Materials, Third Edition, PWS Publishing Company, Boston, 1990, p. 260.

σ_x =internal stress, Mpa
M_z = the moment about the z-axis, N-m
t = the thickness of the coating, m

This stress can then be compared to the stress range for various overcoating materials to determine if they are suitable for a particular overcoating project.

APPENDIX 1

Coating Stress Measurement Techniques and Devices

Stress Measurement Using Deflection

Here coating materials are applied at a uniform thickness to one side of a thin steel foil. Figure 1 shows a sketch of this apparatus. The foil is clamped vertically or horizontally during the test and then exposed to the test conditions. Prior to testing, the deflection of the foil (if any) is measured to serve as a baseline. At the completion of testing the deflection is re-measured and is used to determine the stress induced by the coating system. Referring to Figure 1, a deflection to the left indicates a shrinking stress while a deflection to the right indicates an expansive stress. A shrinking type stress would impart a tensile, peeling action on the undercoat and possible subsequent failure. An expansive stress would put the undercoat into compression.

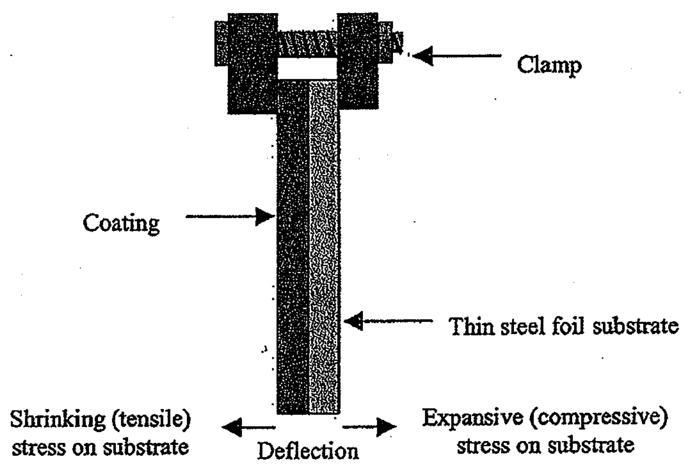

Figure 1. Coating Stress Determination by Deflection Measurement Device.

At the completion of testing the stress is determined using the equation:

$$\sigma = \frac{DEd^3}{3\delta l^3(d+\delta)(1-\upsilon)}, \text{ where:}$$

σ = internal stress, MPa
D = deflection, mm
E = substrate elastic modulus, Mpa
d = substrate thickness, mm
δ = coating thickness, mm
l = length of panel, mm
ν = substrate Poison ratio

Capacitive Sensors for Displacement Measurement

These are non-contact, displacement sensors sometimes called proximity sensors. These sensors consist of probes that are typically built into machinery to detect the motion of shafts inside journal bearings or the relative motion of other machine elements. The sensors measure relative distance or proximity as a function of either electromagnetic or capacitive (electrostatic) coupling between the probe and the target. Because these devices rely on inductive or capacitive effects, they require an electrically conductive target. In most cases, they must be calibrated for a specific target and specific material characteristics in the gap between probe and target.

Electromagnetic proximity sensors are also called eddy current probes because one of the most popular types uses eddy currents generated in the target as its measurement mechanism. More accurately, this type of sensor uses the energy dissipated by the eddy currents. The greater the distance from probe to target, the less electromagnetic coupling, the lower the magnitude of the eddy currents, and the less energy they drain from the probe. Other electromagnetic probes sense the distortion of an electromagnetic field generated by the probe and use that measurement to indicate the distance from probe to target.

Capacitive proximity sensor systems measure the capacitance between the probe and the target and are calibrated to convert the capacitance to distance. Capacitance is affected by the dielectric properties of the material in the gap as well as by distance, so a change of lubricant or contamination of the lubricant in a machine environment can affect calibration.

State-of-the-art capacitive sensors manufactured by a company called Capacitec, Inc. of Ayer, MA were used in the test program to measure deflection. Some product literature is provided below.

Direct Stress Measurement Using Strain Gages

A direct measurement of the stress induced by a coating material can be performed using a thin film strain gage. A strain gage is a device usually made of a thin metallic wire embedded in a non-conductive thin film material, which is adhered to the material being measured. Currently miniature fiber optic (FO) strain gages are also available. When a stress is applied at the surface of this material it creates an elongation or compression of the strain gage. An elongation of the strain gage indicates an expansive (compressive) stress in the coating while a compression of the strain gage indicates a shrinking (tensile) stress in the coating. As the strain gage is stressed its electrical properties, in this case resistance, changes. This change in resistance is used to determine the change in length of the strain gage wire, which when divided by the initial length gives the strain, by the following equation:

$$\varepsilon = \frac{\Delta L}{L}, \text{ Where:}$$

ε = strain
ΔL = the change in length, mm
L = the original length

Knowing the strain induced on a material, the stress induced along that surface can be determined. This is calculated based on the modulus of elasticity, which can be found for many materials. The stress is calculated using the following equation:

$$\sigma = \varepsilon G, \text{ Where:}$$

σ = internal stress, Mpa
ε = strain
G = modulus of elasticity, Mpa

Figure 2 shows the configuration of a FO strain gage on a steel shim. FO gages manufactured by Luna Innovations of Blacksburg, VA were used in the test program. The operating principles and literature for Luna FO strain gages are included in this Appendix.

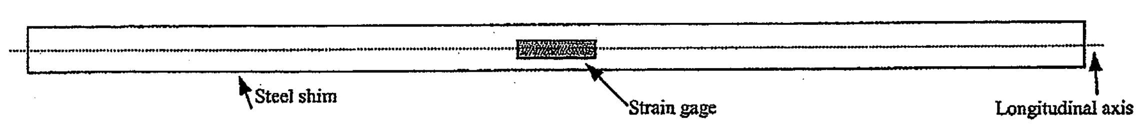

Figure 2. Strain gage orientation

APPENDIX 2

Coating Systems Used

Table 1. Coating systems used in the test program

Manufacturer	Name	Chemistry	Applied WFT
Keeler & Long	Poly Silicone Enamel	Alkyd	5-6 mils
Benjamin Moore	DTM Acrylic Gloss M-28	Acrylic	5-6 mils
Wasser	MC Luster	MC Urethane	5-6 mils
Carboline	Carbomastic 90	Epoxy	9-10 mils
Ameron	MIL-P-24441 Type IV	Epoxy	9-10 mils

APPENDIX 3

Results

Table 1. Coating thickness trials

Reading	Coating thickness (DFT), mils					
	B1	B2	B3	D1	D2	D3
1	3.8	4.5	4.4	5.3	5.6	4.5
2	4.5	4.4	3.7	5	4.9	5.2
3	4.2	5	3.6	4.9	4.8	3.9
4	5.6	4.6	3.6	5.2	5.1	5.3
5	5.6	4.5	4.3	5	5.1	5.2
6	4.8	5.2	5	5	4.9	5.2
7	5.4	5	5.3	4.9	4.9	5.3
8	5	5	5	5	5	5.2
9	5	4.8	4.4	4.9	4.7	5.2
10	4.4	4.5	4.1	4.9	4.6	5.2
Average	4.83	4.75	4.34	5.01	4.96	5.02
STD deviation	0.607	0.284	0.611	0.137	0.276	0.457
WFT - measured	4-5 mils	4 mils	4 mils	4 mils	4 mils	4 mils
WFT - Calculated	7.32	7.20	6.58	7.59	7.52	7.61

B1 - B3: brushed applied.
D1 - D3: applied using a drawdown blade.

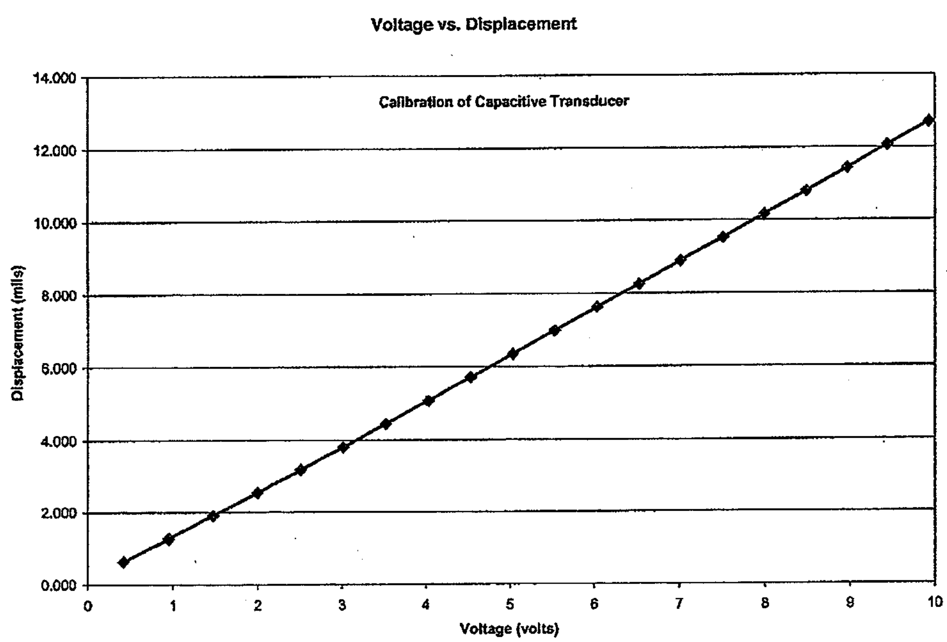

Figure 1. Calibration curve for capacitive sensor.

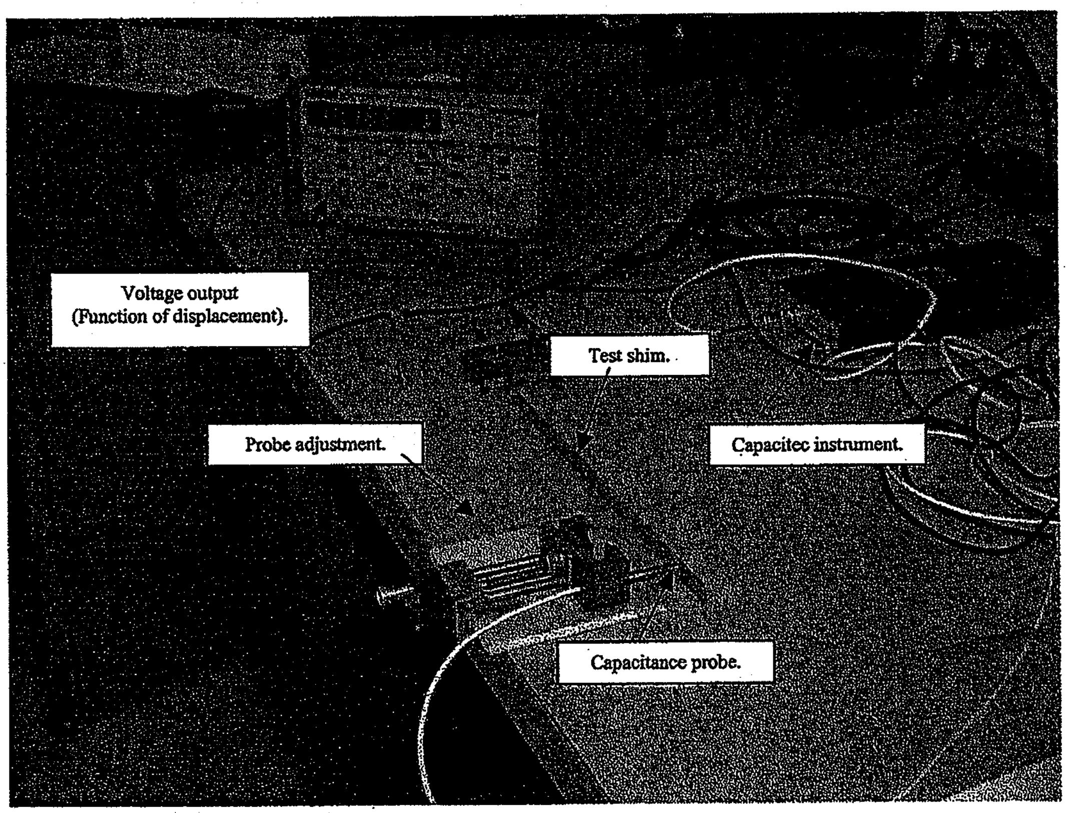

Figure 2. Experimental setup for measuring deflection using a capacitive sensor.

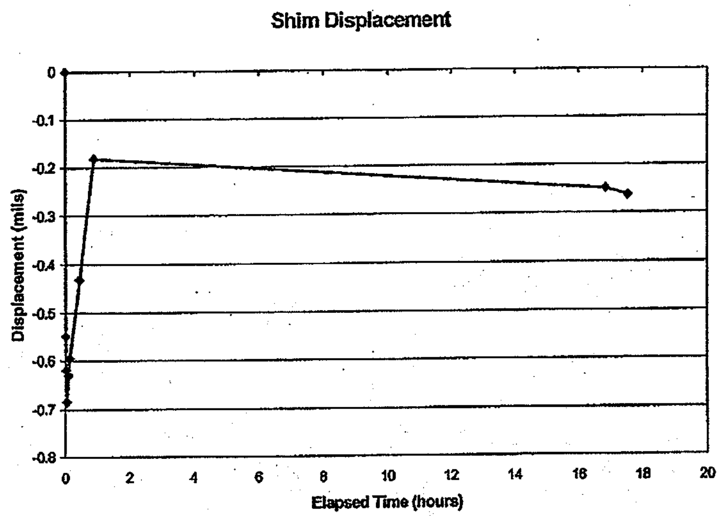

Figure 3. Shim Displacement

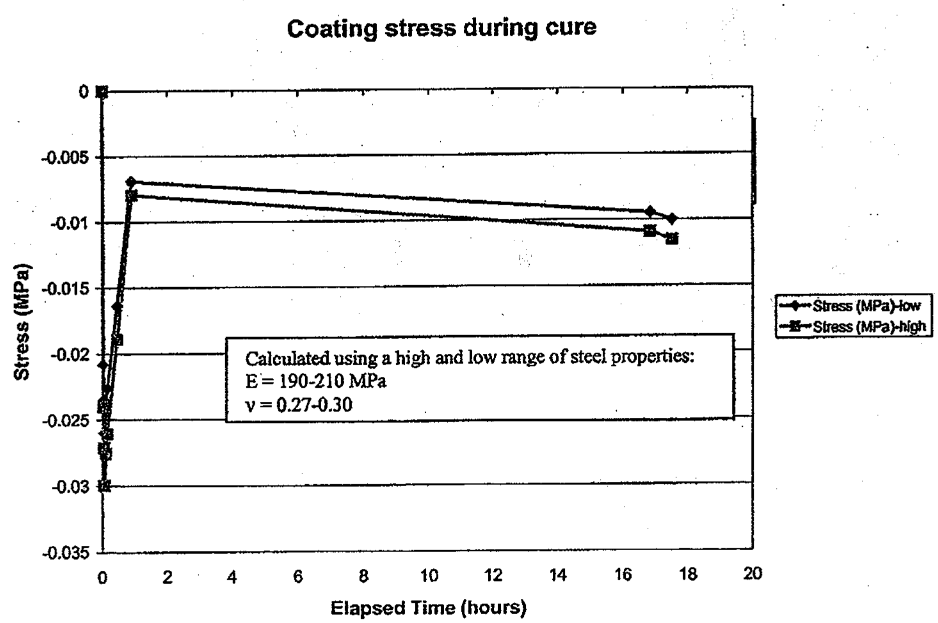

Figure 4. Determination of Coating Stress Levels Using Deflection Method.

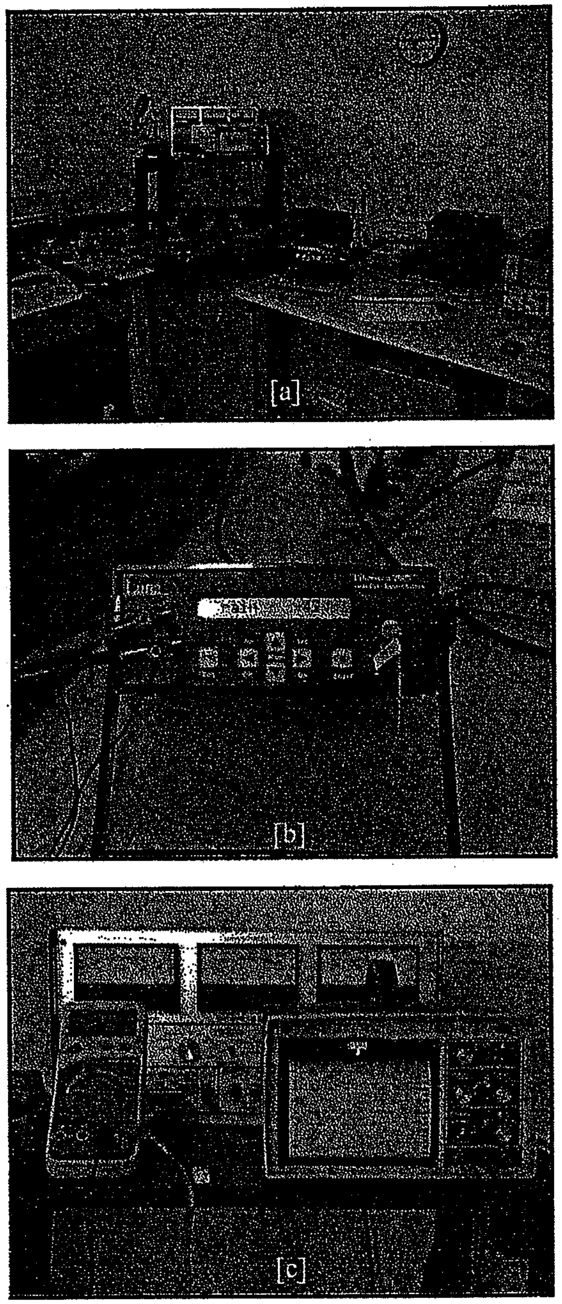

Figure 5. Laboratory set up for coating stress measurements using fiber optic strain gage apparatus (a) Overall set up (b) Fiberscan 2000 micro-strain measuring device (c) Recording and measuring analog output (1 mV = 1με).

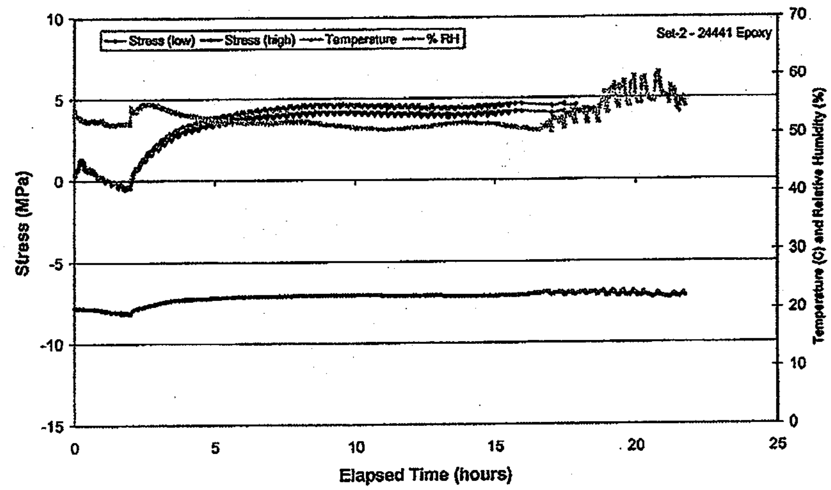

Figure 6. Coating stress measurements for MIL-P-24441 epoxy obtained with the FO strain gage technique.

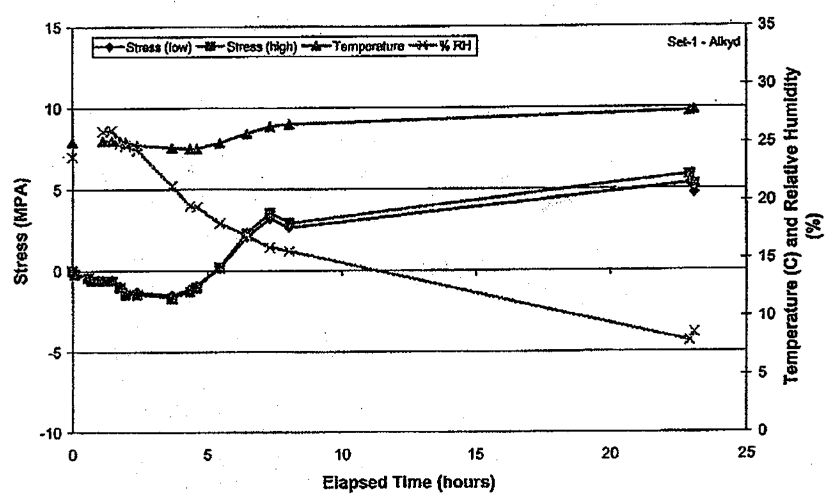

Figure 7. Coating stress measurements for an alkyd system obtained with the FO strain gage technique (Set-1).

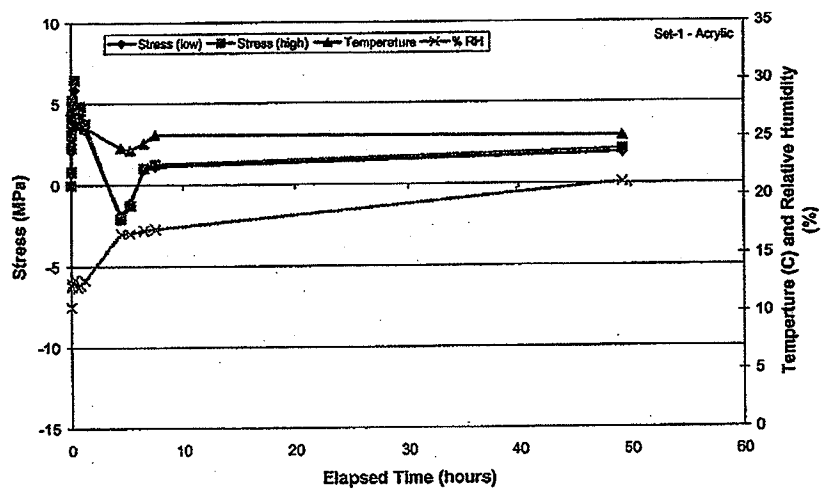

Figure 8. Coating stress measurements for an acrylic system obtained with the FO strain gage technique (Set-1).

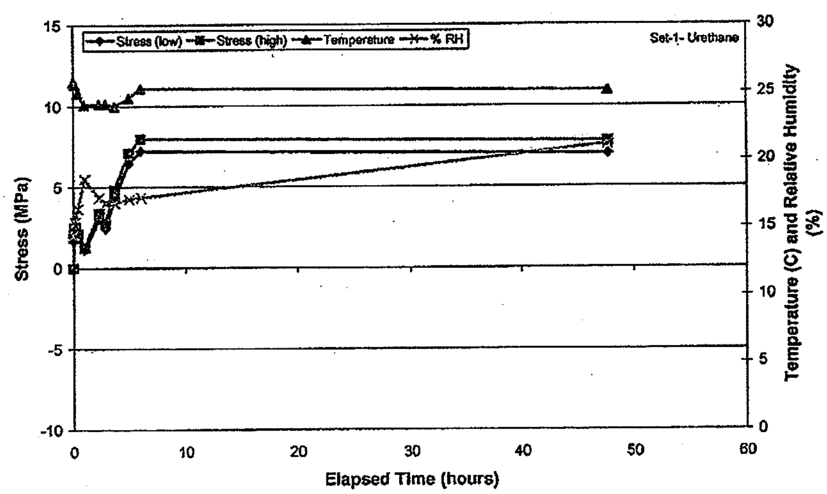

Figure 9. Coating stress measurements for a urethane system obtained with the FO strain gage technique (Set-1).

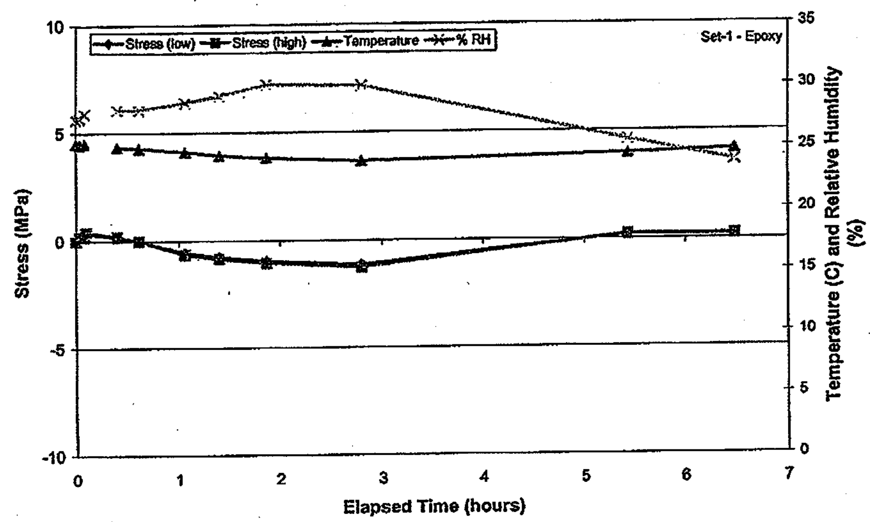

Figure 10. Coating stress measurements for carbomastic epoxy system obtained with the FO strain gage technique (Set-1).

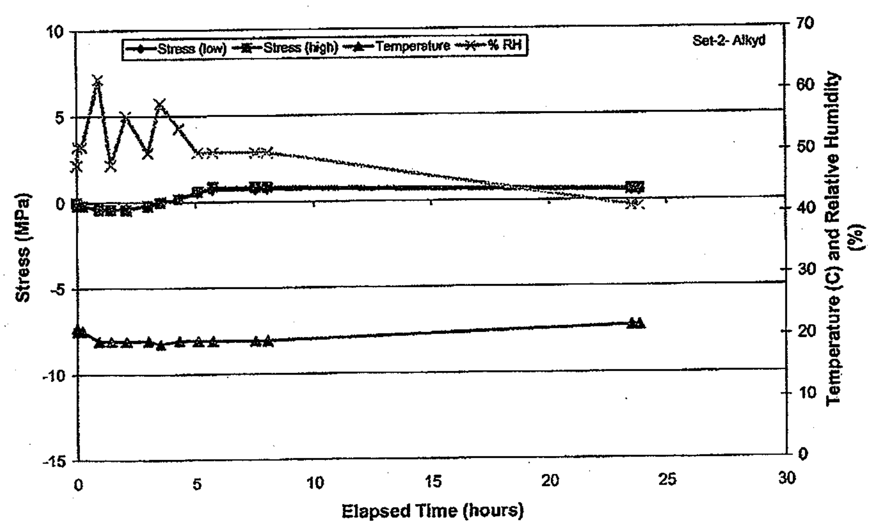

Figure 11. Coating stress measurements for an alkyd system obtained with the FO strain gage technique (Set-2).

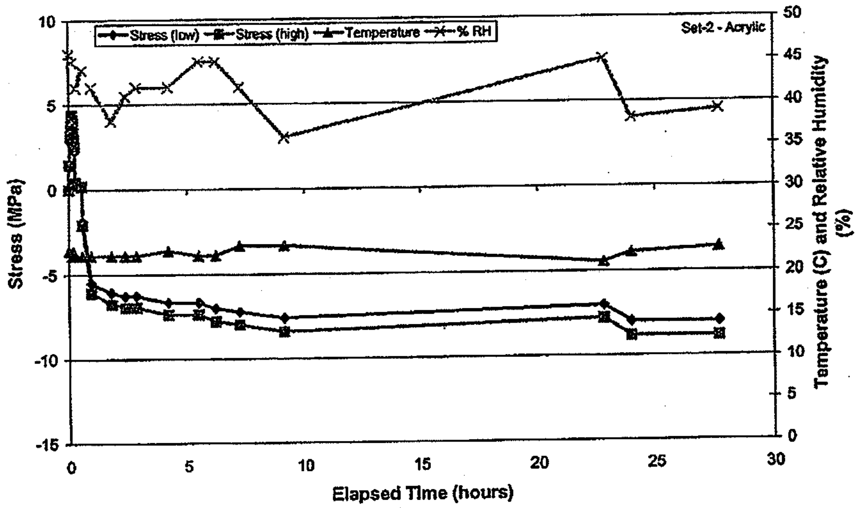

Figure 12. Coating stress measurements for an acrylic system obtained with the FO strain gage technique (Set-2).

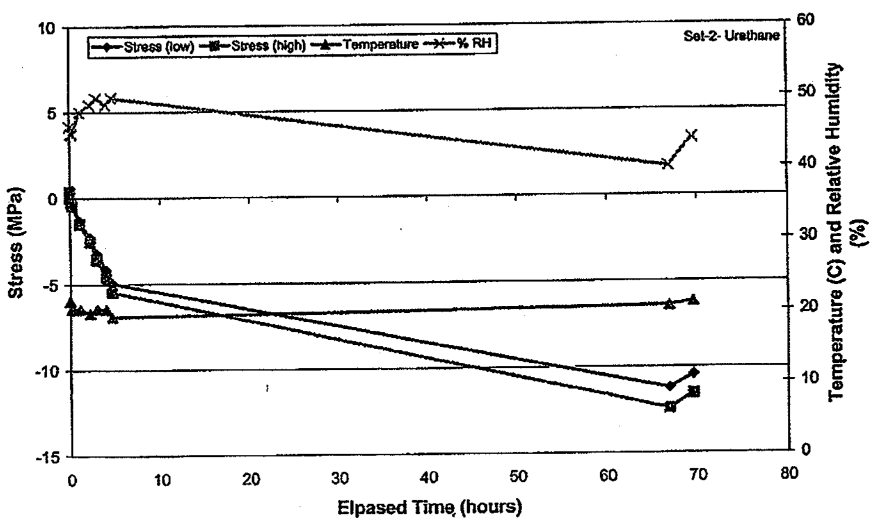

Figure 13. Coating stress measurements for a urethane system obtained with the FO strain gage technique (Set-2).

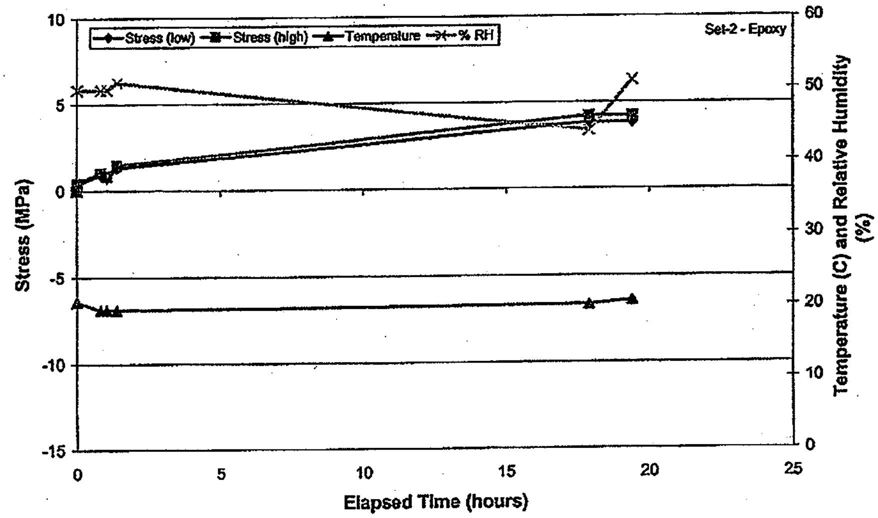

Figure 14. Coating stress measurements for a carbomastic epoxy system obtained with the FO strain gage technique (Set-2).

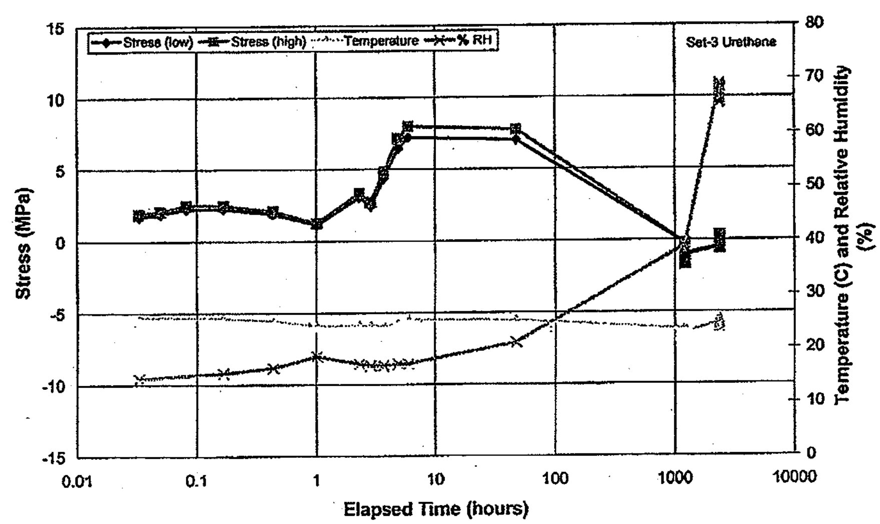

Figure 15. Coating stress measurements (long-term data) for an alkyd system obtained with the FO strain gage technique (continuation of Set-1 specimens).

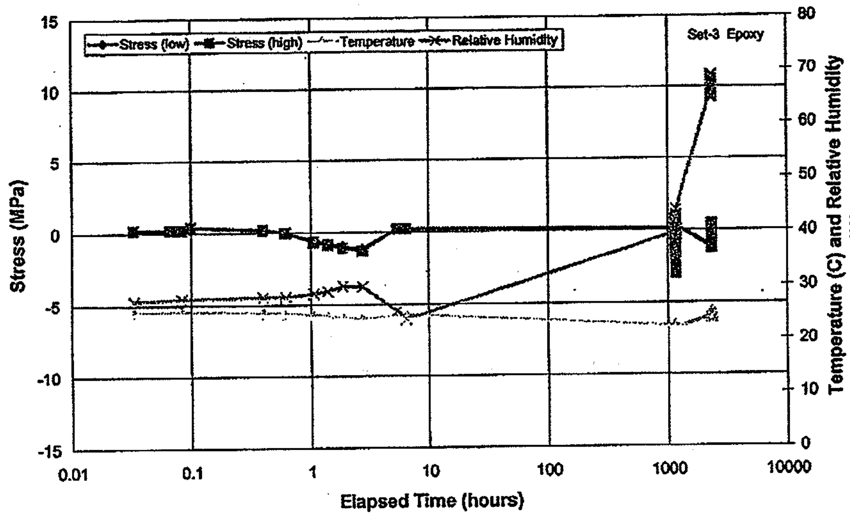

Figure 16. Coating stress measurements (long-term data) for an epoxy system obtained with the FO strain gage technique (continuation of Set-1 specimens).

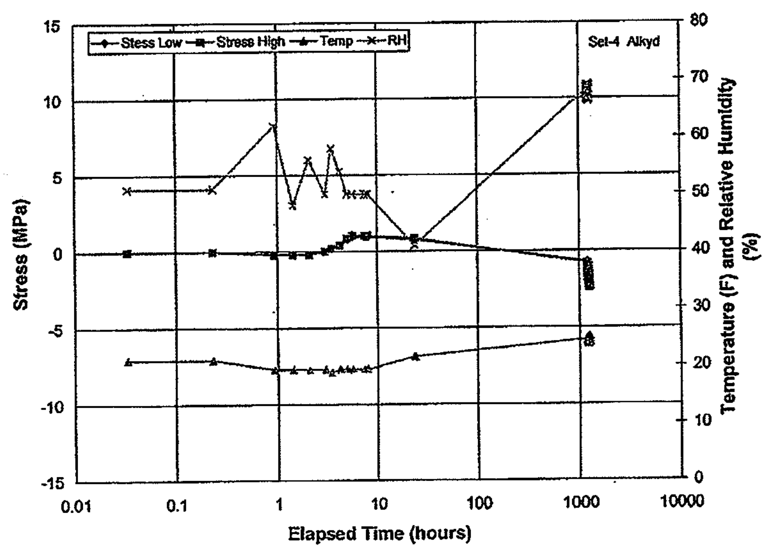

Figure 17. Coating stress measurements (long-term data) for an alkyd system obtained with the FO strain gage technique (continuation of Set-2 specimens).

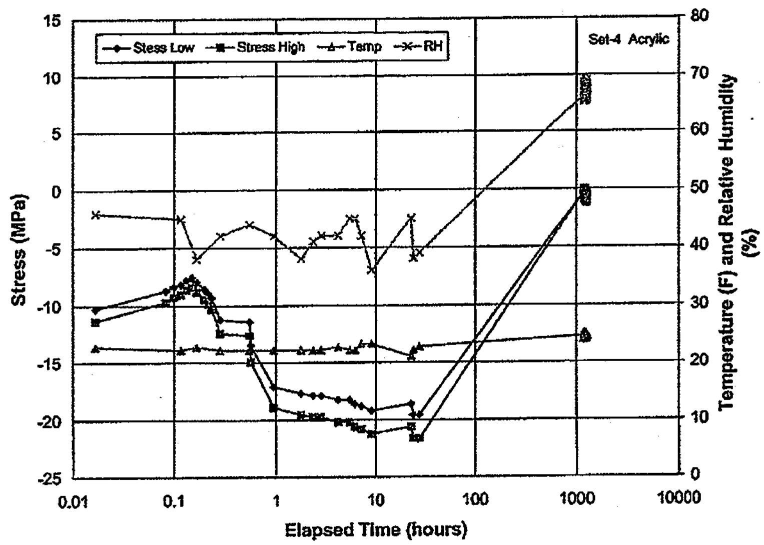

Figure 18. Coating stress measurements (long-term data) for an acrylic system obtained with the FO strain gage technique (continuation of Set-2 specimens).

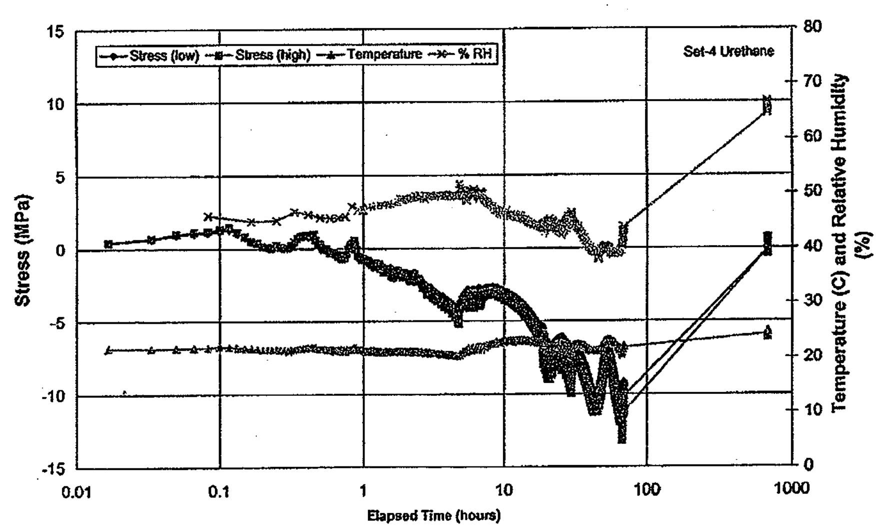

Figure 19. Coating stress measurements (long-term data) for a urethane system obtained with the FO strain gage technique (continuation of Set-2 specimens).

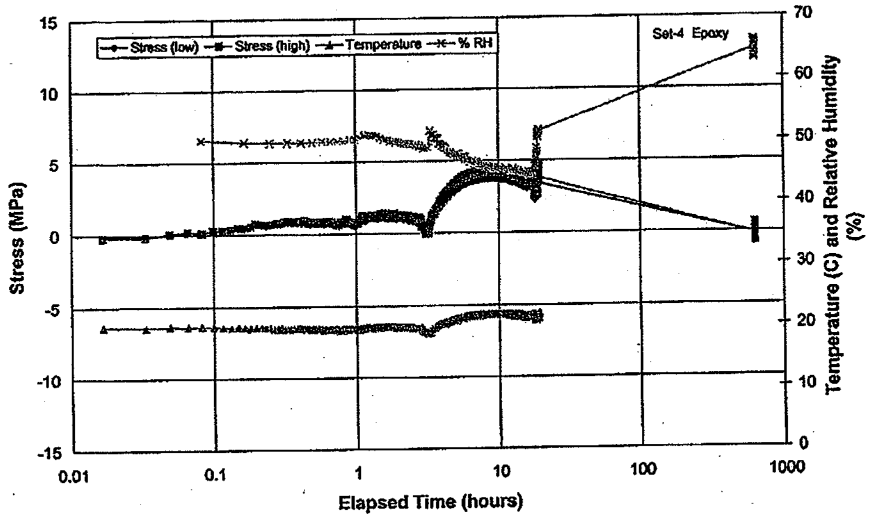

Figure 20. Coating stress measurements (long-term data) for an epoxy system obtained with the FO strain gage technique (continuation of Set-2 specimens).

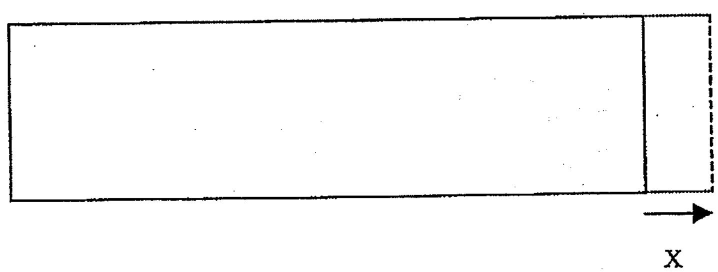

Figure 21. Pre-stressed Elastic Material Adhesion Tester

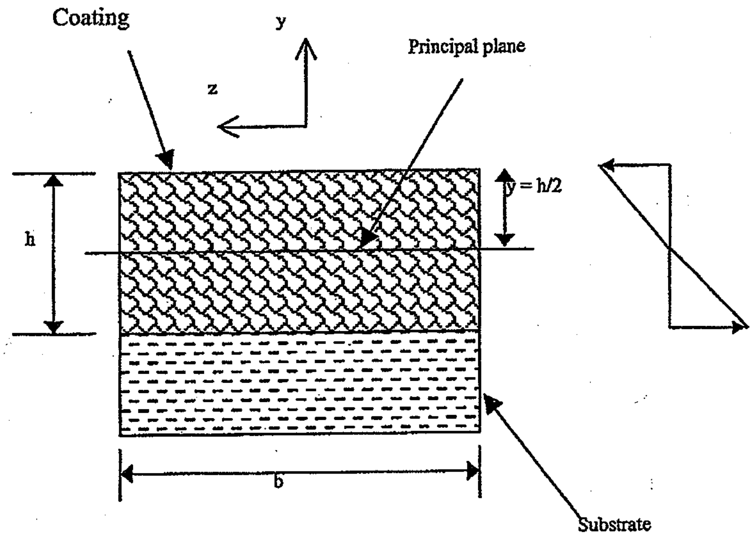

Figure 22. Stress distribution diagram.

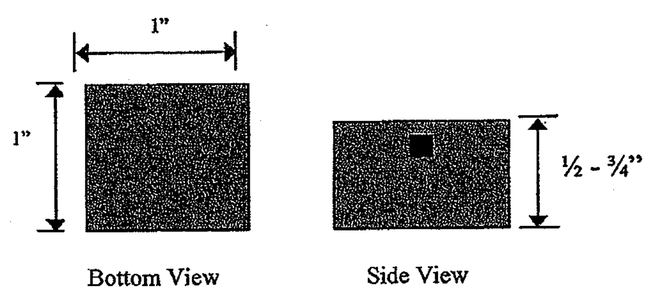

Figure 23. Dolly for Mechanical Tester.