CARBON FIBER SUBFRAME DEVELOPEMNT – CORROSION MITIGATION STRATEGIES AND TEST RESULTS

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Abstract

A research carbon fiber reinforced polymer, CFRP, composite front subframe was designed and manufactured for the Ford Fusion to investigate the opportunities to reduce weight and improve fuel economy, as well as the challenges associated with composites. Cyclic corrosion testing was conducted to check for the occurrence of galvanic corrosion on metal parts and bolts joined to the CFRP subframe. Some interfaces were tested with potential mitigation actions in place, such as e-coated steel for control arm brackets, stainless steel for compression limiters and rivets, glass veil design with machined carbon fiber faces and Nylon 11 over-coating on washer and bolt shanks. A vehicle and four components were tested to evaluate the subframe assembly corrosion performance. Posttest parts were analyzed for part damage and material loss. Significant material loss was observed at the steering gear to stainless steel, and at the control arm to CFRP interfaces. Stainless steel and CFRP were compatible materials and no galvanic corrosion was observed at these interfaces. The high clamp load and recessed fitting of the bolted joints prevented moisture ingress between the fasteners and the CFRP surfaces and no galvanic corrosion developed on those interfaces, even without Nylon 11 overcoating. The CFRP subframe achieves a 7.3 kg (28%) mass reduction over a stamped steel subframe and an 82% part reduction by replacing the 45 steel parts with two molded parts and six inserts.

Background and Requirements

Carbon fiber reinforced polymer, CFRP, composites are alternatives to conventional steel or aluminum construction materials and they offer a vehicle light-weighting benefit to improve fuel economy. A research CFRP composite front subframe was designed and manufactured for the Ford Fusion to investigate the opportunities, as well as the challenges associated with application of this material to the vehicle. The conventional steel subframe of Fusion is shown in Figure 1.

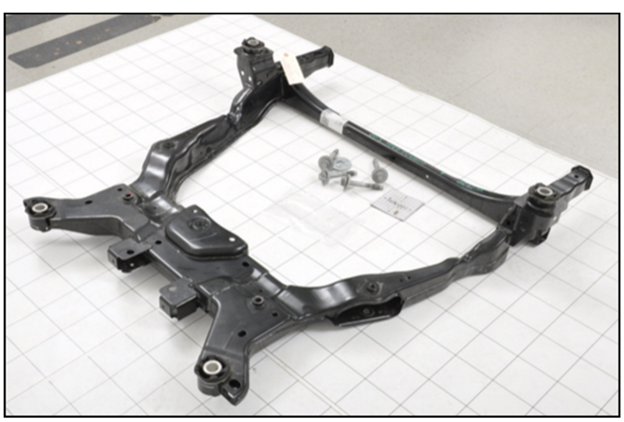


Figure 1: Ford Fusion steel subframe

The CFRP subframe has a compression molded upper clam shell panel and a compression molded lower panel. The two parts were joined together by adhesive and rivets. The carbon fiber subframe also has over molded steel body mounts and compression limiters. In addition, suspension components are joined with the subframe at seven locations by steel bolts. Both vehicle and component corrosion tests were conducted to assess the susceptibility of the interfacing parts to galvanic corrosion. The vehicle test used production chassis fasteners with an aluminum rich coating over an inorganic zinc rich basecoat. The lower control arm brackets were e-coated to mitigate galvanic corrosion at their interfaces to the CFRP subframe, and the compression limiters were stainless steel. The component test comprised a 2 x 2 design of experiments with glass veil and Nylon 11 hardware coating in consideration for the bolted interfaces.

Carbon Fiber Subframe Prototype

The CFRP composite subframe prototypes were produced by Magna International. The design and combination of materials achieves a 7.3 kg (28%) mass reduction over a stamped steel subframe. The subframe achieves an 82% part reduction by replacing the 45 steel parts with two molded parts, which incorporate six over molded steel parts. The two moldings, an upper clam shell and a lower close out panel, are joined by adhesive bonding and structural rivets. Details of the subframe components are shown in Figure 2. The finished, assembled part is shown in Figure 3.

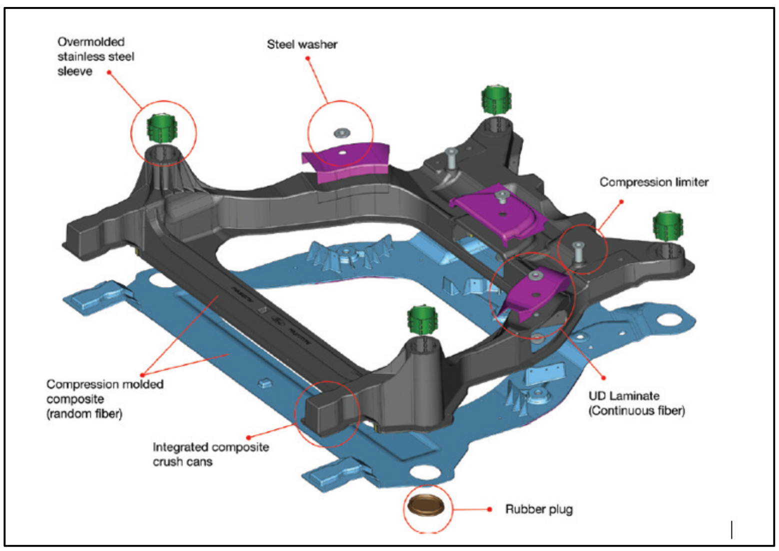


Figure 2: CFRP composite subframe components

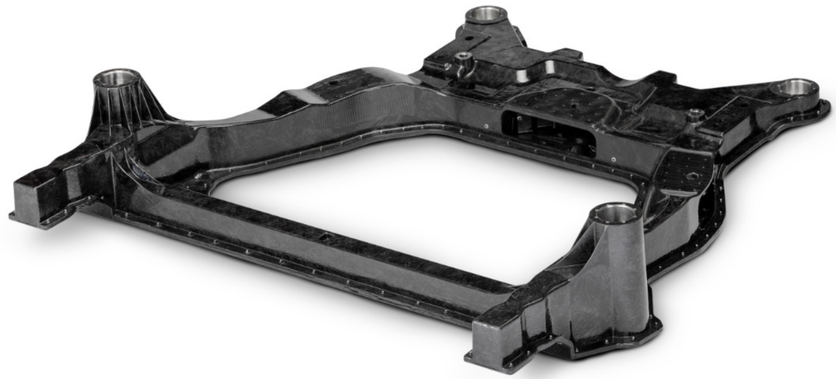


Figure 3: CFRP composite subframe prototype part

Carbon Fiber Subframe Corrosion Considerations

A subframe carries the suspension of the vehicle. Suspension components, such as the control arms, the steering gear, the stabilizer bar and the roll restrictor are joined with the subframe by brackets and heavy-duty fasteners that are made of steel.

Carbon is electrically conductive and electrochemically very noble compared to conventional vehicle construction materials such as steel and aluminum. Therefore, when steel or aluminum is connected to a CFRP component, it may be susceptible to galvanic corrosion. This situation can be exacerbated when a large surface area of carbon is coupled to small metallic parts (such as fasteners, bolts and nuts) and both are connected by an efficient electrolyte. In these circumstances, the rate of galvanic corrosion is extremely high due to the high cathode to anode surface area ratio (Ac/Aa) [1]. A subframe and suspension parts are located under the vehicle body and near the front wheels and as such are subject to a severe corrosion environment in vehicle service.

To assess the occurrence and severity of galvanic corrosion between the carbon fiber composite and the steel and aluminum suspension components and fasteners, cyclic corrosion testing was undertaken. Details of the interfaces of interest are given in the following paragraphs.

Stainless Steel Inserts and Aluminum Organic Coated Hat Washers

The CFRP composite subframe has six steel inserts. They are load bearing elements at the four body mounts and the two steering gear joints of the subframe. The inserts are made of stainless steel and are co-molded with the CFRP material (Figure 4). The detail of the body mount insert is shown in Figure 5.

At other joint locations steel washers with an aluminum organic coating were used. This coating is a combination of organic and inorganic resins suspended with powdered zinc and aluminum pigments in a high-solids system [2] and is a recommended bolt finish for exterior applications [3]. This finish was applied to prevent direct contact between CFRP composite and fasteners. The washers were of top hat geometry, covering not only the fastener bearing area but a portion of the walls of bolt holes in the carbon fiber composite as well. The washers placed at the control arm front joint (Pt. 3) are shown in Figure 6.

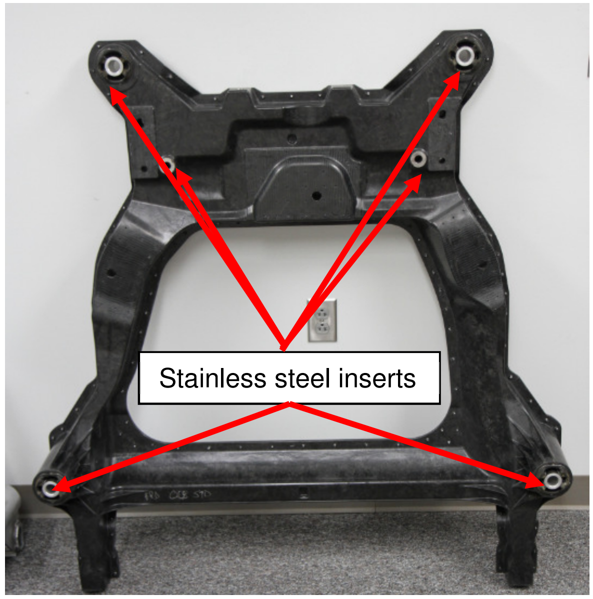


Figure 4: stainless steel insert in subframe

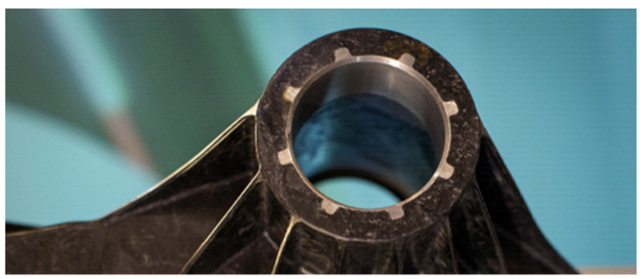


Figure 5: stainless steel insert at subframe body mount

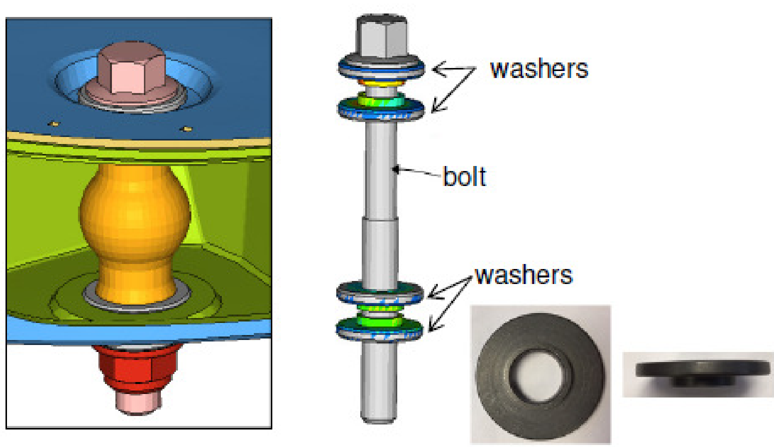


Figure 6: washers placed at control arm front joint

Chassis Required Finishes

E-Coated Brackets

The control arm rear joints have steel brackets holding the bushings. The brackets are e-coated. It is a standard requirement for chassis brackets. There is no additional actions to separate the e-coated brackets and the CF composite surfaces at the control arm rear joints (Pt. 4). The Pt. 4 joint is shown in Figure 7.

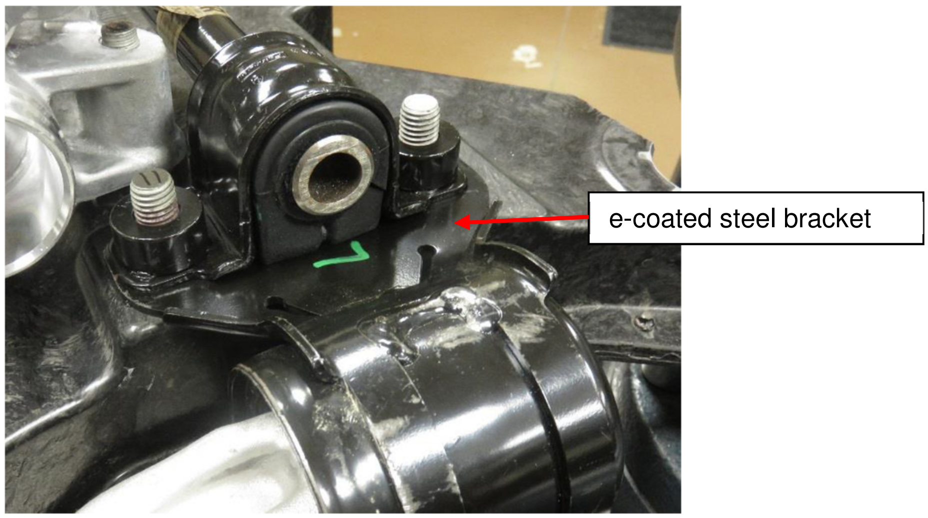


Figure 7: control arm rear joint with e-coated bracket

Fastener Finishes

All bolts joining the CF subframe with suspension components had an aluminum organic type corrosion protection coating, similar to the washers described earlier. The single flat washer at the steering joint was also coated with the same finish. The nut of Pt. 3 joint was finished with a micro layer corrosion protection system consisting of a high zinc- and aluminum-containing inorganic basecoat with an aqueous inorganic topcoat that provides lubricity for consistent torque tension control.

Figure 8: fasteners with aluminum organic finish

Additional Actions

Glass Veils

Standard build CFRP subframes have machined carbon fiber faces at joint locations that require flat surfaces (Figure 9). Those surfaces were wiped with Chemlease MPP2180 sealer. Certain subfames were built with a thin glass veil added to the control arm front joint and the roll restrictor joint top surfaces shown in Figure 10. This feature was tested to investigate the benefits of the glass veil for corrosion prevention.

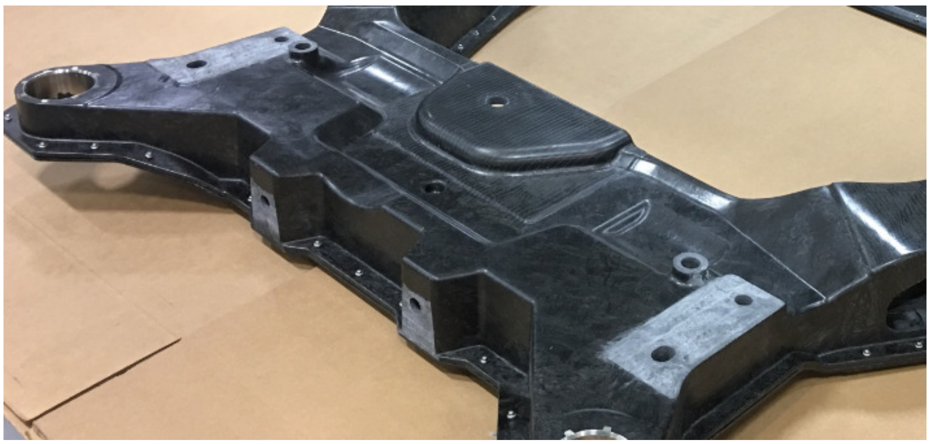


Figure 9: CFRP subframe machined “Faces”

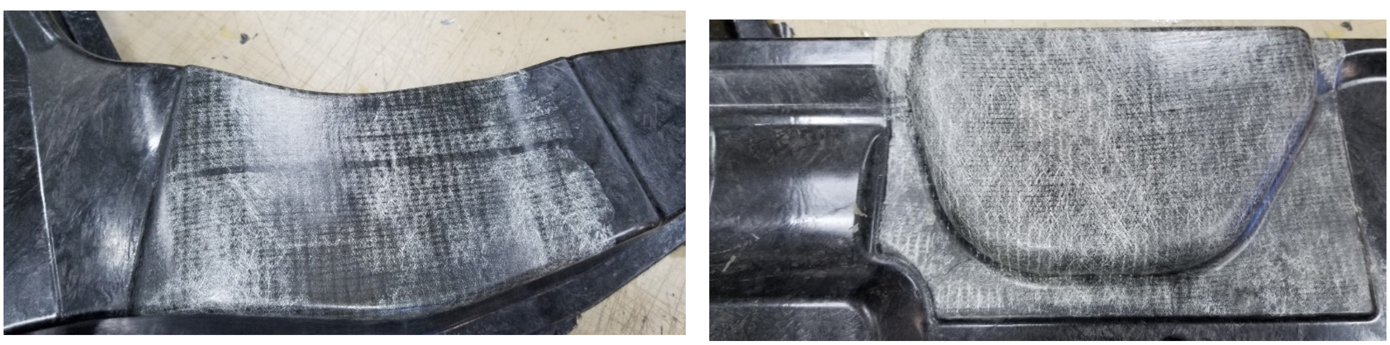


Figure 10: CFRP subframe joint surfaces with glass veils

Nylon 11 Coated Fasteners

Another option for corrosion prevention is Nylon 11 coated fasteners. Selected numbers of bolts, washers were coated with Nylon 11. The coating covers all surfaces of washers, top hats and shanks of bolts shown in Figure 11. To maintain the joint integrity the thread areas of bolts are not coated.

Figure 11: Nylon 11 coated fasteners

Proving Ground Vehicle Corrosion Test

A standard build CFRP composite subframe was installed in a production Fusion and tested at Ford Michigan Proving Ground for corrosion. The test followed Ford's global procedure of vehicle accelerated corrosion test for passenger cars, SUVs, light trucks and commercial vehicles. It represents approximately a vehicle's half-life for the worst customer condition in the most environmentally and corrosion demanding markets [4].

Visual inspection of the underbody was conducted throughout the vehicle corrosion test and photos of the subframe after 4, 8 and 12 weeks of testing are shown in Figures 12-14. Red rust was observed on the rivets and bolts but no loss of function occurred.

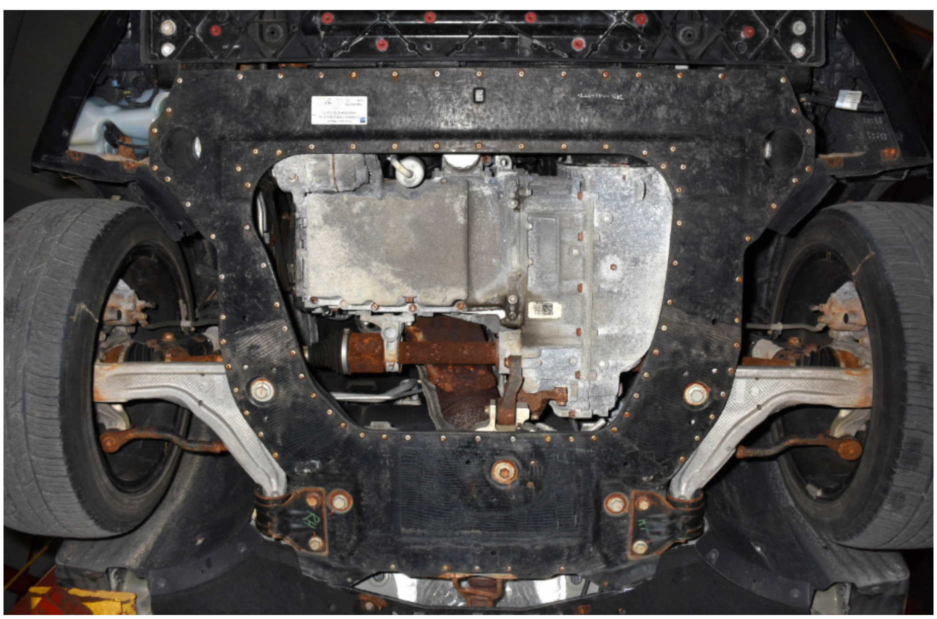


Figure 12: CFRP subframe – post 4 week corrosion test

Figure 13: CFRP subframe – post 8 week corrosion test

Figure 14: CFRP subframe – post 12 week corrosion test

Laboratory Component Corrosion Test

Four CFRP subframes were tested at Ford Michigan Proving Ground (MPG) for 12-week component corrosion procedure [5]. The subframes were assembled with suspnsion components, including control arms, steering gears, roll restrictor bushings and stabilizer bars. The component test environment differs from the vehicle test in that the salt solution was applied to the entire part manually, rather than by impingement as a result of driving on salt-road highways. The laboratory test also does not incorporate effects due to engine heat, dirt and gravel impacts and vehicle movement. The component test setup is shown in Figure 15.

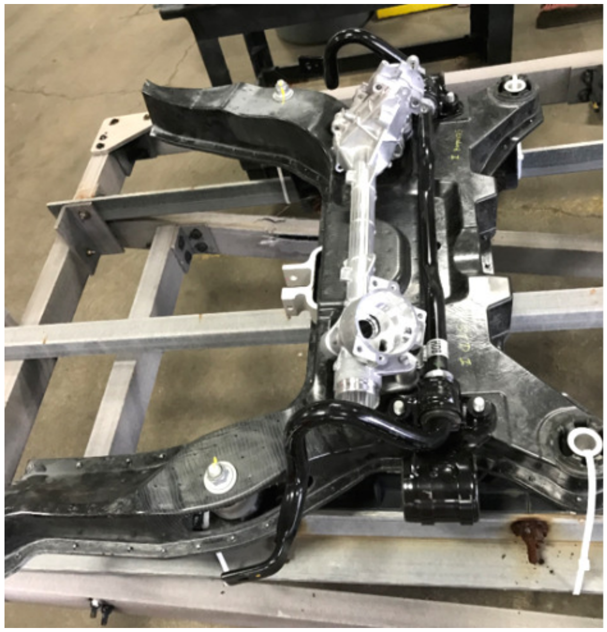


Figure 15: CFRP subframe component corrosion test setup

A 2X2 design of experiments was setup to investigate the corrosion mitigation strategies for the bolted interfaces. The matrix involves two subframe designs and two fastener coatings listed in Table 1.

Table 1: CFRP Subframe Component Corrosion Tests DOE

	Design	
Fastener Coating	Standard	With Glass Veil
Standard (zinc/aluminum)	A-1	A-2
With Nylon 11	B-1	B-2

The post-test subframe assemblies were photo documented and disassembled at Ford Central Laboratories. Joints and fasteners were visually evaluated for corrosion performance. Rust was observed on all fasteners and on a numbers of rivets. There was no evidence of loose joints. The aluminum steering gear and housing, control arm rear joint brackets and the steel fasteners were submitted to the Metallurgy Lab for gage loss measurement in locations of interest.

Steering Gear Analysis

The aluminum steering gear was mounted to the CFRP subframe through stainless steel compression limiters (sleeves), as shown in Figure 16. The sleeves themselves did not exhibit corrosion; however, the mating surfaces on the steering gears experienced considerable metal loss at the interface (Figure 17). These observations confirm that stainless steel is compatible with CFRP but it may induce galvanic corrosion on an adjoining less noble metal, such as aluminum.

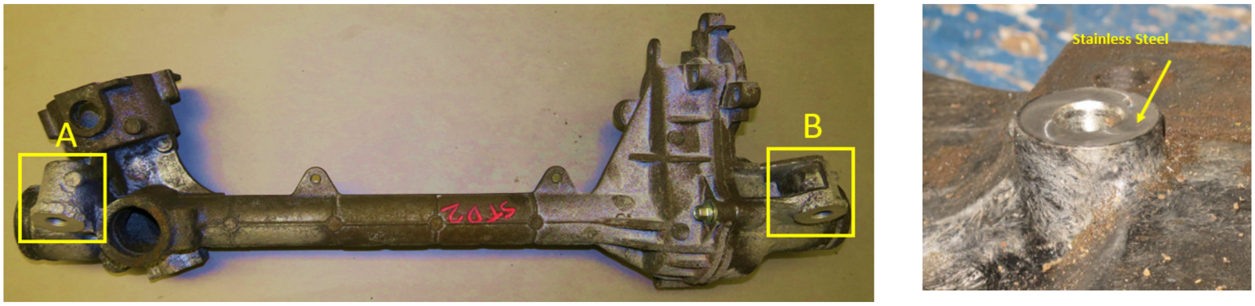


Figure 16: steering gear mounting surface

Figure 17: metal loss observed on steering gear mounting surfaces

The steering gears were optically scanned so the amount of metal loss could be measured when compared to the nominal CAD model. An example of this analysis is shown in Figure 18 for mounting surface A. The summary of steering gear material loss for the component tests is shown in Table 2. The vehicle test data are not included as the steering gear was replaced during test for an unrelated test.

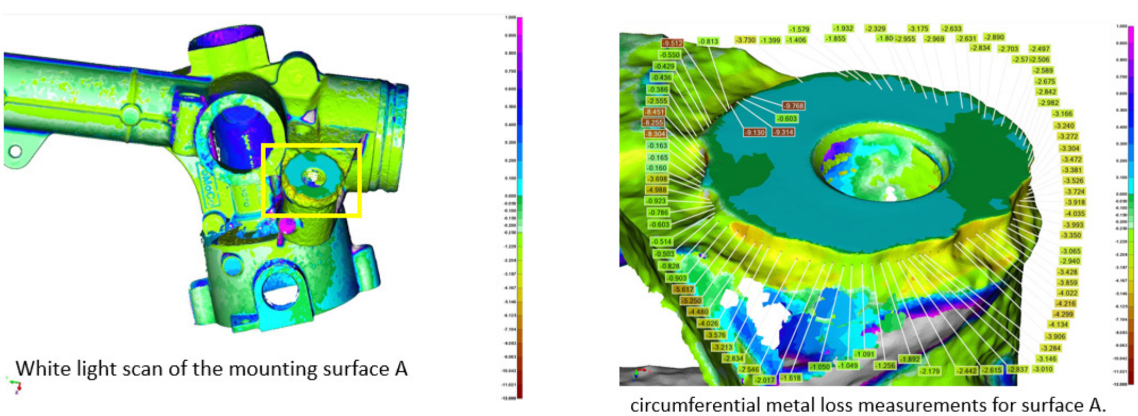


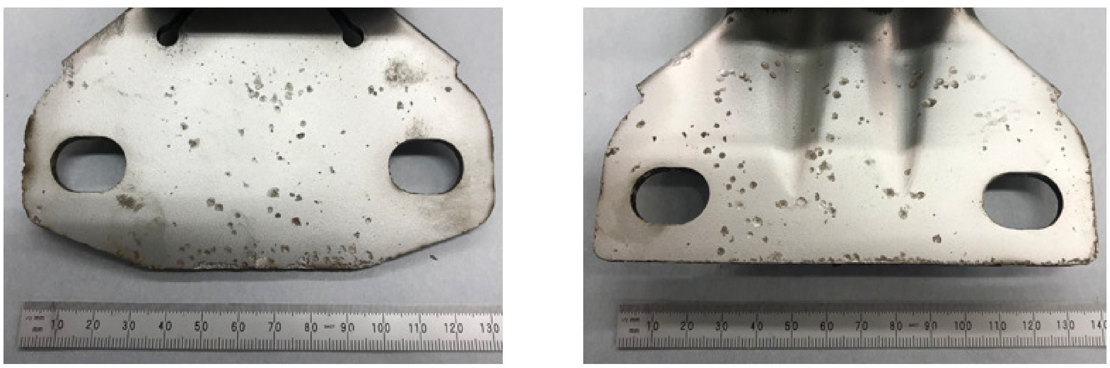
Figure 18: steering gear mounting surface metal loss measurement

Table 2: Metal loss measurement summary for the steering gear mounting surfaces

Component ID	**A-1**		**B-1**		**A-2**		**B-2**	
Interface ID	A	B	A	B	A	B	A	B
Average Metal Loss (mm)	2.88	1.89	3.02	0.97	3.20	1.47	3.28	1.42
Std. Dev. (mm)	2.27	1.34	2.16	0.47	2.13	0.90	2.67	1.01

Lower Control Arm Bracket Analysis

The lower control arm brackets are e-coated and directly joined to the subframe. The mounting surfaces of the tested lower control arm brackets were glass bead blasted to remove the e-coat and corrosion product. Significant pitting of the underlying steel substrate was revealed, see Figure 19. A point micrometer was used to determine the depth of the pitting, and a summary of the pit depth analysis is given in Table 3. The left/right orientation is from a view of the component from the front of the vehicle. A large variation of pit quantity and depth was observed across samples. A pictographic comparison of all samples that were analyzed is shown on Figure 20.



LCA bracket surface that interfaces with the top of the subframe.

LCA bracket surface that interfaces with the bottom of the subframe.

Figure 19: control arm bracket pitting

Table 3: Pit Depth Analysis Summary of Control Arm Interface

	A-1				B-1				A-2				B-2				Vehicle			
	Left		Right		Left		Right		Left		Right		Left		Right		Left		Right	
	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom	Top	Bottom
Maximum (mm)	0.35	0.35	0.47	0.46	0.15	0.22	0.22	0.44	0.24	0.41	0.28	0.59	0.24	0.63	0.29	0.37	0.38	0.48	0.36	0.76
Average (mm)	0.19	0.22	0.15	0.20	0.12	0.11	0.14	0.31	0.14	0.18	0.15	0.31	0.13	0.26	0.12	0.26	0.20	0.23	0.17	0.48
St. Dev. (mm)	0.08	0.06	0.12	0.12	0.03	0.05	0.06	0.11	0.06	0.09	0.08	0.13	0.06	0.13	0.07	0.07	0.08	0.16	0.09	0.21

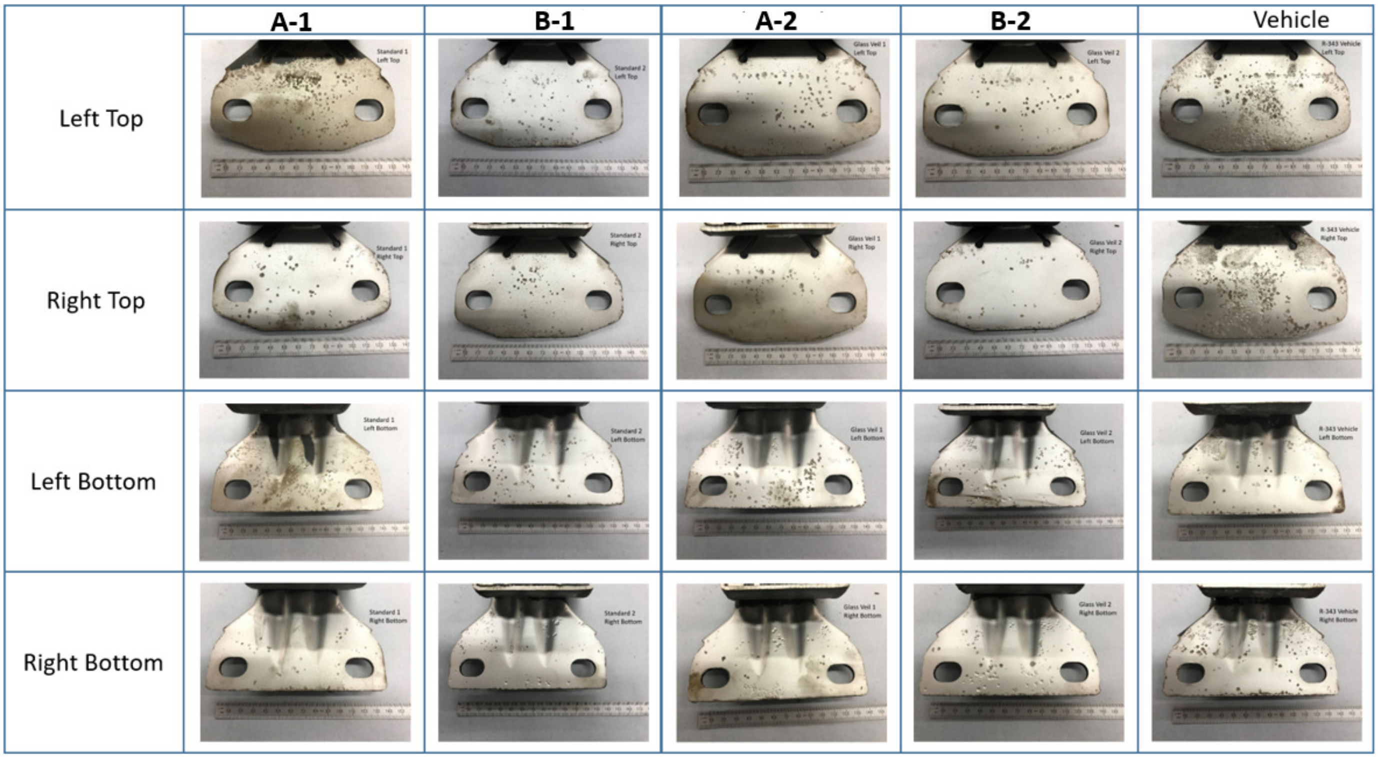


Figure 20: pictographic comparison of all samples

Fastener Summary

Fasteners at the control arm front joints and the roll restrictor joint were studied in detail to check for any benefits of the glass veil and nylon coating strategies. The locations of the fasteners selected for the study are shown in Figure 21 and their appearance at the end of test is shown in greater detail in Figure 22.

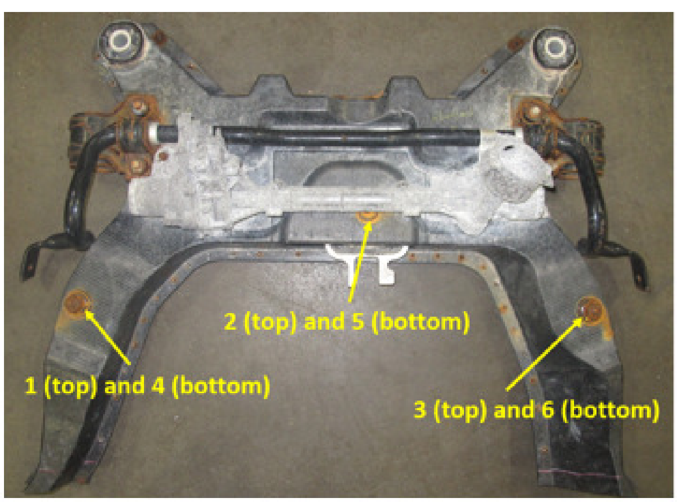


Figure 21: fasteners selected for rust study

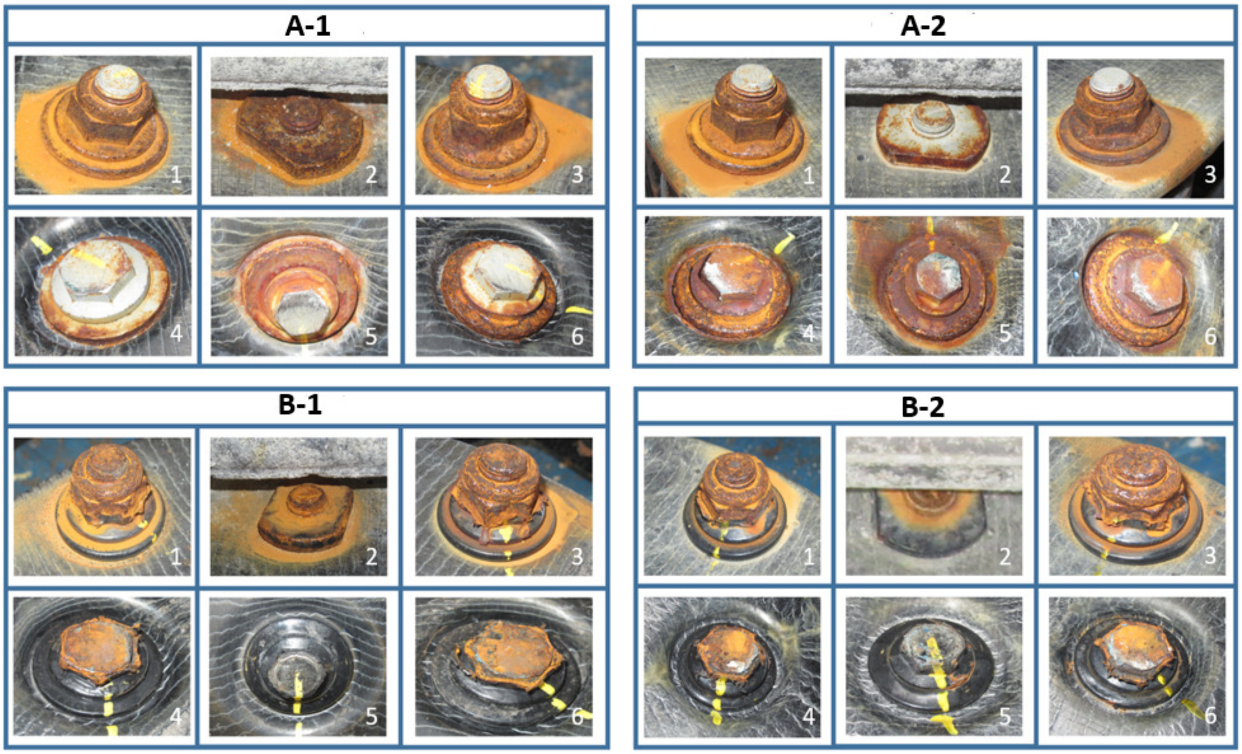


Figure 22: fasteners after 12 week laboratory component cyclic corrosion test

Inspection of these fasteners indicated that the nylon 11 coating adhesion to the bolt/nut heads deteriorated, allowing the development of red rust, see for example B-1.1 and B-1.3. This deterioration could be due to damage of the coating during assembly and subsequent corrosion exposure. Washers with nylon coating did appear to have enhanced red rust resistance compared to bare washers, see for example B-1.5 compared to A-1.5 and B-2.5 compared to A-2.5.

The glass veil incorporated on subframes A-2 and B-2 was tested as a possible isolator for the washers to CFRP surface. Inspection of the washers to CFRP interfaces revealed that even the uncoated washers directly interfacing the CFPR surface did not develop corrosion, see Figure 23. It is speculated that the high clamping load and, in some cases, the recessed location of the washers, occluded moisture, avoiding corrosion. Therefore the effectiveness of the glass veil could not be assessed in this analysis.

Figure 23: interfacing surface of washer to CFRP subframe without glass veil

Summary and Next Steps

Corrosion mitigation strategies are required to protect the metal parts and fasteners interfacing with the carbon fiber composite subframe and exposed to a corrosive environment. Standard actions included stainless steel inserts, e-coated brackets, and chassis required fastener finishes. Glass veil and Nylon 11 coating were proposed as additional protection methods.

The proving ground vehicle corrosion test investigated the effectiveness of the standard corrosion mitigation strategies. Red rust bleed was observed on bolt hats/nuts, rivets and the steel brackets. There was no evidence of loose fasteners and no functional failures occurred.

The stainless steel inserts showed good condition without material loss, confirming this material's compatibility with CFRP.

The aluminum steering gear mounting surfaces were not compatible with the stainless steel inserts. Significant galvanic corrosion of the aluminum mating surfaces to the stainless steel inserts was observed and quantified.

The steel lower control arm brackets exhibited pitting on the surfaces in contact with the carbon fiber. The e-coat paint was not sufficient to avoid corrosion on the steel brackets for this design.

The Nylon 11 which was applied to the washers, bolt shanks, and fastener flanges on two of the subframes appeared to have provided some degree of corrosion protection, most successfully on the washers.

The effectiveness of the glass veil as an isolator should be investigated in follow-up experiments.

Acknowledgements

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