BOND-LINE READ-THROUGH INVESTIGATION FOR COMPOSITE CLOSURE PANELS: INITIAL DOE RESULTS

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Abstract

Bond-line read-through (BLRT) is a distortion in a Class “A” surface that has no impact on the structural performance of automotive body panels, yet it diminishes a customer’s perception of the quality of a vehicle. The root causes of this distortion are poorly understood. When a panel is discovered to exhibit BLRT in production, the most straightforward solution is to increase the thickness of the outer panel – essentially adding weight for appearance. The Automotive Composites Consortium Joining Working Group (ACCJWG) has a multi-year project targeted at developing a better understanding of the causes of this distortion so that OEMs can use minimum thickness body panels and still meet customer expectations for surface appearance quality.

In the first phase of this project, the ACCJWG developed a tool for quantifying the visual severity of this distortion. The ACCJWG then partnered with Meridian Automotive Systems to complete a series of experiments to understand the material and process variables that influence BLRT and to determine how to minimize the severity of this distortion without increasing the thickness of the outer panel. The format and results of the first two experiments of this series will be discussed.

The first experiment was a screening experiment to determine whether any of the eight factors evaluated impacted the severity of BLRT. The factors evaluated in that experiment were type of substrate, degree of cure of the SMC, type of adhesive, consistency of bond-line thickness, pattern used to apply the adhesive, distortion in the inner panel, temperature at which the adhesive was cured, and type of electric bonding nest. Six factors were found to have a statistically significant effect on BLRT severity, although the effect of three of the factors may have been confounded by an uncontrolled covariate. Two factors were found to not impact BLRT severity.

The temperature at which the adhesive was fixture cured was found to be the factor with the greatest impact on BLRT severity in the first screening experiment. Consequently, a second experiment investigated this factor in more detail. This experiment was a two factor, full factorial experiment with three replicates at each condition. The factors evaluated were the type of adhesive and the temperature at which the adhesive was cured. One adhesive was an epoxy adhesive while the other was a urethane adhesive. The cure temperatures were room temperature, 120°F, 240°F, 270°F, and 300°F.

Introduction

The appearance of an automobile’s exterior is one of the most important factors to a customer when they are choosing what vehicle to purchase. Consequently, manufacturers work hard to ensure that the surface produced is the Class “A” surface intended. While there are many benefits to using adhesives in automotive body components, their use can result in a distortion in a Class “A” surface. This distortion has been termed “bond-line read-through” (BLRT).

There have been efforts to determine what causes this distortion in a surface [1-4]. Unfortunately, the results of experiments can contradict each other. This is most likely due to the fact that an instrument capable of objectively quantifying the severity of BLRT did not exist. The Automotive Composites Consortium Joining Working Group (ACCJWG) collaborated with Visuol Technologies and EOS Technologies to develop a metric capable of providing an objective measure of this distortion [5].

Once the measurement system had been demonstrated to correlate to visual assessments of the severity of these distortions, it could be used to quantify the severity of BLRT in experiments designed to identify the root causes of this distortion. The ACCJWG has an ongoing collaboration with Meridian Automotive Systems to complete a series of experiments to understand the root causes of BLRT. The results of the first two experiments are summarized in this paper.

Bond-Line Read-Through Measurement

The BLRT measurement tool developed as part of this project is based upon the ONDULO technology. A detailed description of how the ONDULO technology works is available in an earlier publication [5]. The reader should note, however, that the BLRT measurement described in that publication is not the current version of the algorithm. An updated description of the format of the algorithm and a demonstration of the correlation of the BLRT scores to visual assessments will be published at a later date.

The output of the ONDULO technology is a map of the local curvature values at each point in a surface. The BLRT measurement algorithm first filters the curvature data to remove short wavelength defects, such as paint induced waviness (e.g. orange peel) and roughness, and to remove long wavelength deformations, such as deformation in the part shape, since these features do not affect the perception of BLRT. An example of a filtered curvature map is shown in Figure 1. If the filtered curvature map contains defects that are not related to BLRT (e.g. paint pops or ejector pin mark-offs) these defects can be removed from the data by a masking operation so that they do not affect the BLRT severity score. The green regions in Figure 1 are masked pixels.

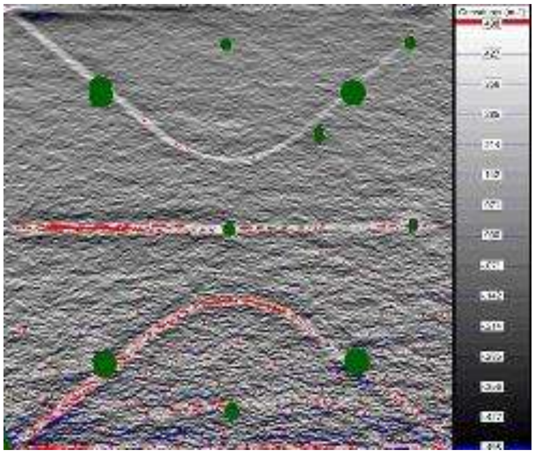

***Figure 1**. Curvature Map of a Panel with BLRT after Filtering and Masking.*

To calculate a BLRT severity score, the data in the filtered curvature map is thresholded to identify the pixels with curvature values above the limit that was found to correspond with visible distortions. Those remaining pixels are grouped into discrete defects. An example of the BLRT score map derived from the filtered curvature map in Figure 1 is shown in Figure 2. Note that the ONDULO technology is more sensitive than the human eye, so while in this case the curvature map appears to show a distortion along the entire bondline, the bondlines on the upper right and lower right of the panel are not visible to the unaided eye.

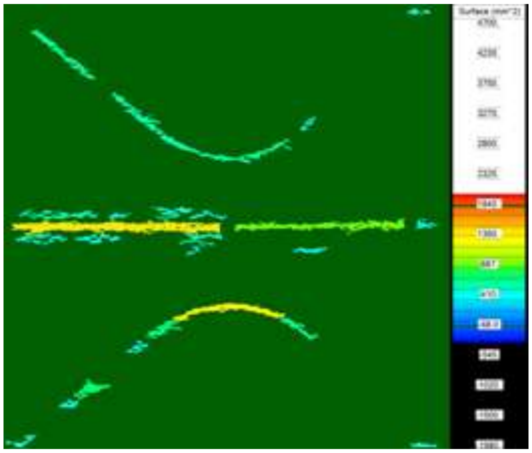

***Figure 2**. BLRT Score Map for the Panel in Figure 1.*

The severity "score" for each discrete defect on a panel is calculated by squaring the mean curvature of that defect and multiplying that by the size of the defect. The severity score for the entire panel is then the sum of the scores of all the defects on the panel.

The ACC's ONDULO system is a portable system designed to be flexible enough to measure a wide variety of parts. Consequently, the screen onto which the grid pattern is projected is nearly perpendicular to the part being measured. The camera is positioned at a 45° angle to the part. As a result, the level of contrast is lower at the bottom of the part than at the top. This difference in contrast across a square part is demonstrated shown in Figure 3.

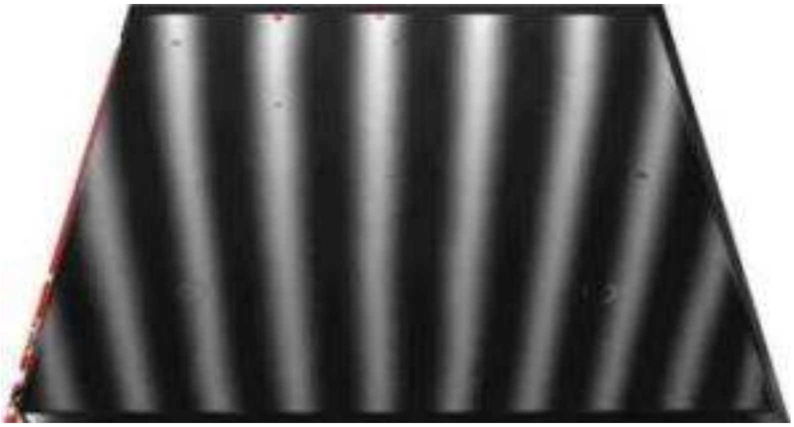

***Figure 3**. "Raw" Image of an Assembly Showing the Variation in Contrast from Top to Bottom*

The reduction in contrast at the bottom of the part results in a higher level of noise in the curvature data at the bottom of the resultant maps. Since this variation in contrast is due to the configuration of the ACC's ONDULO system, each assembly was measured twice to minimize the impact of the noise on the calculated BLRT severity scores. The first image was used to calculate the severity of the read-through on the "top" 60% of the assembly, including the center bond line. The assembly was rotated 180° and a second image was captured. This image was used to calculate the severity of the read-through on the "bottom" 40% of the panel. The two scores were then added together to calculate a score for the entire assembly. Rotating a part using a production representative ONDULO system would not be required as the screen would be positioned parallel to the part such that the level of contrast, and therefore the amount of noise, would be more consistent across the part. Data was captured on the assemblies in the "raw", "primed", and "painted" states. The final statistical analysis was completed using only the data from the panels after painting since in production panels are ultimately determined to be acceptable or unacceptable after painting.

BLRT Root Cause Analysis Assemblies

The assembly used to investigate the root causes of BLRT mimicked a typical automotive closure panel. Closure panel assemblies typically consist of a Class "A" outer panel that is bonded or hemmed to a structural inner panel. The inner panel carries the component loads and provides attachment points for hinges and trim. On a fully assembled vehicle it is largely hidden from the customer by the Class "A" outer panel on one side and interior trim panels or hood liners on the other.

The assemblies built in this project consisted of a 610mm x 610mm flat plaque bonded to a specially designed inner panel. A 610mm x 610mm flat "outer panel" was selected since the Automotive Composites Consortium (ACC) owns both a compression and an injection molding tool of this size and configuration. In addition, it is relatively easy to obtain flat sheets of steel, aluminum, or thermoplastic to bond to the inner panel if required for the experiment. The ACC molding tools can mold plaques in a variety of thicknesses. The panels used in both experiments were 2.5mm thick.

The first experiment included steel as one "outer panel" material. The steel "outer panels" in that experiment were 610mm x 610mm sheets of 0.7mm thick, 210 bake-hardenable steel. This particular thickness and grade of steel is typical of conventional automotive steel closure panels. To ensure good paint adhesion to steel in production, a polymeric coating (i.e. "electrocoat" or "e-coat") is applied to the steel through an electrophoretic deposition process that is the first step in the painting process. The bake required to cure this coating is typically the highest temperature bake in the painting process. Unfortunately, urethane adhesives degrade at temperatures required to cure e-coat. Consequently, the assemblies in this work could not be e-coated after bonding. To ensure good paint adhesion to the steel, the steel "outer panels" were e-coated as free standing panels prior to bonding. The steel sheets were prepared by Mittal Steel and e-coated at Ford's service parts depot in Brownstown, MI.

The 610mm x 610mm SMC "inner panel" used in these experiments was designed to have features common to both automotive hoods and roofs. All inner panels in this work were molded from SMC, regardless of the material used for the outer panel. A schematic of the inner panel is provided in Figure 4. This tool was also designed to mold panels from 1.0mm to 5.0mm thick. The panels used in these two experiments were 2.5mm thick. The bond flanges that represent "lightening hole" flanges on hood inner panels are 12mm, 24mm, 36mm or 48mm wide. The remaining bonding flanges are 24mm wide. Ten holes were drilled in the inner panel prior to bonding. These holes were used to hang the assemblies for painting, to allow fluid to drain from the assembly after power washing, and to vent the assembly cavities during paint bakes.

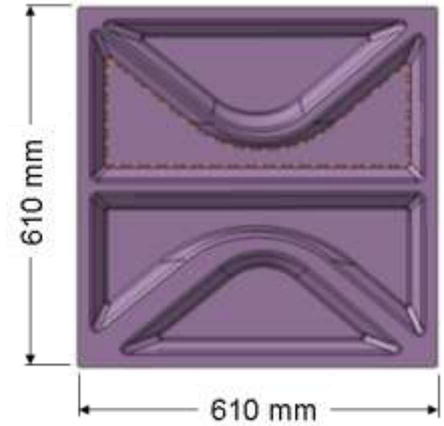

***Figure 4**. ACC BLRT Root Cause Analysis Inner Panel.*

A small cooling fixture was built to allow the SMC panels to be cooled in either a "flat" configuration or a "warped" configuration. While panels rarely become warped in production, the crown and sweep of an inner and outer panel of an assembly may not match exactly. Adding a controlled amount of warp is a relatively easy way to simulate this mismatch.

The cooling fixture was designed so that it could be used after molding either inner panels or outer panels. The panel is supported at all four corners and at the center. Upon removal from the compression mold, a panel is placed on the fixture and clamped into place on the corners. If the shim packs at the corners are the same height, the panels will be flat. If shims are either added or removed at one or more corners, the panel will be warped by a controlled amount after it has cooled.

ACC BLRT Bond Cell

In production, SMC assemblies are typically bonded using a two-part adhesive prior to being primed or shipped to the OEM. The adhesive must reach handling strength before the assemblies can progress through subsequent steps in the manufacturing process. Since two-part adhesives commonly take at least two hours to reach handling strength at room temperature, part suppliers typically fixture cure the assemblies to reduce the time required to manufacture a part.

To simulate this manufacturing process, an electrically heated bonding fixture was built to fixture cure the ACC BLRT assemblies. The fixture was built with removable sections to allow the team to evaluate the effect of heating the entire panel (using a "full nest") as well as the effect of heating only the bond-lines (using a "skeletal nest"). To heat only the bond-lines, the heaters to the sections between the bond-lines can simply be turned off or the sections can be removed. In all experiments discussed here, the sections were removed from the nest in the “skeletal nest” configuration.

Adhesive was applied to the inner panel to ensure that the bead was properly located on the bond flanges of the inner panel. Consequently, the flat "outer panel" is located in the top of the fixture and held in place by vacuum with four suction cups. The inner panel is placed in to the fixture after the adhesive has been applied to it and is also held in place by vacuum with four suction cups. Vacuum was used to hold both panels against the fixture to improve heat transfer between the fixture and the part and to improve the consistency of the bond gap around the panel.

A small up-acting bond press was built to actuate the fixture. The press was sized to accommodate both an electrically heated fixture and a hot air fixture, although the hot air fixture has not yet been built. The press closes on stops to control the gap between the fixture halves. Shims can be added to or removed from the corner posts to allow for varying panel thicknesses and for varying nominal bond gaps. In addition, the press was designed to allow additional shims to be added to either the right or left side of the press, creating a bond-line on one side that is thicker than the bond line on the other side. The press can accommodate as much as a 5mm difference in the bond gap from right to left.

To cure assemblies, panels were held in place in the fixture with vacuum, the press was closed on stops and the adhesive was fixture cured for the prescribed time and temperature. The vacuum was released, the press opened, and the assembly was removed from the fixture.

Panel Finishing

Exposing bonded assemblies to the thermal stresses of the painting process is believed to exacerbate BLRT. In addition, BLRT is more visible to the unaided eye after painting. Consequently, all assemblies were painted after bonding. Because the heat history to which a panel has been exposed is believed to affect BLRT severity, all assemblies, regardless of their composition, were painted using the same process.

The painting process was intended to be representative of the process a closure panel would experience when painted on-line in an OEM paint shop using liquid primer. A typical on-line painting process consists of a conductive primer application at the SMC supplier, e-coat application and bake, a second primer application and bake, and basecoat/clearcoat application and bake. That process, however, had to be modified slightly for this project. First, since some of the panels were bonded using a urethane adhesive which will degrade at typical e-coat bake temperatures, the e-coat application and bake was omitted from the painting process. In addition, steel/SMC hybrid assemblies would not normally be conductively primed. So that all the assemblies manufactured in these experiments, including those made with previously e-coated steel, experienced similar heat histories, all were conductively primed at Meridian and then painted at ACT Test Panels in Hillsdale, MI.

After ONDULO curvature data was obtained on the parts in the "as-bonded" (“raw”) state, the parts were primed at Meridian-Shelbyville using their production system. The panels were attached in a vertical orientation to paint racks built for these parts. Meridian-Shelbyville's conductive priming process included an initial power wash step typical to SMC painting processes. The parts were dried at 93°C for 15 min after power washing. A Red Spot UAE2560C conductive primer/surfacer was then robotically applied at a nominal film build of 25μm. The primer was allowed to flash off for 15 minutes. The temperature during flash-off started at 27°C but finished at 38°C. The prime was then baked at 115°C for 20 min. The assemblies were shipped to Ford Research & Advanced Engineering after priming.

After ONDULO curvature data was obtained at Ford on the primed panels, the assemblies were shipped to ACT Test Panels for top coating. The assemblies were first cleaned and dried. The panels were then primed using Dupont 708DM730 at a nominal film build of 23μm. The panels were baked at 152°C for 30 min to cure the prime layer. The panels were then painted with 13μm (nominal) Dupont 648DN027 black basecoat and 46μm (nominal) Dupont RK8014 clearcoat. The basecoat/clearcoat layers were allowed to flash off for 20 minutes prior to baking at 143°C for 30 min. The assemblies were returned to Ford Research & Advanced Engineering and curvature data was collected a third time.

First Screening Experiment

The team created a list of all the factors that have been proposed as contributors to BLRT. That list contained forty-two potential factors. Since that was too many factors to contain in a single experiment, the team prioritized the list and chose eight factors to include in a first screening experiment. Screening experiments are designed to determine whether a factor has an influence on the result. Based on the engineering experience of the team, factor levels were selected to be far apart while still remaining within the expected limits of response linearity. This was done to ensure that the experiment captured a possible effect in the presence of experimental noise. Since some of the factors resulted in combinations that could not be built (e.g. heating only the bondlines and room temperature cure), the experiment was broken into two groups of sixteen runs. The factors included in this experiment and their levels are summarized in Tables I and II.

***Table I**. Factors Included in the First Screening Experiment, Part A*

Factor		Low Level	High Level
A	Adhesive Modulus	364 MPa (Urethane)	3296 MPa (Epoxy)
B	Variation in Bond-line Thickness	None	3mm
C	Adhesive Application Pattern	Continuous	Drops
D	Warp in the Inner Panel	None	Warped
E	Outer Panel Substrate Stiffness	2.5mm SMC	0.7mm 210BH Steel
F	Bonding Temperature	RT	300°F

***Table II**. Factors Included in the First Screening Experiment, Part B*

Factor		Low Level	High Level
A	Adhesive Modulus	364 MPa (Urethane)	3296 MPa (Epoxy)
B	Variation in Bond-line Thickness	None	3mm
C	Adhesive Application Pattern	Continuous	Drops
D	Warp in the Inner Panel	None	Warped
G	Degree of Cure of the Outer Panel	Undercured SMC	Fully Cured SMC
H	Bond Nest Configuration	Skeletal Nest	Full Nest

In Part A of the experiment, the SMC outer panels were fully cured. The bonding nest was set up as a full nest in that portion of the experiment. In Part B, all of the assemblies were bonded at 300°F. The nominal bond-line thickness throughout the experiment was 1mm. When the bond-line thickness was varied by 3mm (factor B), the bond-gap was 1mm on the right hand side of the assembly and 4mm on the left hand side.

Results from the First Screening Experiment

Many of the assemblies that were cured at 300°F exhibited BLRT after the adhesive was cured in the fixture. None of the assemblies that were cured at room temperature, however, exhibited read-through prior to priming. While in some cases, particularly in some of the assemblies cured at room temperature, the BLRT severity increased after priming, priming did not consistently increase the severity of BLRT. Panels that did not exhibit quantifiable BLRT after priming did not develop BLRT during the painting process. Similarly, the relative severity of BLRT did not appear to change much between priming and painting in the panels that already exhibited BLRT after priming.

BLRT severity scores in these assemblies after painting varied between 0 and 1054. Filtered curvature maps showing these extremes are provided in Figures 5 and 6.

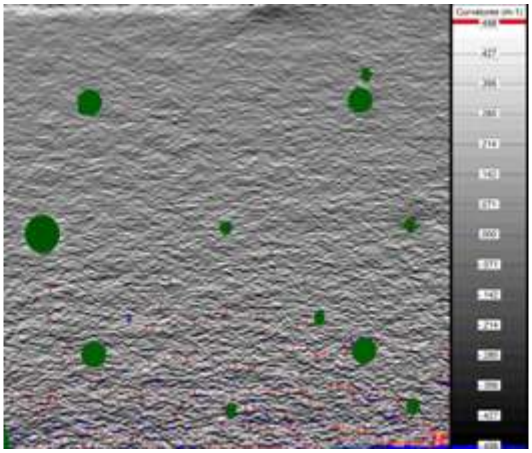

***Figure 5**. Filtered Curvature Map for a Panel with a BLRT score of 0.*

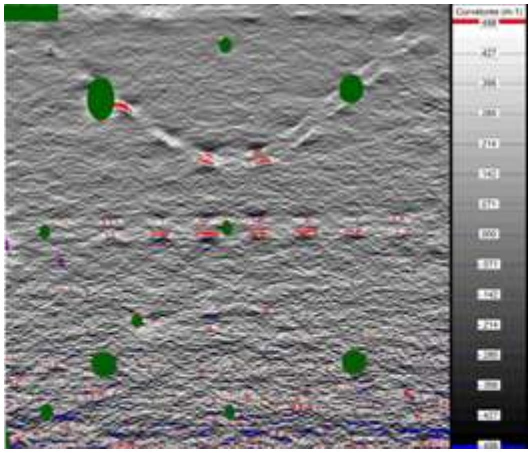

***Figure 6**. Filtered Curvature Map for a Panel with a BLRT score of 1054.*

The data from each part of the screening experiment was analyzed separately using a stepwise-backward multiple linear regression technique. This is a statistical analysis technique in which factors that are not found to be statistically significant are removed from the regression analysis one-by-one until only the factors with a statistically significant effect remain.

In addition to evaluating the effect of the control factors in the regression analysis for Part A, four interactions were included as well: outer panel substrate stiffness X adhesive modulus; outer panel substrate stiffness X variation in bond-line thickness; outer panel substrate stiffness X adhesive application pattern; and adhesive modulus X adhesive application pattern. The form of the regression equation that was found to best model the results of Part A is shown in Equation 1.

$$\text{BLRT Score} = \beta_o + \beta_A A + \beta_B B + \beta_C C + \beta_D D + \beta_E E + \beta_F F + \beta_{AC} AC + \beta_{AE} AE + \beta_{BE} BE + \beta_{CE} CE \quad (1)$$

The factor designations (e.g. A, B, etc) in Equation 1 correspond to the letters assigned to each factor in Table I. In general, the coefficients (β_i) shown in Equation 1 can assume positive or negative values.

When all ten terms (i.e. factors and interactions) were included in the regression analysis, the resulting regression equation had an R-Sq(adj) of 99.5%. While there are only four degrees of freedom for error remaining when this many terms are included in the equation, no other set of factors and interactions resulted in a regression equation with an R-Sq(adj) above 64%[1]. In addition, removing a factor or interaction from this regression equation reduced both the correlation (R-Sq(adj) value) of the equation and the statistical significance of at least one other factor. Consequently, all of these factors and interactions should be considered to have an impact on the BLRT severity.

The benefit of using regression analysis is that the coefficients of the regression equation indicate the relative importance of each factor/interaction on the response (e.g. BLRT score) and if changing from the low level of a factor to a high level of a factor increases or decreases the response (i.e. the “directionality” of the effect). Nevertheless, one must always be careful with statistical analyses. In this experiment, some of the results suggested by the statistical analysis corroborated practical experience, while others appeared to be counterintuitive. Further examination of both the panels and data from this experiment indicated that an uncontrolled covariate may have confounded the effects of three of the factors in this experiment. The team considered this to be a very important result, but has chosen not to identify that covariate at this time. This factor will be the subject of a future experiment.

The regression analysis showed that even though all the factors included in Part A had a statistically significant effect on the BLRT severity, some factors had a larger effect on the BLRT severity than others. The factor with the strongest effect on BLRT severity in Part A was the temperature at which the adhesive was fixture cured. This result was not surprising. The team decided to examine the relationship between cure temperature and read-through severity in more detail to determine whether the relationship between BLRT severity and cure temperature is purely linear. The preliminary results from that experiment are discussed below.

The type of outer panel material used in the assembly was also found to affect BLRT severity. In this case, however, the material with the higher levels of BLRT severity was not the one that the team had expected. The team has theorized a likely explanation for the trend found in the data and will investigate the effect of outer panel characteristics via CAE analysis.

Regression analysis of the BLRT score data collected on the assemblies manufactured in Part B did not identify a regression equation with the same high level of correlation as that for the data from Part A. The equation with the highest correlation included only three factors and one interaction. The third factor was left in the equation even though it did not have a statistically significant effect on the BLRT severity. Nevertheless, it was left in the regression equation since that improved the correlation and since it is generally recommended to include a main factor in the regression equation when that factor is part of an interaction. This regression equation with four terms had an R-Sq(adj) value of 64.3%. Since that indicates a fit of 80% of the data, this equation is considered to be an acceptable predictor of response (e.g. BLRT score). The statistically significant effects in Part B had also been found to be statistically significant in Part A. This statistical analysis indicated that three of the factors had no effect on BLRT severity and could be omitted from future experiments.

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[1] *An R-Sq(adj) value of 64% corresponds to an 80% correlation ($0.8^2 = .64$). Generally 80% correlation is considered the minimum acceptable correlation for a “good fit” between the data and the model.*

One of the factors that was not found to be statistically significant in Part B was the bond nest configuration. This result was unexpected. While the results of this experiment indicated that the BLRT severity was the same regardless of whether an assembly was bonded in a full nest or a skeletal nest, the authors point out that the sample configuration used in this work has bond-lines covering a much greater percentage of the assembly than what would typically be seen in a production part. Consequently, the authors caution that the design of the bonding nest could impact BLRT severity in larger parts with a greater distance between bond-lines.

Effect of Fixture Cure Temperature Experiment

The factor in the first experiment that had the greatest influence on the severity of the bond-line read-through was the temperature at which the adhesive was fixture cured. This was not a surprising result; nevertheless, the team wanted to establish a more explicit relationship between cure temperature and bond-line read-through severity. In particular, the team wanted to determine whether the relationship between BLRT severity and fixture cure temperature is linear for the two adhesives used in this work.

This experiment was a two factor, full factorial experiment. To determine whether the relationship between BLRT severity and fixture cure temperature is linear, five cure temperatures were included in the experiment. Three replicates were manufactured at each condition to improve the sensitivity of the analysis. The factors and factor levels included in this experiment are summarized in Table III. The cure time was dependent upon the fixture cure temperature. The time the assemblies were cured in the fixture at each temperature is summarized in Table IV.

Table III*. Factors and Factor Levels for the Effect of Cure Temperature Experiment*

Factor	Factor Levels
Type of Adhesive	Urethane, Epoxy
Adhesive Cure Temperature	RT, 120°F[2], 240°F, 270°F, 300°F

Table IV*. Cure Time and Temperature Used in the Effect of Cure Temperature Experiment*

Cure Temperature	Cure Time	
	Urethane	Epoxy
RT	2 hours	Overnight
120°F	25 min	3 hrs (est)[1]
240°F	120 s	300 s
270°F	105 s	180 s
300°F	90 s	120 s

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[2] Assemblies were not made at 120°F using the epoxy adhesive. These assemblies would have required a three hour cure time in the bond cell. There was not sufficient time allotted in the experiment to manufacture these assemblies.

All assemblies in this experiment were manufactured from fully cured SMC inner and outer panels. The inner panels were cooled without an induced warp. The adhesive was applied as a continuous bead. The bond nest was set up in a skeletal configuration with a 1mm nominal bond gap.

Preliminary Results from the Effect of Fixture Cure Temperature Experiment

Final results from painted assemblies manufactured in this experiment were not available as of the date of this publication. Nonetheless, data had been collected on the “raw” assemblies and the assemblies after priming. These preliminary results suggest that the relationship been cure temperature and BLRT severity is different between the two adhesives. Figures 7 and 8 contain a filtered curvature map from one panel bonded at each temperature for the urethane and epoxy adhesives, respectively.

The reader should note the images shown in Figures 7 and 8 are captured from primed assemblies. Primed assemblies have a much lower reflectivity, and therefore lower contrast, than painted assemblies. Since curvature values cannot be calculated when the contrast is too low, much of the data is either missing or is excessively influenced by noise in the bottom half of these maps.

Because the assemblies had not yet been painted, final BLRT severity scores were not yet available for this experiment. Nevertheless, a trend of increasing read-through is visible in the curvature maps for the assemblies bonded with urethane adhesive (i.e. Figure 7). While the BLRT severity also appears to increase with increasing temperature in the assemblies bonded with epoxy adhesive, the effect of fixture cure temperature appears to be more pronounced in the assemblies bonded with urethane than in those bonded with epoxy. In addition, the assemblies bonded with epoxy appear to have a higher minimum BLRT severity than those bonded with urethane.

Summary

Two experiments were completed to investigate the root causes of bond-line read-through (BLRT). BLRT severity data obtained using the ONDULO technology was used to quantify the severity of the distortions on the assemblies manufactured in these experiments. The first experiment was a two part, eight factor screening experiment. Regression equations were calculated to relate BLRT severity to experiment factor levels. The statistical analysis indicated that three of the factors evaluated in that experiment may not have a substantial influence on BLRT severity. Results from this experiment, however, may have been confounded by an uncontrolled covariate. Further experimentation is required to confirm the effect of that factor. The factor that was found to have the largest effect on BLRT severity in the screening experiment was the temperature at which the adhesive was fixture cured. Preliminary results from a follow-up experiment to explore the relationship between the type of adhesive and the fixture cure temperature indicate that the urethane is more sensitive to cure temperature, but the epoxy creates a higher nominal amount of read-through. These results will have to be confirmed after the assemblies manufactured in that experiment have been painted.

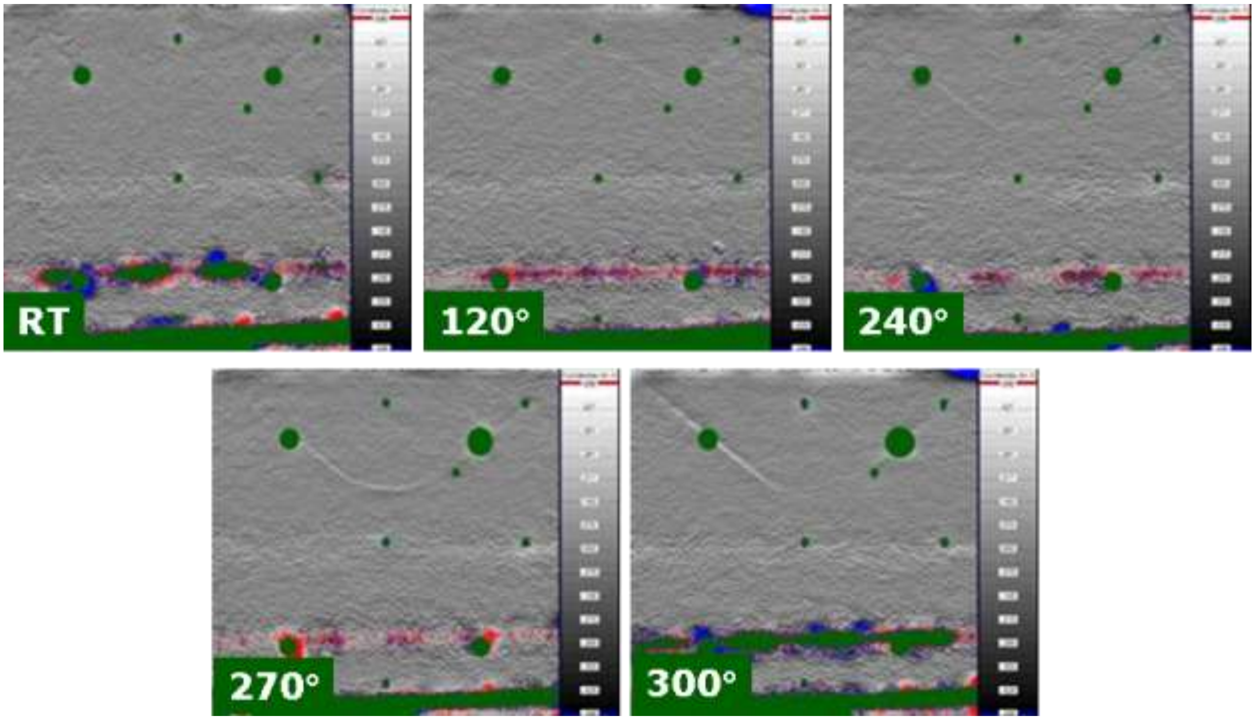

Figure 7. *Filtered Curvature Maps from Assemblies Bonded with Urethane Adhesive and Cured at Different Temperatures*

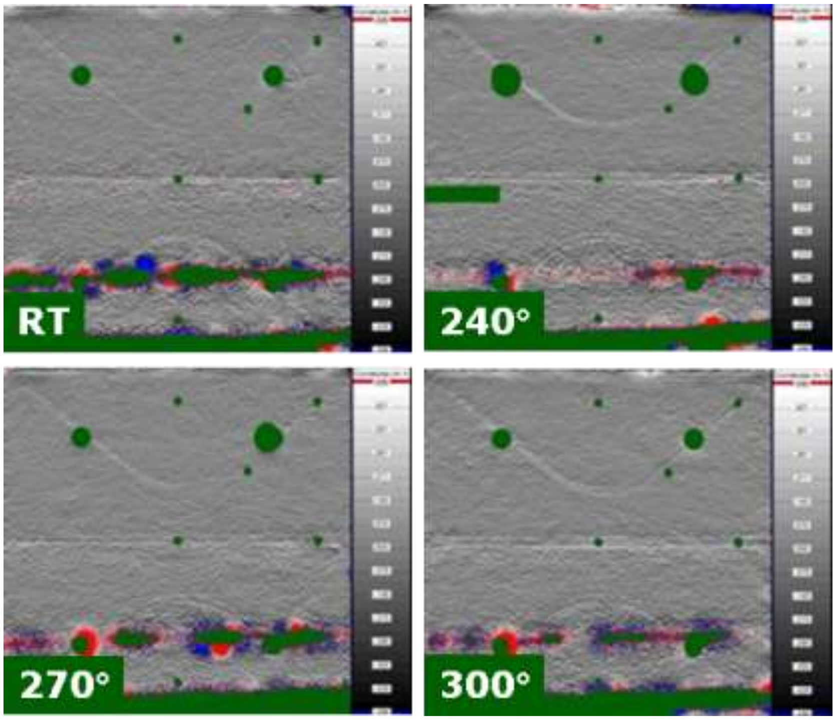

Figure 8. *Filtered Curvature Maps from Assemblies Bonded with Epoxy Adhesive and Cured at Different Temperatures*

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