Pull-Off Adhesion Test for Coatings on Large Pipes: possible variations in failure location and mode.

S. G. Croll[1], C. Siripirom[1], B. D. Keil[2]

[1] North Dakota State University, Dept. of Coatings and Polymeric Materials, P.O. Box 6050, Dept 2760, Fargo, ND 58108-6050. PH (701) 231-9415. E-mail: Stuart.Croll@ndsu.edu

[2] Northwest Pipe Company, 5721 SE Columbia Way, Suite 200, Vancouver, WA 98661. PH (360) 397-6343. E-mail: bkeil@nwpipe.com

Abstract

Pull-off adhesion testing per ASTM D-4541 is a commonly used quality control check for coatings on large diameter steel water pipe. During the testing a metal dolly is glued to a pipeline coating then pulled off, to assess adhesion of the coating. In practice, results are very sensitive to circumstances and have large standard deviations compared to their mean value. It is clear from a simple inspection of Griffith's equation for the strength of materials that the pull-off stress at failure increases with the stiffness of the materials, the interfacial failure energy and is diminished by presence of existing cracks or flaws. Finite element stress analysis explored the effect of the coating and glue stiffness as well as some of the other possible reasons for variation in the results, i.e. pipe curvature, misalignment of the dolly, as well as the effect of scoring through the coating and glue around the dolly. The tensile modulus of three polyurethane coatings, an epoxy adhesive and a cyanoacrylate adhesive were measured and showed that it was possible for a polyurethane coating to be stiffer than an adhesive used to fix the dolly in place. The location of the maximum strain, in the glue or the coating, was used as an indicator of where the adhesive failure was likely to occur within the overall joint. Results indicate that the influence of dolly misalignment on the coated pipe is greater than the influence of the pipe curvature itself. If the dolly was aligned perfectly, the greatest strain, and thus most likely location of failure was on the crest of the pipe at the pipe-coating interface. The value of the strain was not a strong function of the curvature of the underlying pipe surface. If the dolly was misaligned, then the locus of failure shifted to where the glue was thinnest, but remained at the coating-pipe interface, if the glue is stiffer than the coating. However, if the coating was stiffer than the glue, then the location of the

greatest strain indicated that failure was more likely to be at the glue-dolly junction in all cases, rather than at the coating-pipe interface. Users should be aware of how these, and other possible, variations affect the pull-off results if they rely upon single dolly pull values to assess the overall adhesion or use the test method to assess the likely reliability of a coated steel pipe in service.

Introduction

Steel pipelines used to transport water often have large fractions of their length buried underground, or otherwise inaccessible. One of the principal threats to the long term life of the pipeline is corrosion of the steel, so external polyurethane coatings are applied to prevent water and dissolved salts from attacking the pipes. Pull-off adhesion testing of the coating to the pipe, according to ASTM D-4541, is a universally used procedure to check the quality of the coating and its application to a properly prepared steel pipe. If the values obtained meet a standard, for example AWWA C222, then depending on the results of other tests, the coated pipe is deemed suitable for long term service.

The pull-off adhesion test is notorious for the variation in the results [Devries 2002, Ramos 2012, Croll 2012] and this paper explores some of the reasons for the variation.

In practice, the test is performed just after the pipe sections are coated, in the factory, or in storage, or at the job site. Thus the test is performed under environmental conditions that vary from cold to hot, humid or dry, and so on. Commonly, the test is performed where the engineer can reach, which might be on the side of a large diameter pipe. One can already appreciate the difficulty in obtaining reproducible results.

Causes of variability include problems in surface preparation, adhesive application, curing, thickness and evenness of adhesive, alignment of the pull-off dolly and variation introduced by the operator of the test equipment. The investigation here focuses on two forms of misalignment; when the substrate is not flat, as is specified in ASTM D-4541, and when the dolly is not set parallel to the substrate.

The need to maintain perfect alignment in the pull-off test has been realized for many years [Anderson[1] 1988] where it is suggested that good techniques can reduce the standard deviation to 10% of the mean, or less. This has also been suggested in other publications dealing with detailed stress analysis of adhesive joints [Anderson[2] 1988]. But, clearly, normal practice makes this difficult to achieve. Large differences in values are seen, even using the same materials, but at different institutions [Ikegami, 1996][ASTM 2009].

There are two complementary approaches to understanding the strength of a material or an adhesive joint. The energy approach, like other thermodynamic approaches, indicates whether a change, here the adhesive failure, may occur. This is often the simplest approach and may be all that is necessary. Stress analysis is much more complicated, but may be necessary because it provides the mechanistic information, indicating where the failure is most likely to start and progress.

Analyses of material systems, including adhesive joints, assume that the adhesive materials are homogenous and continuous. Typical coatings contain pigment particles, extender particles, may be phase separated and exhibit other inhomogeneities. In most discussions of adhesion, a coating or adhesive is assumed to be a single, deformable homogenous layer between two rigid adherends, and that the average stress across the area of the joint is sufficient to characterize the strength of the joint. In testing adhesion of coatings, the glue used to adhere the dolly to the coating is usually assumed to be part of the dolly and not to require consideration in the analysis. This implies that it must be very rigid compared to the coating, as well as adhere very well. Except in the most detailed analyses, the materials that form the joint are assumed to obey Hooke's law, i.e. be linear and elastic in their mechanical properties. In contrast, polymeric coatings and adhesives are intrinsically non-linear, viscoelastic materials.

Thermodynamic Approach to Adhesion Failure

Griffith's equation [Griffith 1921] for the strength of materials was a very important advance since it recognized that most material's strength was limited by cracks and flaws that were already present. The equation describes how brittle failure depends on the properties of materials and that failure is due to enlargement of a crack or flaw. A crack in this context may be actual damage or an interface where the adhesion between polymer and a pigment particle, for example, is very weak.

$$\sigma = \sqrt{\frac{2E\gamma}{\pi a}} = Stress_{External} + Stress_{Built-in}$$

Where:

E = Young's modulus of the material
γ= Interfacial energy of adhesion/area = energy required to create new crack surface within a material or interface (strain energy release rate)
a = radius of the existing crack (assuming a circular shape)
σ= Griffith fracture stress, the critical stress above which brittle failure occurs as a crack propagates, this is usually applied externally, but if the materials already have stress built in, from their curing chemistry, for example, the amount of external stress required is less.

The tensile modulus is appropriate in this equation because failure usually opens the crack wider, and stretches the material at the crack tip. This equation is often applied to polymer failure because failure usually occurs, suddenly, at very high strain-rates across the crack tip, and polymers are approximately brittle under these circumstances. If the polymer does not behave like a brittle, linear elastic material, then γ must include the energy dissipated in processes leading up to the crack propagating, e.g.

yielding, fibril formation etc. which can give energies orders of magnitude higher than that for crack propagation only [Shull 2000, Creton 2000, Crosby 2000]. The Griffith equation has been used widely in engineering and physical science, to describe the failure of many materials.

When one measures the stress necessary to pull a dolly and the adhering coating away from the substrate, it gives a value for the term on the right hand side of the equation. It does not give a value for γ which is the parameter relevant for the adhesion and there is no way to separate this parameter without other information. Any internal stress, caused by curing shrinkage or accidents of coating or glue application will diminish the external stress necessary for fracture.

Pull-off values can be increased by coatings that have higher values of modulus, have smaller pre-existing cracks and have other mechanisms for dissipating energy within the materials.

Adding a filler to a polymer increases the mechanical modulus and may increase the measured pull-off, as pointed out above. However, fillers may agglomerate and diminish the strength considerably because the rupture will be initiated at the agglomerate, i.e. they produced a large Griffith flaw. Large (micro) particles of filler have stress concentrations around them that form at the poles (even if the particle was perfectly spherical without sharp edges) with respect to the stress direction [Fond 2001] so the interface around a filler is a likely starting point for rupture. There is considerable interest in the use of nano-fillers where the particle size is less than the yield zone of the polymer and so one should get the advantage of the increase in modulus without the disadvantage of causing a large flaw that initiates failure. Unfortunately, nano-particles are very difficult to disperse so they can form agglomerates that are much larger and so form larger flaws and so lose the advantage.

The pull-off test for adhesion often produces a failure within the coating or within the glue, or at an interface or failure that changes its location across the overall area of the fracture. In a typical test, we have the coating and glue that may fail in a cohesive sense and we have the coating-substrate, coating-glue, glue-dolly interfaces that may fail in an adhesive sense. The failure will occur at those locations, adhesive or cohesive, that due to their properties offer the least resistance to the external stress.

There is a variant by Kendall [Kendall 1971] of the Griffith approach specifically for an adhesive between two perfectly rigid adherends, that ignores the possibility of pre-existing cracks and cohesive failure. It gives a result in a similar form:

$$\sigma = \sqrt{\frac{K\gamma}{t}}$$

Where:

σ = pull-off adhesion stress

K = bulk modulus of the adhesive layer since it is constrained between rigid bodies and no crack exists
γ= interfacial energy of adhesion/area
t = thickness of the adhesive/coating layer

Again, the measured pull-off stress is a value determined by a combination of parameters, not solely the interfacial adhesion.

The interfacial energy of adhesion must depend on the nature and number of the interactions between the coating material and the material of the substrate. Coatings studied by this test are rarely chemically linked to the substrate, nor interpenetrate the substrate. The interactions between a polymer and a substrate will depend on the polymer chain conformation at the substrate and the polymer moieties that are interacting with the material of the substrate. Polymer modulus will depend on the bulk properties of the composition, including crosslink density, chain stiffness etc. Interfacial interactions are not necessarily dictated by the bulk properties of the coating.

Even if the alignment in the pull-off test is perfect and all the other conditions have been met rigorously, the stress distribution along the bond line is not even. It is well known that stress concentrations occur at the edges of joints, at crack tips or other heterogeneities. The path of the failure crack can be understood from the stress intensities and the properties of the materials at the microscopic level. The expenditure of mechanical energy in all the processes leading up to failure will depend, of course, on these stress concentrations and their locations. Average stress across the whole joint area is significantly smaller than that at the stress concentration and since the failure will be determined by the maximum stress, average stress is not useful for correlation with other properties. The energy approach is simple, but it has already shown that in the dolly-glue-coating-substrate system, the pull-off test might produce a variety of results depending on the interfacial or cohesive fracture energies, material stiffnesses, and which material or interface has a crucial flaw. In order to gain more insight about how material properties and test geometry affect the how the adhesive or cohesive failure occurs, it is necessary to examine the stress, or strain, distribution within the system.

Stress Distribution

Films between a rigid dolly and a rigid substrate, are constrained by adhesion on both sides. Thus there can be a large hydrostatic stress due to this confinement which is largest in the center. This effect will be greater in less compressible materials, with a Poisson’s ratio closer to 0.5, see Figure 1. In practice, the coating thickness is much less than in the cartoon here, so the effect is greater. In reality the coating (and the glue) is not cut perfectly even with the dolly circumference, but extends, somewhat inconsistently, little way beyond.

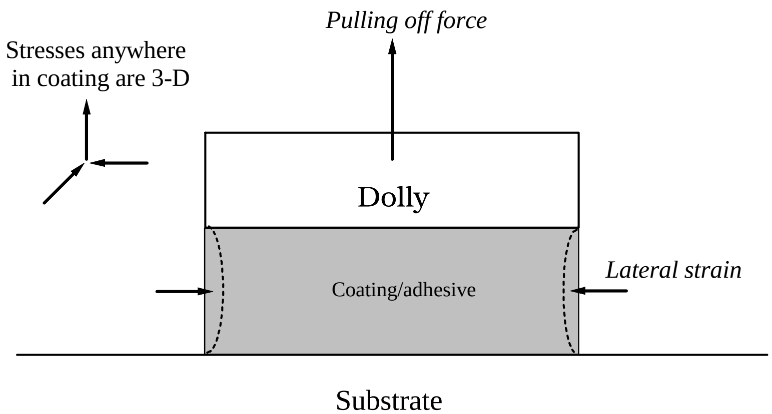

Figure 1. Schematic of the pull-off adhesion test illustrating how constraints produced by adhering to a rigid substrate and a rigid dolly cause multi-directional strains in the deformable coating and glue.

There is also a substantial stress concentration due to the edge of the joint and the sudden transition between polymer and metal properties, at the outer rim of the coating, or glue. Where the failure occurs will depend on where the stress is highest, where the energy necessary to create cracks is least and where the flaws are. The pull-off test seems simple but the stresses are complicated by the singularity at the rim of the adhesive dolly and how the geometry confines the material.

When failure occurs, the mechanical energy stored in the coating due to the stress field is greater than the material's strain energy release rate, and the crack propagates across the sample. Ideally, in an adhesion test this would be across the adhesive interface, but it may take other directions depending on the direction of the greatest stresses and the planes of weakness within the materials. If the pull is misaligned so that the load is essentially applied only at one edge of the specimen, it causes a partially peeling action with low "adhesion" values and the scatter in such data is large [Anderson[1] 1988]. Some have looked at the stress distribution in imperfect joints. Unsurprisingly, a disbonded area at the edge of the joint makes it weaker by increasing the stress singularity there and a spew fillet tends to increase the strength of the joint [Temma 1990].

Since there is no closed-form equation(s) giving the deformation or stress field, even in a perfectly formed, perfectly aligned pull-off configuration, the use of finite element analysis was used to gain more insight into the performance of the pull-off test under various circumstances. The finite element method is a common approach to solving the stress, or strain distribution in complicated situations. The method relies upon breaking down the overall shape into many, tiny and simple shapes, like a mosaic, in which the necessary equations can be solved (because the shapes are simple). Even rounded features can be modeled if the simple shapes are small enough.

The coating was simulated as an elastic, continuous, homogenous, even layer on a pipe of varying diameter, from 0.2 m (8 inches) diameter to 2.1 m (84 inches) The coating thickness was usually set at 0.8 mm (31.5 mil). The glue thickness, in level gluelines, was standardized at 0.05 mm (2 mil), since that was the greatest value suggested by the manufacturers of the cyanoacrylate. Like the coating, the adhesive was assumed to be elastic, continuous, homogenous and even. The adhesive dolly was given a 20 mm (0.8 inches) diameter and was analyzed in a level position, i.e., when the middle of the dolly was tangential to the pipe, or when it was slanted at 3 degrees away from tangential. This geometry was analyzed on pipes of various diameters and on a completely flat plane.

The adhesion dolly was modeled using the mechanical properties of aluminum and the steel pipe was modeled using the mechanical properties of structural steel. The pull-off stress applied was 10.34 MPa (1500 psi) which is a value required in AWWA C222, for the tensile adhesion of polyurethane coatings on steel pipes. The load was imposed on the top surface of a dolly that was 5 mm thick. Under these conditions, neither metal pipe nor dolly suffered significant deformation and maintained the coating-pipe contact area and the glue-dolly area constant. All the materials in the simulations were elastic so strains were reported here to indicate where the most deformation occurs and thus where a failure might be initiated [Strawbridge 1995; Chai 1996]. The results used here are the values, directions and locations of the principal strains and their maxima, caused by the pull-off load. If the visualization selected was stress, it was difficult to distinguish high values of stresses in the glue and coating because the rigid substrate and adhesion dolly were also bearing high values of stress. The only substantial strains are within the glue and the coating so the focus here is only on the strains within the coating or glue, as a guide to where the joint failure might be initiated. The aluminum dolly and steel substrate are stressed to the same level as the coating and the glue but deform much less. However, they are large and even though their strains are small they will store mechanical energy that is released into the failure crack, once it is initiated.

The simulation of a coating tested on a flat surface did not include the pipe explicitly in the model, but modeled the coating as having its base confined to remain constant in area.

The geometry was drawn, meshed and then solved using the Structural Mechanics module of Comsol Multiphysics® 4.3a. "Physics-based" automatic meshing for the finite element analysis was employed in this investigation since the scope of the project did not include developing separately the optimum mesh size and pattern for the separate components of the system. The problem involves parts that are very different in size. The pipe has a diameter of a meter or larger, but the coating is less than a millimeter in thickness and the glue is much thinner again. The finite element mesh must be fine enough to capture the stress field in the smallest component, but not so small in the very large components or the memory available in the computer is exceeded. The mesh fineness must model the change in deformation at the interfaces between materials and changes in shape. The meshing was done at a very fine level with each geometry so that the results were internally consistent, at least. Within the analyses done here, the numerical results vary approximately 5% going from 'normal' to extra-fine' meshing.

Figure 2, below, shows the overall simulation with its mesh and a more detailed view of the mesh used for the dolly, coating and glue.

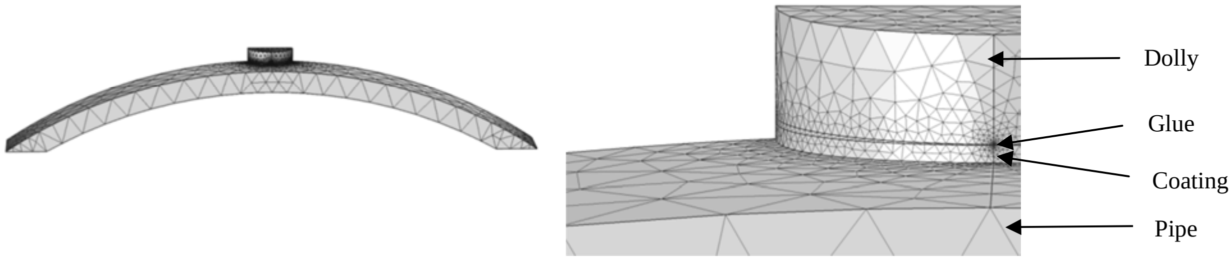

Figure 2. Overall and detailed view of the mesh used in the finite element computer simulation of the pull-off test on a pipe. The coating beyond the scoring around the dolly is not included since it is separated from the coating under stress.

It is worth noting that any inconsistency in the drawing of the components, or if a mesh was chosen too coarsely, made a substantial difference where the greatest value of strain occurred because the finite element analysis predicted and modeled a stress concentration at such places. This indicates that any imperfection or inconsistency in the preparation of the adhesive joint in practice would have a similar effect, indicating that the pull-off test is very sensitive to small variations in experimental practice.

Mechanical Property Values.

Although it is difficult to estimate the strain-rate in a tensile pull-off adhesion test, they are typically completed in 30-60 seconds and the simulation results (see later) suggest maximum strains of 1-2% at 10.34 MPa (1500 psi). Moduli of three coatings were measured in a dynamic mechanical analyzer (TA Instruments Q800) using a tensile sinusoidal strain of amplitude 0.05% at 1 Hz, see Table below, and are probably approximations good enough for consideration in calculations here. Values for coatings formed from 2-component mixtures will vary according to the quality of mixing, the temperature of mixing, and the length of time that they are allowed to cure.

Tensile Modulus of Polyurethane Coatings at 23 ºC, from 3 suppliers.

Coating	*Modulus, GPa*
A	0.6
B	1.8
C	1.4

It was difficult to measure the Poisson's ratio of the coatings. A value of 0.45 was chosen for the simulations here since the polyurethane coatings are clearly tougher and more rubbery than the epoxy adhesive. The 3M DP-460 2-component epoxy was found to have a modulus of 1.8 GPa and a Poisson's ratio of 0.38 (manufacturers data). However, there are reported values in the literature for this adhesive as high as 3.0 GPa and as low as 1.4 GPa (lower than one of the coatings). Actual values of modulus will vary substantially with mixing, temperature and curing time as well as strain-rate.

Cyanoacrylate adhesives are converted from monomers to thermoplastic polymers by reacting with the moisture adsorbed on the surfaces of the joint. The quality of the cure will also depend on joint thickness, since the moisture must penetrate everywhere from the joint surfaces. The manufacturers usually recommend that the glue thickness should be kept below 50 μm. Although cyanoacrylates cure very quickly, they are unlikely to be as rigid as the epoxy and their cure will vary greatly depending on environmental temperature and humidity. No published value for the modulus of such adhesives could be found in a literature search, probably because the values depend so much on individual circumstances. However, a sample, using 3M CA-100, was made in a rectangular mold using several applications of the glue, waiting until each layer had cured with the moisture in the atmosphere, before adding another layer. The modulus should be indicative of the values that might be expected. The sample made here proved to have a modulus at 23 ºC of 0.9 GPa. This value is lower than for two of the polyurethane coatings and lower than the modulus for the epoxy adhesive.

Results and Discussion

The coating and the glue were treated as Hookean materials, however it is well known that polyurethane coatings and adhesives are non-linear and viscoelastic. There are several devices that apply the pull-off stress in such tests, made by different manufacturers, each with their characteristic rate of loading. Some devices use manual application of the load, some not. These simulations calculated the deformation under a static load. There are many variations in properties that a simulation such as this may explore, those here are chosen to represent the range of possibilities rather than to be exhaustive. In most of the calculations, the glue was given a modulus of 1.8 GPa and the coating had a modulus of 0.8 GPa (softer than the adhesive, and not the same as any of the coatings). However, it is clear that the coating and glue may have comparable properties, and it would be mistaken to view the glue as being part of the dolly. Some of the simulations explore when the glue and the coating have the same properties, or when the glue is softer than the coating.

In all simulations, the maximum value of the first principal strain occurred in the tensile direction, located around the circumference of the coating or the glue as one should expect from the stress concentration there. However, the layer in which these occurred was sensitive to the prevailing circumstances.

Level Adhesion Dolly

The dolly was drawn level on the curved pipe, and calculations used the material parameters in the table below:

Material	Tensile Modulus, GPa	Poisson's Ratio
Coating	0.8	0.45
Glue	1.8	0.38

The maximum value of the first principal strain was calculated to be 0.017, and did not vary much with pipe diameter. The strain was tensile in the pulling direction. The location of the maximum first principal strain was at the coating - substrate interface, on the crest line of the pipe, see Figure 3.

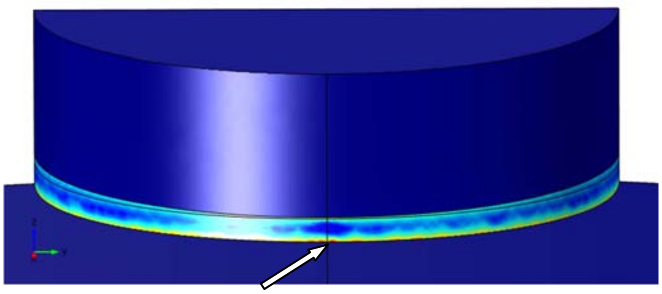

Figure 3. Distribution of the first principal strain in the coating between a level dolly and the steel pipe. The arrow indicates the position of the maximum tensile strain.

Here since the glue is stiffer than the coating, the greatest deformation is imposed on the coating where the glue is thinnest and deforms the least. The failure should start on the crest of the pipe, regardless of its curvature, between coating and substrate, because that is where the maximum strain occurs.

Now, when the coating is as stiff as the glue (or stiffer), calculations show that the maximum strain depends on the modulus of the glue and it occurs at the glue-dolly boundary over the crest of the pipe, again where the glue is thinnest, see figure 4.

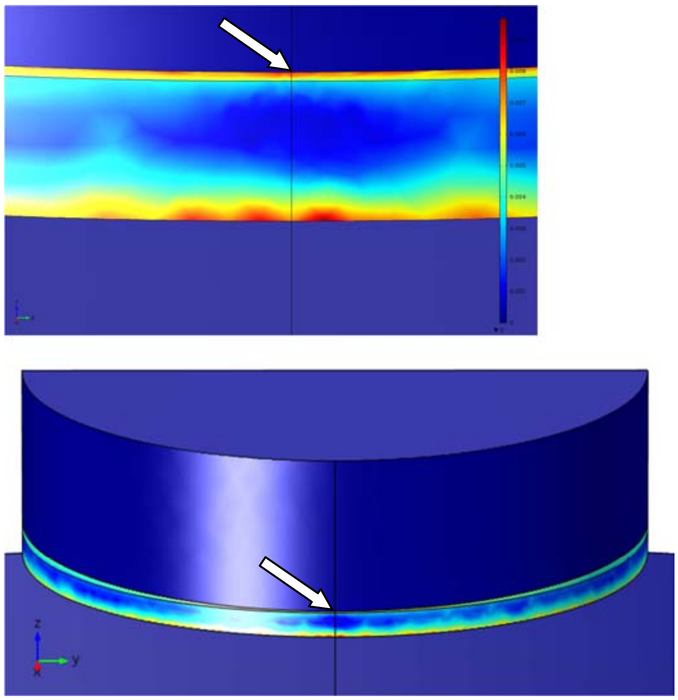

Figure 4. When the coating and glue have the same modulus, the maximum value of the first principal strain is at the glue-dolly intersection, over the crest in the pipe. Includes expanded view.

Thus, if the coating modulus becomes comparable to that of the glue, then the likely failure location becomes the glue. This result is consistent with the discussion earlier that was based on the simple Griffith equation. Some coatings often show failures initiating at or through the glue; this might be due to their adhesion to the pipe but, it might also be due only to the stiffness of the coating being comparable to the glue.

Slanted Adhesion Dolly

The material parameters were the same as above but the dolly was slanted at 3º from level. In all cases the greatest value of the first principal strain occurred at the circumference as always, but now at the junction of the coating and steel substrate where the combined coating and the glue was shortest, i.e. at the thin end of the slanted glue, see Figure 5.

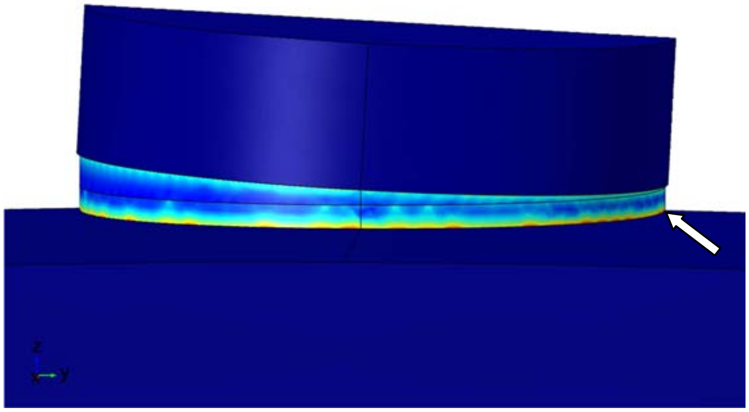

Figure 5. Distribution of first principal strain under a dolly adhering with a slanted glue line. The maximum value of the first principal strain is where the glue line is the thinnest.

The maximum value of the strain is very close to the value when the dolly is level (0.016 – 0.018), but its position has changed from the crest line of the pipe to where the glue is thinnest.

The maximum value of the second principle strain (second largest) occurred at the circumference of the dolly-glue-coating, directed radially inwards to the center of the geometry. This is what might be expected by virtue of the stress concentration around the periphery and the stress produced by the confinement of the glue and coating between the rigid dolly and rigid pipe, see Figure 1. The value of the maximum value of the second principle strain proved to be about a tenth that of the first principle strain but somewhat sensitive to the mesh size in the calculation, so values are not presented.

Conclusions

Gluing a dolly to a coating, then pulling it off in order to estimate the adhesion of a coating to the substrate is not a simple test. Although, the force is applied in a tensile mode to the dolly, the stresses within the glue and the coating are 3-dimensional and much more complicated due to the confinement caused by adhesion to the dolly on one side and the substrate on the other, so the average tensile stress calculated from the tensile load and the area of the dolly may not be the crucial value of stress where the failure occurred.

There is no certainty that the interface that fails will be the adhesive interface desired. Using the simple Griffith equation for the strength of materials, it is clear that, depending on the stiffness of the coating versus that of the dolly adhesive, and the importance of flaw size, the tensile force may cause a cohesive failure within the coating or the glue, or an adhesive failure at the glue-dolly interface or the glue-coating interface besides where the test is intended to probe, the coating-substrate interface. Even if all the mechanical energy applied in the test contributes to the adhesion failure, the breaking stress recorded measures a combination of the stiffness of the coating and its energy of adhesion to the substrate. It cannot, itself, measure the interfacial adhesion in isolation.

Polyurethane coatings and the adhesives are organic polymers that have much more complicated mechanical properties and modes of failure, so it is very common that only a small part of the mechanical energy expended during the test contributes to the adhesive failure, so the pull-off load recorded is much larger than it would be if it were characteristic of only the adhesion. Even before detailed computing of the deformation distribution in the joint, it is clear that the pull-off test is not simple. FEA simulations confirmed the high sensitivity of the pull-off adhesion test to experimental conditions. Coarse meshing produced apparent stress concentrations that indicate that any real stress concentrations caused by damage, imperfection or inconsistency in the adhesive joint in practice could change the location of the initial failure point, and greatly affect the value of the overall adhesion stress recorded.

In the finite element analysis the radius of the pipe has little effect on the value of the maximum strain for a level dolly. Its location was always around the outer periphery of the coating due to the stress concentration at the edge. In practice, the curvature of the pipe is important since it would be more difficult to place the adhesive dolly perfectly level on more tightly curved pipe and it would more difficult to score around the dolly without causing damage, and thus ‘Griffith’ flaws, in the glue or coating.

If the dolly adhesive was stiffer than the coating, the maximum strain was calculated to be at the coating-pipe interface and so the pull-off test would be more likely to test the coating-pipe interface. If the coating was not as stiff as the glue, the maximum strain occurred at the coating-glue interface and the test result would be for that interface, which is entirely consistent with the more general deductions made when discussing the layers in the system and how the Griffith equation represented their strength. For a dolly slanted at 3 degrees, if the glue was stiffer than the coating, the location of the maximum principal strain (and thus stress in the coating) was (as in the level case) between coating and pipe, but where the glue line was thinnest. If the coating was the stiffer layer under a slanted dolly, then the most likely failure location again shifted to the interface between the glue and the dolly. Altogether, the FEA stress analysis indicates that the location of the failure that dictates the recorded stress is sensitive to the details of the test geometry and the materials involved.

There are 2 consequences of providing a coating with a high tensile modulus. Firstly, a stiffer coating would produce a higher value of pull-off stress, regardless of the value of the interfacial energy of adhesion. Secondly, the location of the failure, in the tensile pull-off test, may shift into the glue, giving the impression of superior coating adhesion. With either argument, the coating has an apparently higher adhesion without having changed its actual interaction with the substrate.

Clearly, the adhesion test on coated pipelines suffers many uncertainties. Only some of them are caused by the curvature of the substrate. However, there has been no alternative test proposed that is as useful in establishing that the coating application and steel pipe preparation are competent. Until a different or improved technique is introduced for measuring adhesion, we must use the pull-off test but be careful to understand what it tells us, and remember what it cannot tell us.

"If a problem has no solution, it may not be a problem but a fact - not to be solved but to be coped with over time." Shimon Peres, Prime Minister of Israel.

Acknowledgements

The authors at NDSU are grateful to the Northwest Pipe Company for supporting this research.

References

ASTM D4541 - 09e1 (2009) "Standard Test Method for Pull-Off Strength of Coatings Using Portable Adhesion Testers," ASTM International, West Conshohocken, PA, 2009

AWWA C222-09 (2009) "Polyurethane Coatings for the Interior and Exterior of Steel Water Pipe and Fittings," American Water Works Association, Denver, CO

Anderson[1] G. P., Chandapeta S., Devries K.L. (1988) "Effect of Removing Eccentricity from Button Tensile Adhesion Tests," Adhesively Bonded Joints: Testing, Analysis and Design. ASTM STP 981, W. S. Johnson Ed., American Society for Testing and Materials, Philadelphia 1988, pp. 5 – 12

Anderson[2] G. P., DeVries . L. (1988) "Analysis of Standard Bond Strength Tests," Adhesion and Adhesives Vol. 6, Chapter 3, pp. 55 – 122 Marcel Dekker, NY

Chai H., Chiang M. Y. M. (1996), "A crack propagation criterion based on local shear strain in adhesive bonds subjected to shear," J. Mech. Phys. Solids, 44(10), 1669 – 1689

Creton C., Lakrout H. (2000) "Micromechanics of Flat-Probe Adhesion Tests of Soft Viscoelastic Polymer Films," J. Polym. Sci. B: Polymer Physics, 38, 965–979

Croll S. G., Vetter C. A., Keil B. D. (2012) "Variability of Pipe Coating Pull-off Adhesion Measurements on Cylindrical Steel Pipelines", Pipelines 2012, American Society of Civil Engineers, Miami, August 20th, 2012.

Crosby A. J., Shull K. R., Lakrout H., Creton C. (2000) "Deformation and failure modes of adhesively bonded elastic layers," J. Appl. Phys., 88(5), 2956 – 2966

DeVries K. L., Adams D. O. (2002), "Mechanical Testing of Adhesive Joints," pp. 193 – 234, Chapter 6 in The Mechanics of Adhesion, Eds. D. A. Dillard, A. V. Pocius, Elsevier

Fond C. (2001) "Cavitation Criterion for Rubber Materials: A review of Void - Growth Models," J. Polym. Sci.: Part B: Polymer Physics, 39, 2081 – 2096

Griffith, A. A. (1921). "The Phenomena of Rupture and Flow in Solids". Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 221, 582–593

Ikegami K., Fujii T., Kawagoe H., Kyogoku H., Motoie K., Nohno K., Sugibayashi T., Yoshida F. (1996) "Benchmark tests on adhesive strengths in butt, single and double lap joints and double-cantilever beams," Int. J. Adhesion and Adhesives, 16(4), 219 - 226

Kendall K (1971), "The adhesion and surface energy of elastic solids," J. Phys. D: Appl. Phys., 4, 1186 – 1195

Ramos N. M. M., Simões M. L., Delgardo J. M. P. Q., de Freitas V. P. (2012) "Reliability of the pull-off test for in situ evaluation of adhesion strength," Construction and Building Materials, 31, 86 – 93

Shull K. R., Flanigan C. M., Crosby A. J. (2000) "Fingering Instabilities of Confined Elastic Layers in Tension," Phys. Rev. Lett., 84(14) 3057 – 3060

Strawbridge A., Evans E. (1995) "Mechanical failure of thin films," Eng. Failure Analysis, 2(2), 85 – 103

Temma K., Sawa T., Tsunoda Y. (1990) "Three-dimensional stress analysis of adhesive butt joints with disbonded areas and spew fillets," Int. J. Adhesion and Adhesives, 10(4), 294 – 300