AN INVESTIGATION OF DISSIMILAR MATERIAL JOINING VIA ADHESIVE FOR CLEAR COAT TO SMC

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ABSTRACT

Adhesives are used increasingly in the ground transportation sector, not only for increasing body strength, but also in noise, vibration and harshness (NVH) by isolating noise better than conventional mechanical fastening techniques. Mixed material assemblies are incorporated within modern commercial vehicles where metallic and non-metallic substrates are joined together, while carefully considering environmental impacts and the durability of the joint. In this study, the viability of joining clear coated steel to bare sheet mold compound using a two component polyurethane adhesive was investigated. Lab tests and environmental ageing studies on four different colors of pigmented top-coat revealed joints which outperformed the joints made from bonding electro-coated steel to sheet mold compound surfaces. An actual full vehicle trial for this concept has validated the lab-test results through double lap-shear testing. The correlation factor was derived empirically to link the lab and actual assembly results.

1. INTRODUCTION

In the heavy-duty truck market, different types of joining technologies are carried out at the lower-tier companies to form sub-assemblies which are supplied to the next level until it reaches the final assembly manufacturer to form the full vehicle. During those phases, conventional mechanical fasteners, rivets, and inserts are applied depending on the structures and geometries. There are several ways to approach creating a lightweight concept. Manufacturers can re-design the assembly by merging parts in order to minimize the usage of heavier materials, subsitute a lower density material or combine both approaches during the engineering stage. Non-metallic materials such as plastics and fiber-reinforced polymers (FRP) are being used increasingly in the ground transportation industry as they provide superior mechanical strength and can help meet lower weight targets. They are flexible enough to form difficult curvatures and designs during the manufacturing process and make it easy to integrate structural and non-structural portions into an assembly. As modern joint designs and the surfaces for the mating parts become more varied and complicated, conventional fastening methodologies also become harder to utilize for merging the multiple assemblies into one. Adhesives have become one of the fastest growing solutions for these industry challenges in recent years and rapid development is facilitating product and process improvements. With larger load-bearing surfaces and thin bondlines required for joining, adhesives provide several advantages for difficult conditions during manufacturing and assembly processes. The adhesives can be customized to provide the right strength and durability for the substrates used and to achieve the desired performance requirements, including bonding strength, vibration absorption, sealing and noise reduction. When combined with foam core materials, adhesives can also help provide heat insulation by utilizing the lower heat conductivity of the micro air pockets in the sandwich structure. Adhesives have also been used in the aerospace industry for many decades in conjunction with mechanical fasteners that were used to join composites and aluminum and other materials to reduce the weight. In these cases, the chemical and target performance requirements were primarily dictated by the aerospace industry. Therefore, when it comes to ground transportation applications, the adhesives and substrate surface need to be redefined for use to optimize the performance and cost. When focused on the exterior application of a heavy-duty truck, surface energy, topography and paint adhesion are considered to be the important performances. Additional considerations are the ultra-violet durability, various chemical contact resistances as well as the repairability for aftermarket. Improvements in disassembling adhesive joints, easier repairability, better curing parameters and surface pre-treatments are areas for future exploration in order to minimize the lab-to-field performance differences. In this paper, a continuous improvement project to eliminate paint masking during the assembly process by using adhesives is presented. Engineering and research activities were conducted to minimize the gap between lab and field results and to set performance targets.

2. EXPERIMENTATION

2.1 Test preparation

The test conducted for this study was internal STD 423-0048 which is identical to ASTM D1002. The test parameters are presented in Table 1.

Test	Condition	Standard	Equipment
Lap shear test (Initial condition)	H0 (23 ºC / 50% RH)	STD 423-0048	Tensile test machine Nº 73319
Lap shear test (Cataplasm ageing)	H7	STD 423-0048	Oven Nº 73075 Tensile test machine

Table 1. Test spec with ageing

The lap-shear tests were performed on specimens with the SMC of interest bonded to painted steel panels. Two different SMC variants were selected with four different paint pigment colors to represent the color chart used within the product range. The aim of the test was to determine the performance of the adhesive on the substrates. Tests were conducted in accordance to STD 423-0048 and the thickness of the joint was 1 [mm] max. Figure 1. illustrates the lap-shear sample produced in the corporate lab using a fixture with the thickness adapter torqued according to the specification. No bondline thickness adapters such as glass beads or spacers were used within the adhesive application region.

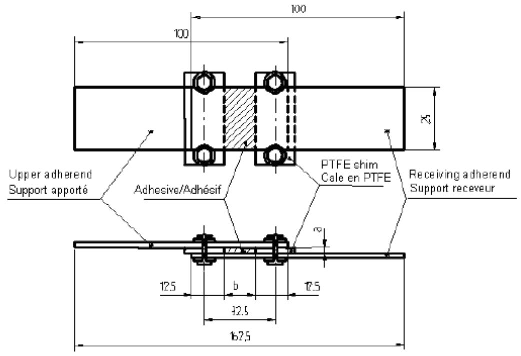


Figure 1. Lap shear test specimen

2.2 Test – Lab specimen

The substrates were prepared as a 12” by 12” - 3 [mm] thickness plaque and cut into individual specimens that were 1” by 4” - 3 [mm]. The coupons were kept within the lab for several days prior to the next steps for the test preparation. Surface preparation on the panels consisted of cleaning with heptane using wipes and then waiting for the complete evaporation just before adhesive application. The samples were then kept a minimum of 7 days at normal conditions (NC = 23°C/50%RH) before the test (initial) or other conditioning (see Table 2.)

Conditioning	Process	Equipment
H0	7 days at NC^2	-
H7	7 days moisture and creep at 60°C	Oven Nº GIME 73039

Table 2. Ageing spec details

Product Reference	Specificity	Material	Color
Gray SMC	GF 33%	SMC	Gray
White SMC	GF 28%	SMC	White
Yellow paint panel	NRV paint process E-coat / Primer / Base-coat / Clear-coat	HDG steel	Yellow
Silver paint panel		HDG steel	Silver
Black paint panel		HDG steel	Black
White paint panel		HDG steel	White

Table 3. Substrates and paint used in the study

In the mechanical tests the bonded joints are loaded to the point of fracture. The nature of the failure (adhesive failure, cohesive failure, substrate failure or a combination of these) provides information about the quality of the bond and about any potential production errors. Regarding tests on samples equilibrated under controlled conditions, a cohesive failure indicates that the interface remained stable despite the influences acting on the bond (e.g. moisture). In contrast, an adhesive failure shows that the bond has failed at the interface and indicates this is the weakest point. This may be caused by incompatibility between the substrate material and adhesive, inadequate surface preparation and/or processing/application errors. Substrates and paint systems that were used for this study are summarized above in Table 3.

2.3 Test – Actual assembly origin

Aside from the lab test using coupons made for the test, test samples from the actual vehicle were obtained and prepared to investigate performances on the actual assembly for reference purposes. Details are depicted in chapter 3.4.

3. RESULTS

Lap shear test were performed for 2 different coupon specimen configurations. The lab tests were done on the coupons prepared according to ASTM-D1002, alternatively the internal standard STD 423-0048. ASTM-D3165 was used on the test specimen obtained from the actual vehicle assembly for an investigation on the lab to field relationships.
Mechanical tests on the bonded joints involved subjecting the samples to increasing shear loads until failure. Failure modes that are classified in this study are outlined in sub chapter 3.1.

3.1 Failure mode description

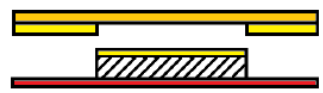
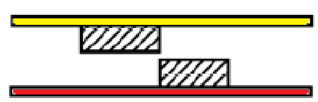
Failure involving ***substrates***		
		
Failure of one or both substrates	Failure inside one substrate (for SMC materials, fiber tear is noticed)	Failure through delamination (focus on painted panel, paint peel is noticed)
Failure involving ***adhesive/glue***		
		
Cohesive failure	Superficial cohesive failure	
Failure involving ***surface***		
		
Adhesive failure	Adhesive failure on both substrates	

Table 4. Failure mode assessment

Table 4. summarizes common failure modes which are commonly used in the lap-shear test assessment. In the climate-controlled test samples, a cohesive failure indicates stable adhesion despite the influences that impact the bond, for example, moisture and creep. On the other hand, adhesive failure indicates that the adhesive-substrate interface is the most sensitive point. This

may result from the chemical incompatibility of the substrate and the applied adhesive, inadequate surface pre-treatment and /or processing and application errors.

3.2 Mechanical performances of the test adhesives

Four different adhesives were selected for the test. Each adhesive's performance results are summarized in Figure 2 ~ Figure 5. For each figure, the 1st quadrant shows the picture of the joint after testing. The 2nd quadrant shows the failure strength under two ageing conditions, where the x-axis and y-axis represent strength in MPa and the lap-shear specimens code, respectively. The 3rd and 4th quadrants show the failure mode assessment in a visual manner for initial condition and after the moisture and creep ageing individually. The charts were color-coded green for more desirable failure modes to better illustrate the results. The legend is included in each graph and the detailed assessment explained in chapter 3.1.

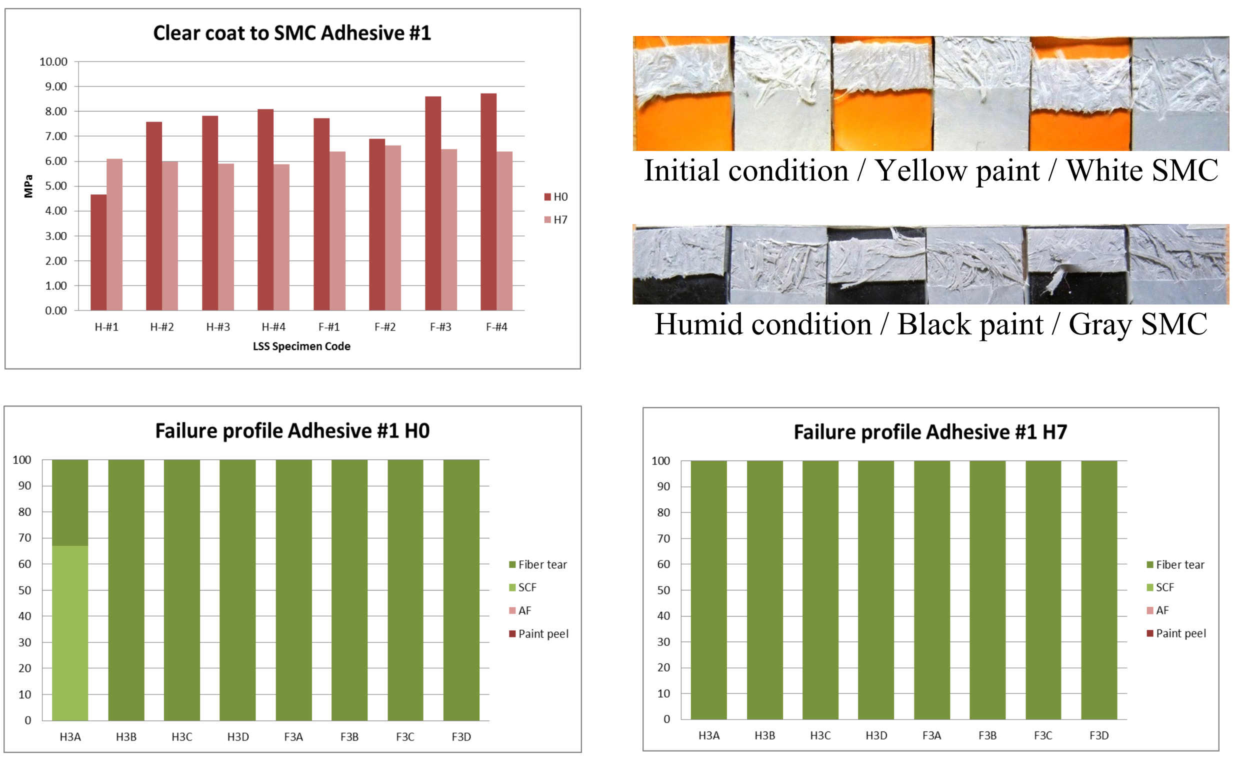


Figure 2. Adhesive #1 Lap shear test result & failure profile

The results on adhesive #1 (Figure 2.) do not show abnormal behavior regarding the adhesion on SMC and painted substrates with different color pigments, except for the first column with the code of H-#1. All strength values before ageing were above 6.8MPa. The average value before ageing (H0) was 7.5MPa and after ageing (H7) was 6.22MPa. Of the products tested in this study, this adhesive had the highest performance after humid ageing. Both before and after ageing, the main failure mode was observed as SMC fiber tear regardless of the SMC selected. One sample showed partial superficial cohesive failure "SCF" (H3A) cured at normal conditions which explains the lowest strength values. Overall, adhesive #1 has shown good behavior after humid ageing. All the results highlighted the good bonding performance on painted substrates.

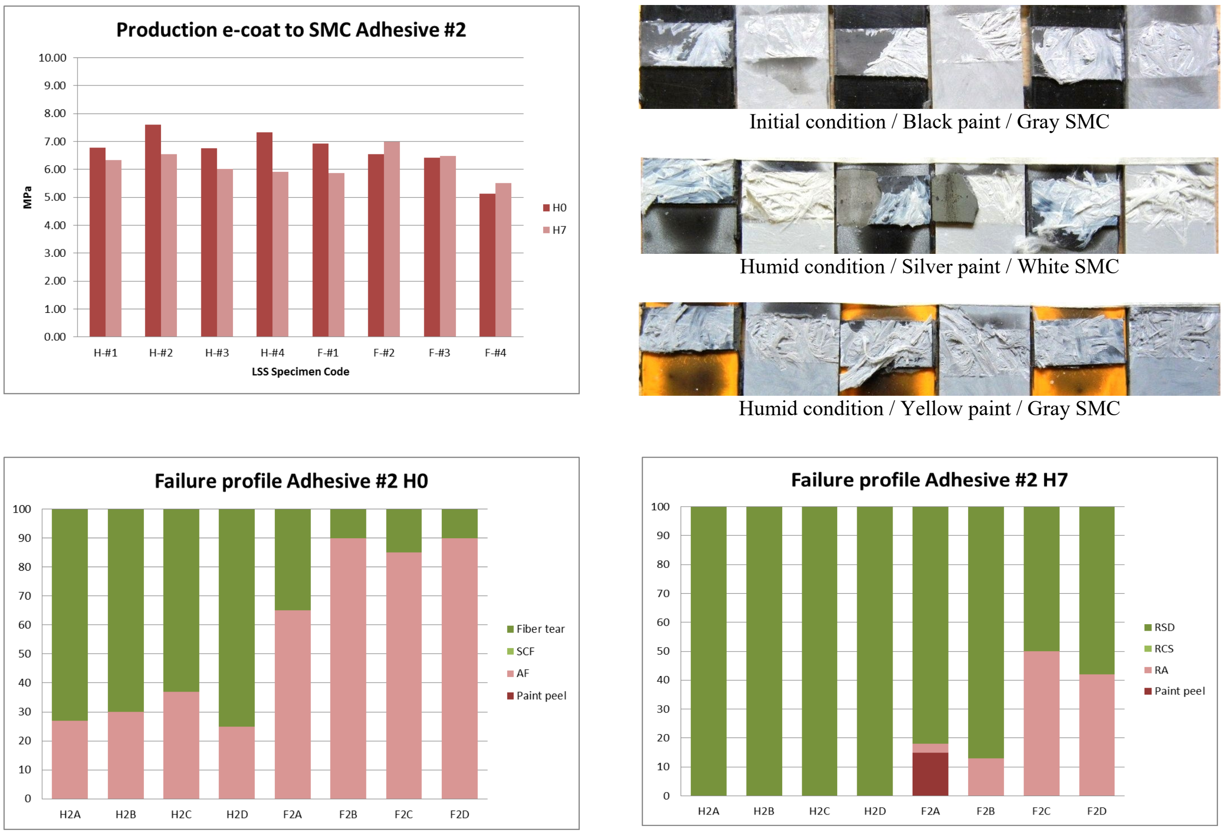


Figure 3. Adhesive #2 Lap shear test result & failure profile

No unusual behavior was observed regarding bond strength on SMC and painted substrates with adhesive #2 (Figure 3.). The results were similar for both SMC grades (slightly lower for the white SMC compared to the gray SMC). The bonding performance after humidity exposure did not decrease significantly. The average values were 6.7MPa and 6.21MPa for H0 and H7, respectively. Adhesive #2, however, did show undesirable failure modes. At the initial state, the adhesive failure was present with gray SMC and dominant on the white SMC. After the H7 ageing, the failure mode improved on samples with gray SMC. Samples made with the white SMC still showed signs of adhesive failure.

The results obtained with the adhesive #3 (Figure 4.) also show slightly better adhesion on gray SMC than white SMC before humidity exposure. The average values at the initial state (H0) is 6.1MPa and after H7, 5.5MPa. Good bond strength after moisture creep ageing was observed. However, the initial failure mode observed on samples with gray SMC was paint peel. Adhesive failure was more significant on white SMC, which highlights the differences between various forms of SMC. The location of the joint failure shows that the weakest bond is between the different coating layers.

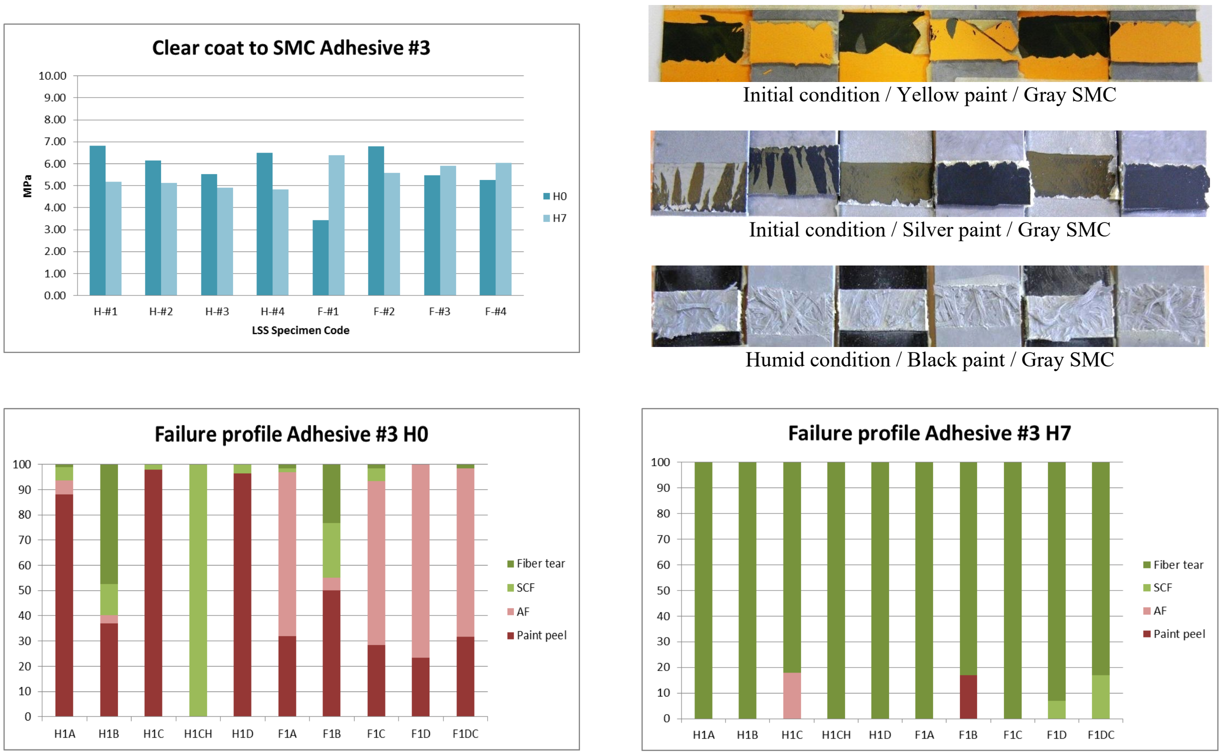
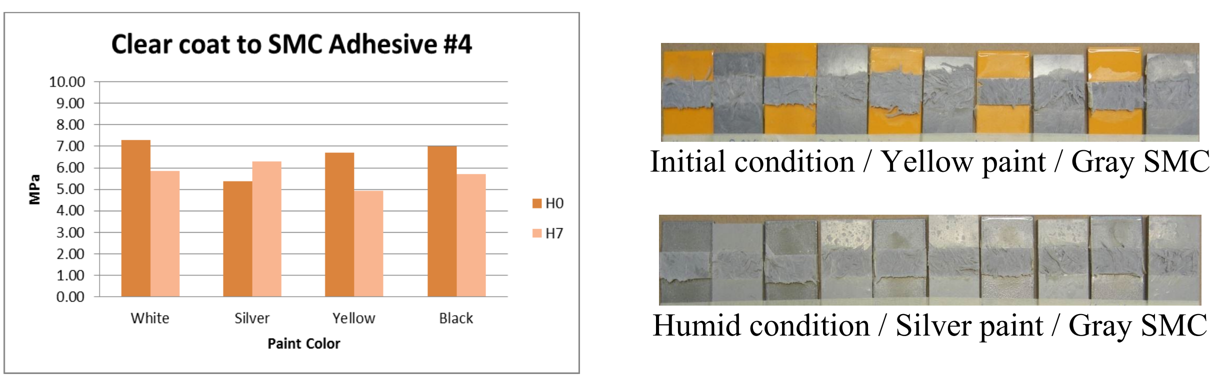


Figure 4. Adhesive #3 Lap shear test result & failure profile



Failure profile Adhesive #4 H0
100% Fiber tear

Failure profile Adhesive #4 H7
100% Fiber tear

Figure 5. Adhesive #4 Lap shear test result

For adhesive #4 (Figure 5.), bonding performance after ageing was slightly lower than the initial stage except for the silver paint. The overall failure tensile strength was not the best among the tested adhesives for this study but satisfied the requirement for the target threshold strength. As for the failure profile, for all paint colors 100% fiber tear was clearly experienced before and after the moisture and creep ageing. It is possible that the silver paint's metal flake changes the adhesion behavior.

3.3 Thickness variation

Due to the different bond line thickness in the actual assembly, Adhesive #4 was additionally tested for two different adhesive thicknesses. Keeping the same ASTM D1002, one test was performed with a 1 [mm] thick bondline and the other with 0.3 [mm] thick bondline. The results are shown in the following Figure 6.

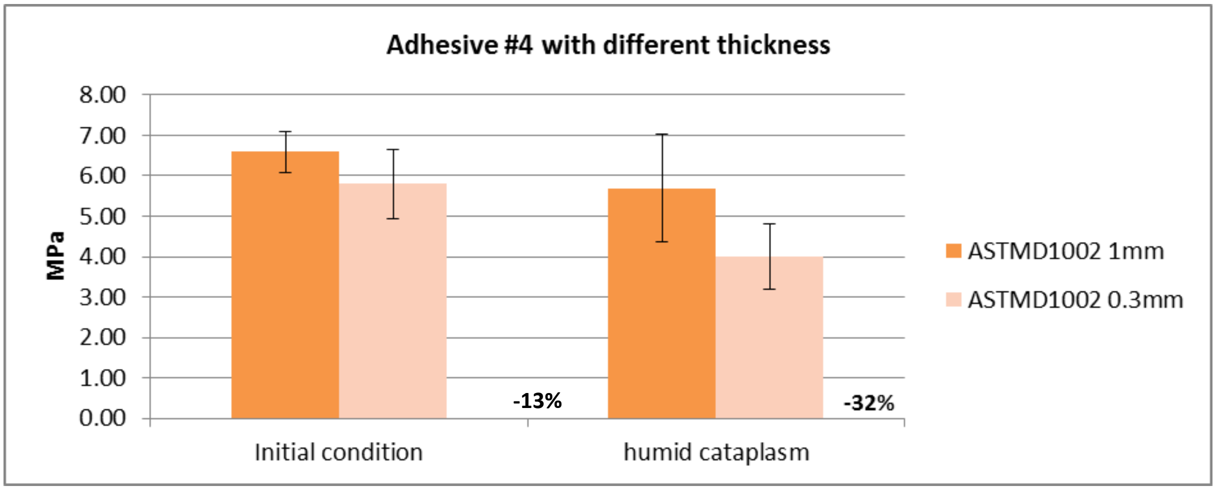


Figure 6. Different thickness result for adhesive #4

It was observed that with a thinner adhesive bondline (0.3 [mm]), the performance decreased by a larger proportion of -32% in comparison to -13% for the thickness of (1.0 [mm]) before and after the ageing cycling. This data confirmed the target strength at 1 [mm] thickness and gave some insight into performance at lower than optimal bondline applications.

3.4 Actual vehicle assembly sampling data

In addition to the lab lap shear results obtained, it was necessary to perform an actual vehicle assembly with the potential adhesive to be applied. The work was done at the final assembly plant with the support from a collaborative partner to closely duplicate the actual mass production process. The Volvo VNL roof to CAB mating rendering can be seen in Figure 7 (a), (b) below.

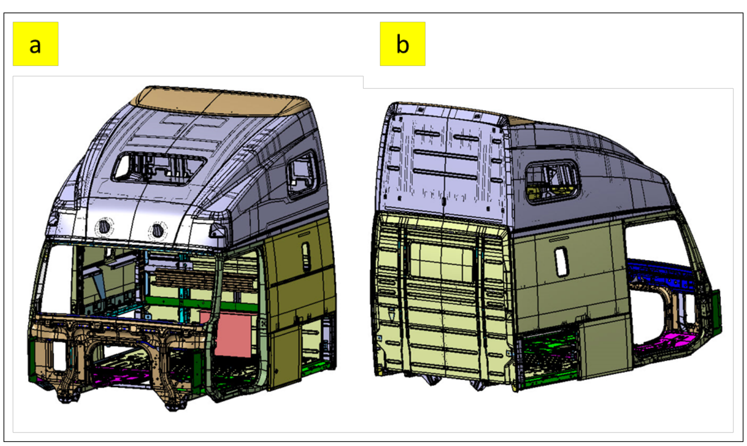


Figure 7. Volvo VNL rendering (a) front view (b) rear side view

Using the glue deck resources and applied by a skilled worker, the roof was mated to the cab by dispensing the adhesive with meter mix dispense equipment. The assembly was allowed to cure for 7 days and prepared for sampling.

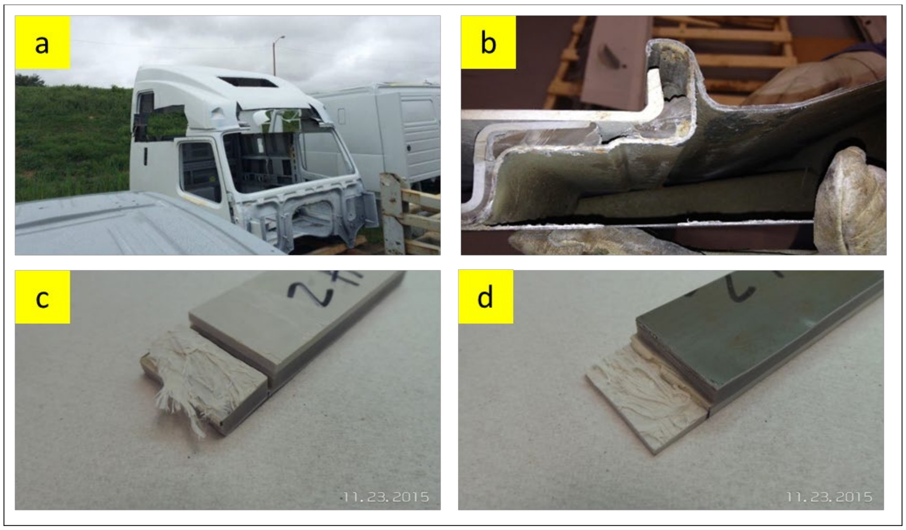


Figure 8. (a) Actual cab after section cut (b) Section view (c) Fiber tear SMC side (d) Fiber tear on clear coated steel side

Four sections were cut out of a bonded Volvo truck VNL roof to cab. The four sections include front, rear and two sides beginning from the door to the rear end as seen in Figure 8-(a). The adhesive bond areas of three of the sections were cut to make double lap shear test samples. As seen in Figure 8-(b), the flow behavior of the adhesive, when the roof was mated under its own weight, could be closely observed and compared to the theoretical expectations. Lap shears from each section were tested immediately after sampling and then again after a seven day exposure in a humidity chamber identical to the previous lab test procedures. Fiber torn samples from the actual assembly are seen in Figure 8-(c) and (d) respectively representing the SMC and the Cab side. One section (front where the sunvisor is being assembled) had a curved geometry where lap shear samples were difficult to obtain. This part was kept for a teardown to measure the breakage strength. Figure 9. shows the cross section of the front cut-out from the actual assembly.

Figure 9. Front cut assembly cross section

4. CONCLUSIONS

4.1 Proof of concept

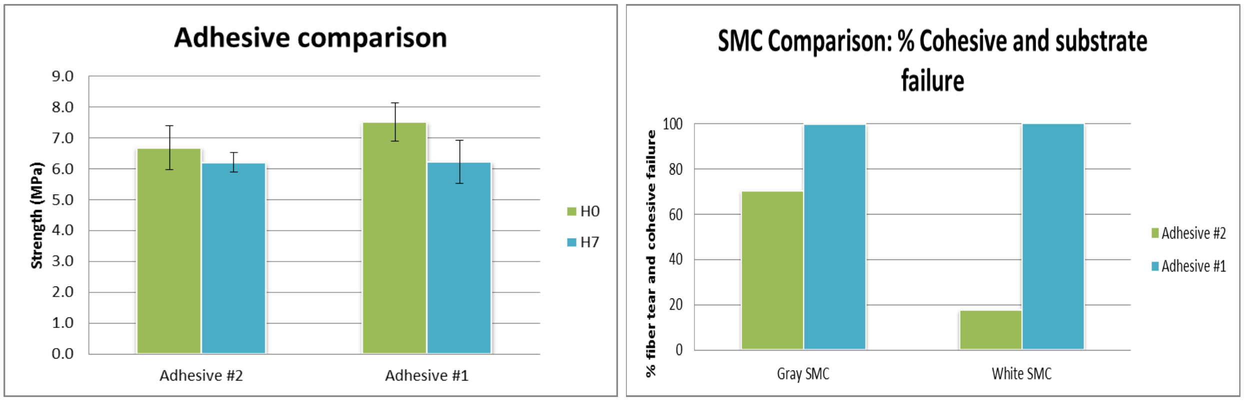


Figure 10. Clear coat to SMC adhesive proof of concept

The primary goal of this project was to investigate if a current production adhesive may be suitable for the clear coat to bare SMC bonding applications. The lap shear strength was generally sufficient, but the failure mode immediately indicated that adhesive #2 was not suitable for the improved assembly process. The different results for the two SMC variants shows that not only the adhesive but also the surface energy and the additive packages within the SMC significantly affects the bonding performance and failure mode profiles. From the data in Figure 10, it was decided that a specific engineered adhesive was needed in order to meet the requirement for the improved assembly process at the final vehicle assembly line. Further investigation into adhesive selection was undertaken, considering the cost and performance for the new application.

Characterization of multiple products was the next step to select the best performing adhesive for the clear coat to SMC assembly. Among the tested adhesives, adhesive #4 was selected for consideration due to its combination of performance and good failure modes. An assembly test on a full size part was conducted with adhesive #4 to see the behavior differences from the lab versus field.

4.2 Actual assembly sampling data in comparison with the lab results

From the four sampling sections from the actual assembly, the RH side section was the best test sample. The initial test resulted in 100% fiber tear of the SMC. After the humidity exposure the failures changed to 100% paint failure to the metal substrate as seen in Figure 11–(a). The LH side section test result was very similar to the RH side section with 100% fiber tear of the SMC at the initial condition. Two of the three lap shear samples that were exposed to humidity had voids in the bond area resulting in lower load values which can be seen in Figure 11–(b). The calculated strength values based on the bond area were comparable to the initial test. Failure mode on these was 100% SMC fiber tear in the areas where adhesive contact was made. The rear samples were the worst of the test samples. There were voids or partial fill of the bond area on all the test samples. The failures of these lap shears occurred outside the bonding area where the adhesive was used. Figure 11–(c) and (d) show the irregular fill of the samples from the rear.

Due to the poor condition of the test samples, this test data was kept for reference purposes only and not considered representative of the performance of the adhesive used to bond these substrates.

Figure 11. (a) Paint failure (b) Voids (c) Irregular fills (d) Irregular fills

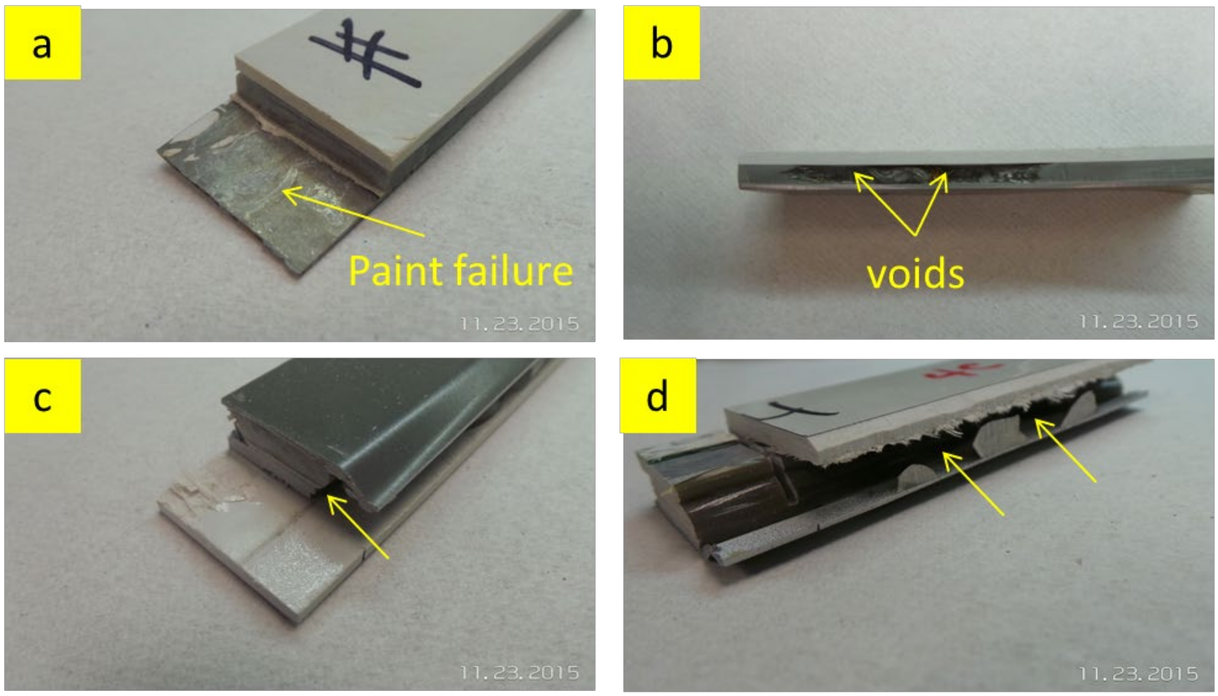


Table 5. summarizes the mechanical performance of the samples from the actual roof to cab assembly. In order to make better real world predictions from lab test results, the two sets of data were compared. It was found that the average results for the full size assembly before humidity ageing are 79% of the similar average lab test result and after humidity ageing the strength of the real world assembly samples were 82% of the lab test predictions.

Section	Condition	Ave. Tensile Strength [MPa]	Failure	Remark
1 - Side (RH)	Initial (H0)	5.2	Fiber tear	-
	Humidity (H7)	4.2	Paint peel	
2 - Side (LH)	Initial (H0)	5.2	Fiber tear	-
	Humidity (H7)	5.2	Fiber tear	
4 - Rear	Initial (H0)	1.8	Fiber tear	Poor sample Reference only
	Humidity (H7)	4.9	Fiber tear	

Table 5. Mechanical performance from the actual assembly

4.3 Adhesive performance review and selection

With the application of the adhesive on the painted surface with clear coat at the final assembly plant, it is possible to eliminate the paint masking process during manufacturing when using the appropriate adhesive. Observations from the study, however, also indicate that the robustness of the paint system is of considerable importance. In some cases, the joint failures are located within the paint system and lead to lower strength values than the values of the samples with SMC fiber tear. This example of joining dissimilar materials using adhesives reinforces the importance of surface preparation before the actual application, as well as the importance of having controlled parameter variation during the process. Based on these results, adhesive #4 has shown satisfactory performance in terms of lap shear strength before and after ageing, as well as excellent failure mode. An adhesive normally used for e-coat to SMC may not give adequate results for application involving painted surfaces joined to SMC. For example, adhesive #2 cannot be used for the painted surface with the clear coat to the SMC joining purposes. Adhesive #3 has shown high values for mechanical properties but the failure modes were not acceptable. Finally, from the lab test results, adhesive #4 was recommended for further consideration at the final assembly trial.

4.4 Further work

This study was done to consider reducing landfill waste from the large usage of the masking materials as well as to improve the current manufacturing process during the final vehicle assembly. Lap shear and actual assembly test revealed that it is possible to execute the concept with the following thoughts for improvement:

- Surface treatment prior to applying the adhesive must be taken into consideration.
- Adhesives quantity to be applied on the assembly shall be optimized with the bead size and viscosity.
- Squeeze out control shall be studied to avoid air capture within the closure as well as to vent the gas during curing.
- Painting thickness control influences with different color pigment and thus precise control needed.
- Bonding performance changes with the different SMC surfaces and thus, the SMC manufacturer's supplied part shall be checked for all quality screens.
- Periodic actual and lab sampling lap shear test shall be done and monitored.

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