CARBON FIBER SUBFRAME DEVELOPMENT – FATIGUE AND STRENGTH CAE AND TEST RESULTS

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Abstract

A research carbon fiber composite front subframe was designed and manufactured for the Ford Fusion to investigate the opportunities and challenges associated with this lightweight material to potentially improve fuel economy. The design process was CAE driven verified with component tests and proving ground vehicle tests. CAE output demonstrated that the carbon fiber composite subframe met performance targets for both high cycle fatigue and critical event strength durability.

Component tests were conducted to verify the subframe's fatigue performance under high cycle loads and strength under quasi static loads. Proving ground vehicle durability test and strength related special event tests were also conducted. The CAE predictions for the component and vehicle tests had various degrees of correlation with the physical test results. Improvements in CAE procedures and material characterization will likely be needed to generate robust CAE predictions of carbon fiber composite structural performance.

Background and Requirements

Carbon fiber composites are alternatives for lightweight materials in automotive component designs. Carbon fiber reinforced plastic components have been used in luxury cars and racecars. The applications of the materials are mostly unidirectional long fiber composites that provide desired mechanical properties with high cost.

The subframe in this research project used EpicBlend SMC, compounded by Magna, a chopped 50k industrial-grade carbon fiber with a modified vinyl ester resin. A continuous carbon fiber material, EpicBlend CFS-Z with 0º/90º non crimped fabric (NCF), was co-molded with the chopped EpicBlend SMC material. The SMC allows complex geometries. The NCF patches provide strength at critical areas [1]. This approach is affordable and scalable for high-volume production. In addition to the co-molding of the two carbon fiber composite materials, four stainless steel body mount inserts and two stainless steel steering gear compression limiters are over-molded.

A 2016 Ford Fusion was selected as the baseline vehicle for the development. It has a perimeter subframe shown in Figure 1. It is challenging to design a subframe with carbon fiber composites considering its much lower modulus and tensile strength comparing to steels. This carbon fiber composite (CF) subframe design was CAE driven. The stiffness and durability performances of the steel subframe were set as reference targets for the CF subframe design. The process started with topology optimization for stiffness followed by durability design. Stress in fastener bearing area was also investigated and washers were introduced to prevent composite damage in fastener bearing areas. CAE results demonstrated that the CF subframe met stiffness, durability and strength targets set for the Fusion steel subframe [2].

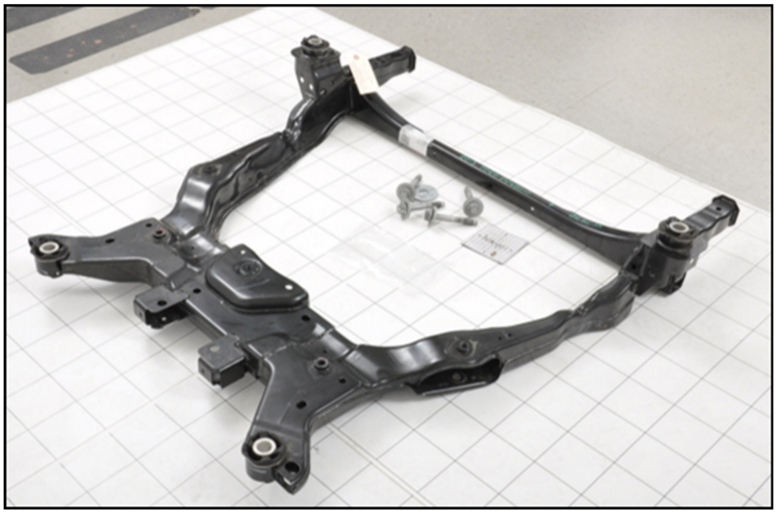

Figure 1: Ford Fusion steel front subframe

To validate the CAE design and prove the quality of the prototype subframe both component and vehicle tests were conducted.

Component tests were conducted to verify the subframe's fatigue performance under high cycle loads and strength under quasi-static loads. There were four loading conditions for fatigue tests and three loading conditions for the strength tests. Under high cycle fatigue loads, the carbon fiber subframes survived the required two accelerated lives. A number of small cracks were observed during the component tests. The majority of cracks did not propagate and the subframes did not lose load carrying capacity. Under quasi-static loads, the subframes exceeded the load carrying capacity requirement for the baseline steel subframe.

Proving ground vehicle durability test and strength related special event tests were also conducted. Numbers of small cracks observed in component fatigue tests did not appear during the vehicle test. There were few cracks in the subframe around the front body mounts and the control arm rear joint. These cracks propagated at certain levels as the test progressed. The cracks did not degrade the subframe's functions on the vehicle. The special event tests included driving over bumps and breaking into potholes. The vehicle passed the Level One test and failed the Level Two test.

The CAE predictions for the component and vehicle tests had various degrees of correlation with the physical test results. Improvements in CAE procedures and material characterization will likely be needed to generate robust CAE predictions of carbon fiber composite structural performance.

Carbon Fiber Subframe Design Highlights

The design of the CF subframe was CAE driven. The CAE design process incorporate the following steps:

Topology Optimization and Design for Stiffness

Topology optimization used the design space to run iterations until the minimal weight was reached and met all stiffness targets set for the optimization. The output of an optimization was a contour plot showing material distribution required to meet all stiffness targets. The topology optimization contour was used to guide the creation of the preliminary subframe design. More CAE iterations were performed to refine the geometries and gauges. Those simulations led to a mature proposal to start durability design iterations. OptiStruct of HyperWorks [3] was the analysis software for this topology optimization and NASTRAN [4] was used for stiffness design simulations.

Design for Fatigue Life

Design for fatigue simulates the subframe's working condition with high cycle load cases, such as start, brake, turn, etc. The load input for this CF subframe development is the GEDL (Generic Endurance Design Load) load cases of the baseline steel subframe. There are 13 driving events listed for the simulation. For each event, there are three forces and three moments applied to every chassis component attachment joint of the subframe. The load cases represent 150,000 miles or 10 years' service of the vehicle. Figure 2 is the plot of the braking event with 20 cycles.

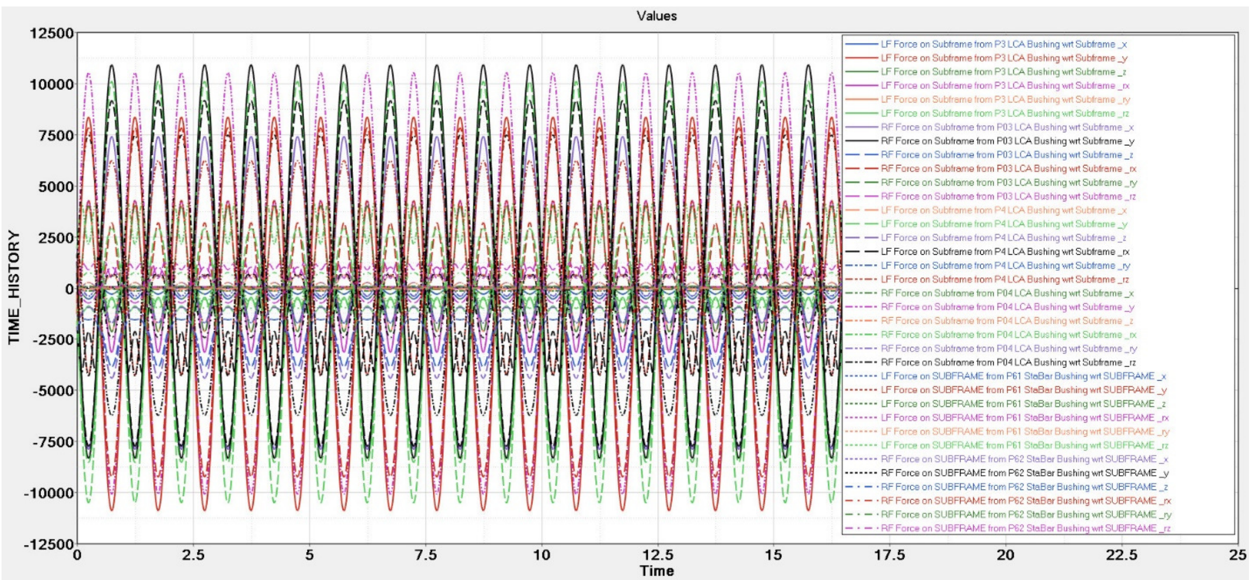

Figure 2: braking event loads applied to joints

There were two steps to simulate the subframe's fatigue life with CAE. Step 1 ran NASTRAN analysis with unit loads applied to joints. The output of the analysis was stresses in the structure. Step 2 used nCode [5] combining NASTRAN output and GEDL load cases as input. The minimal CAE-based life prediction required for production subframes is two lives. CAE simulation did not identify any location with fatigue life less than two (2.0 lives) demonstrating that the subframe met GEDL load design targets.

Design for Strength

The strength design of the subframe is for structure integrity under extreme loading conditions. The production subframe's GSS (Global Suspension Strength) load cases were used for the carbon fiber composite subframe's strength design. There are two levels of load inputs for this design process. Level One loads represent moderate abuse such as driving through bumps. Measurements of Level One performance is the structure permanent deformation. Ford's requirement is that the subframe remain completely functional after multiple Level One events. For ductile material subframe, this requirement limits the permanent deformation to less than one or two millimeters depending on location. Level Two loads represent extreme abuse such as braking into potholes. Measurements of Level Two performance is the structure damage. Ford's requirement is that the subframe remain completely functional, though likely in need of repair, after multiple Level Two events. The subframe must maintain function without any separations or loss of integrity. ABAQUS [6] was the analysis software.

Under Level One loading the design criteria for steel subframes are permanent deformations (deformation after unloading) listed as following:

- Permanent deformation < 1 mm at loading points
- Permanent deformation < 2 mm at rest of the subframe

Under Level Two loading the design criterion for steel subframes limits the plastic strain as following:

- Max. plastic strain of the subframe < 50% of the failure strain of the alloy

Since carbon fiber composites have little or no ductility, the failure criteria under both Level One and Level Two loads are defined as following:

- SMC: Max stress > yield stress (187 MPa)
- Laminates: Tsai-Hill criteria predicted failure

$$\frac{\sigma_{11}^2}{S_{11}^2} - \frac{\sigma_{11}\sigma_{22}}{S_{11}^2} + \frac{\sigma_{22}^2}{S_{22}^2} + \frac{\sigma_{12}^2}{S_{12}^2} \geq 1.0$$

CAE simulation results showed stress of SMC is lower than the yield stress. The Max. Failure Index on the control arm front joint laminates is 1.6 indicating concern at that location (Figure 3). It requires verification by tests.

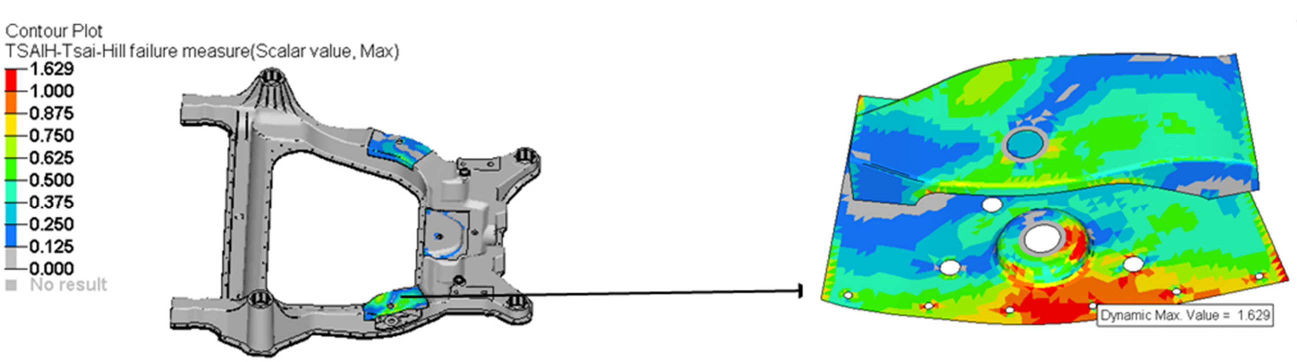

Figure 3: CAE predicted failure on control arm front joint laminate

Design for Bolt Load Retention

Subframe joints for the attached chassis components are bolted joints. This CF composite subframe has M14 and M16 bolts (bolts shank diameters are 14mm and 16mm respectively). The proof loads for M14 and M16 bolts are 95.5kN and 130kN. High bolt proof loads could lead to high stresses in fastener bearing area. Yield or any composite damage of fastener bearing area could affect bolt load retention of the joint.

A common practice to reduce the stress level in fastener bearing area is to add washers. Washers create an effective stress bearing area that is larger than the fastener bearing area. Dimensions of washers are decided by bolt proof loads, the size of fastener bearing area and the yield stress of the subframe material [7]. Washers are introduced to all joints of the CF composite subframe except for the control arm rear joint, which has the bushing brackets covering large areas at and around the joints.

Most washers in the CF composite subframe are “Hat” washers. “Hat” washers cover the top surfaces of bolt holes and small portion of the side wall of bolt holes. “Hat” washers are made of the same steel and have the same finish as for bolts, which is one of the corrosion mitigation strategies in addition to its bolt load retention function. Figure 4 is the control arm front joint with four “Hat” washers.

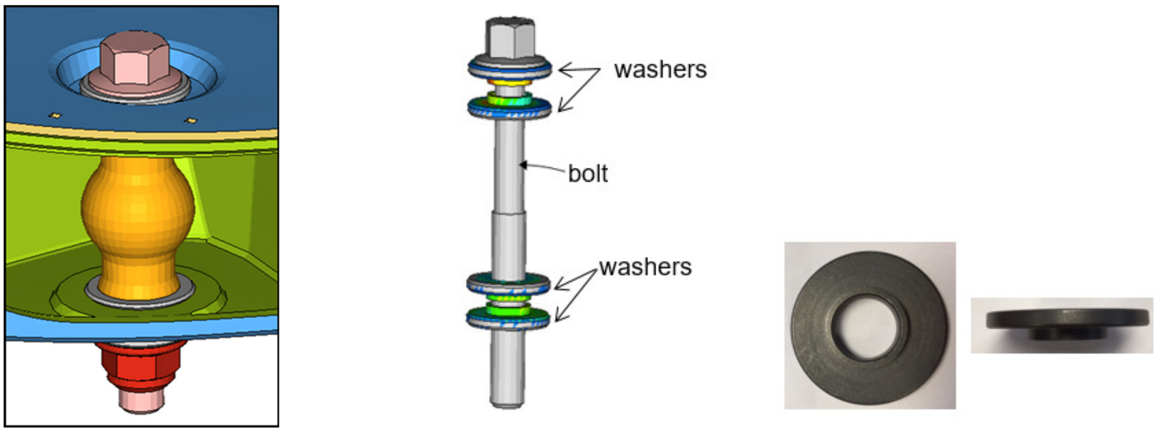

Figure 4: control arm front joint with “Hat” washers

ABAQUS was used to run the fastener bearing area stress analyses. The failure criteria are the same as those for strength design iterations. The control arm front joint surfaces were identified by CAE simulations as areas of concern (Figure 5). The high stress were on laminates. It needs to be verified by tests.

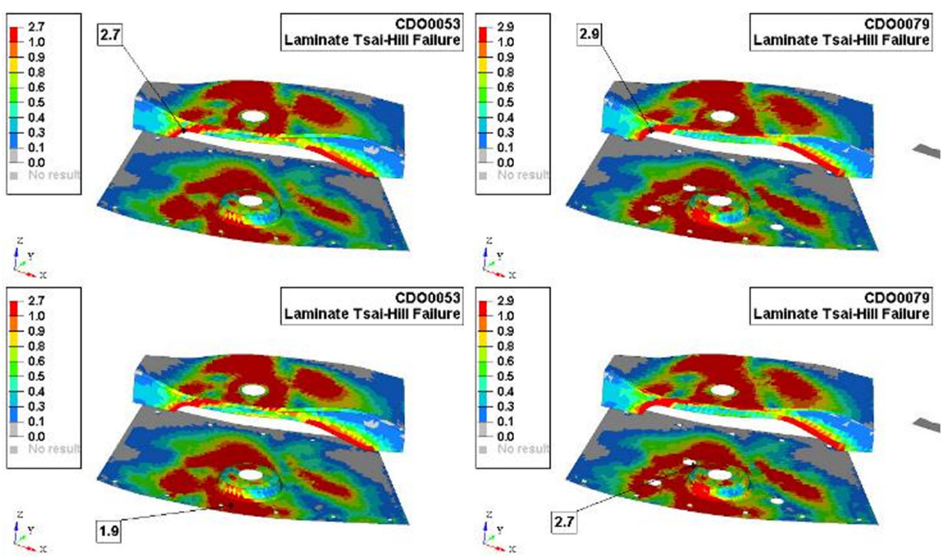

Figure 5: control arm front joint laminate surfaces

CF Subframe Prototype

The CF composite subframe prototypes are produced by Magna International. The subframe utilizes an industrial carbon fiber compounded with a modified vinyl ester resin system in EpicBlendTM CFS-Z SMC that is approximately 50% by weight chopped carbon fiber. The second carbon fiber composite material that is co-molded with the SMC is a pre-preg material that utilizes continuous 0º/90º non crimped fabric that is approximately 56% by weight continuous oriented carbon fiber. 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 that incorporate six over molded steel parts. The two moldings, an upper clamshell and a lower close out panel, are joined be adhesive bonding and structure rivets. Details of the subframe components are shown in Figure 6.

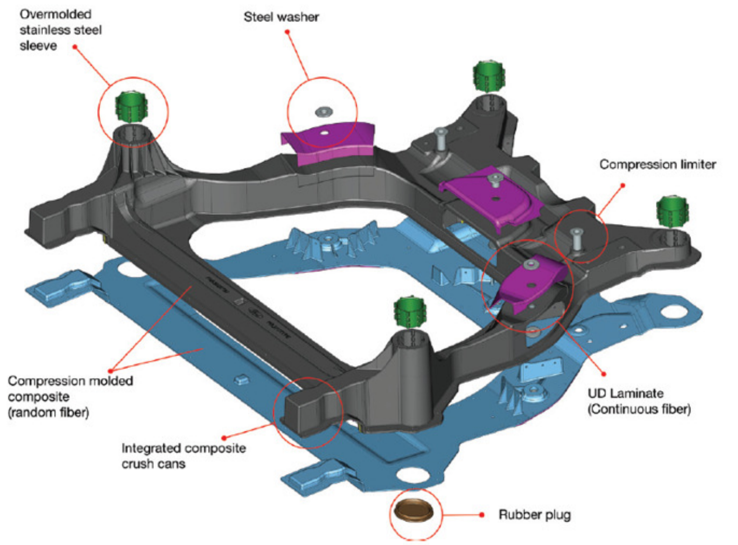

Figure 6: CF composite subframe components

The finished part is shown in Figure 7.

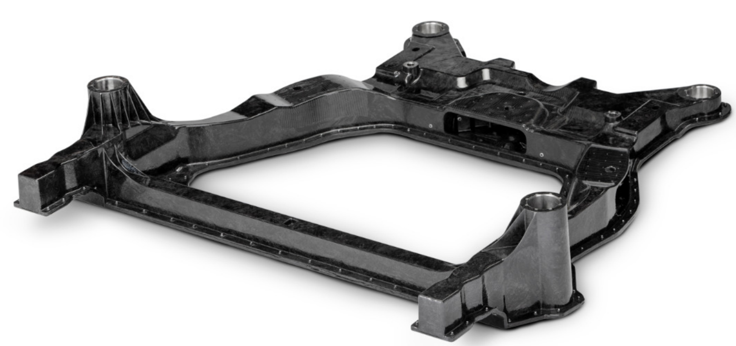

Figure 7: CF composite subframe prototype part

Carbon Fiber Composite Subframe Component Fatigue Tests

Subframes were tested to validate the CAE design and prove the quality of the CF composite prototype. Tests included component durability under fatigue loads and strength under static loads. The fatigue tests were conducted for all four joints of the subframe. A steel subframe was also tested for each setup. The load cases were developed based on the GEDL loads (Generic Endurance Design Loads) of the surrogate part. CAE were conducted to simulate the tests. The outputs were compared with test results. The CAE predictions did not correlate with test results.

Roll Restrictor Fatigue Test

Test Procedure

The subframe was mounted to the bedplate in vehicle position utilizing the body mounts as shown in Figure 8. Horizontal longitudinal block cycle loads were applied 90 degrees to the roll restrictor bushing fastener through a solid loader. The height of the loader was equal to that of the roll restrictor. Lower arm bushings were bolted in the lower arm pockets on all samples.

Horizontal sinusoidal loads of two baseline lives and eight over stress loading blocks were generated from production Fusions' GEDL roll restrictor load events.

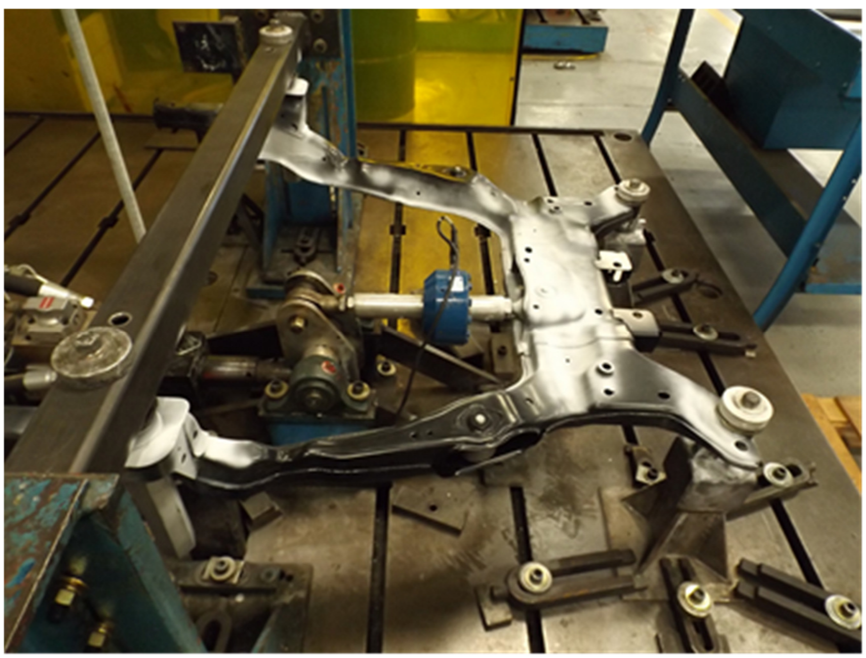

Figure 8: roll restrictor test setup

Test Results

A single steel subframe was tested through two baseline-loading cycles (two lives) and seven over stress cycles. There was no damage detected.

The CF subframe was also tested for two baseline cycles and seven over stress loading cycles. There was visible damage, i.e., small cracks, but without loss of function or load carrying capacity.

For the carbon composite subframe samples, several small cracks were observes through the loading process. Most of the cracks were on the front body mount surfaces. Few were near the loading location and the control arm rear joint (Figure 9). Some cracks were detected before the end of the second baseline cycle. All cracks were stabilized as the loading progressed. The subframe structure maintained its integrity and load carrying capacity through the test. This component test result proved that the CF subframe met the fatigue requirements at the roll restrictor joint.

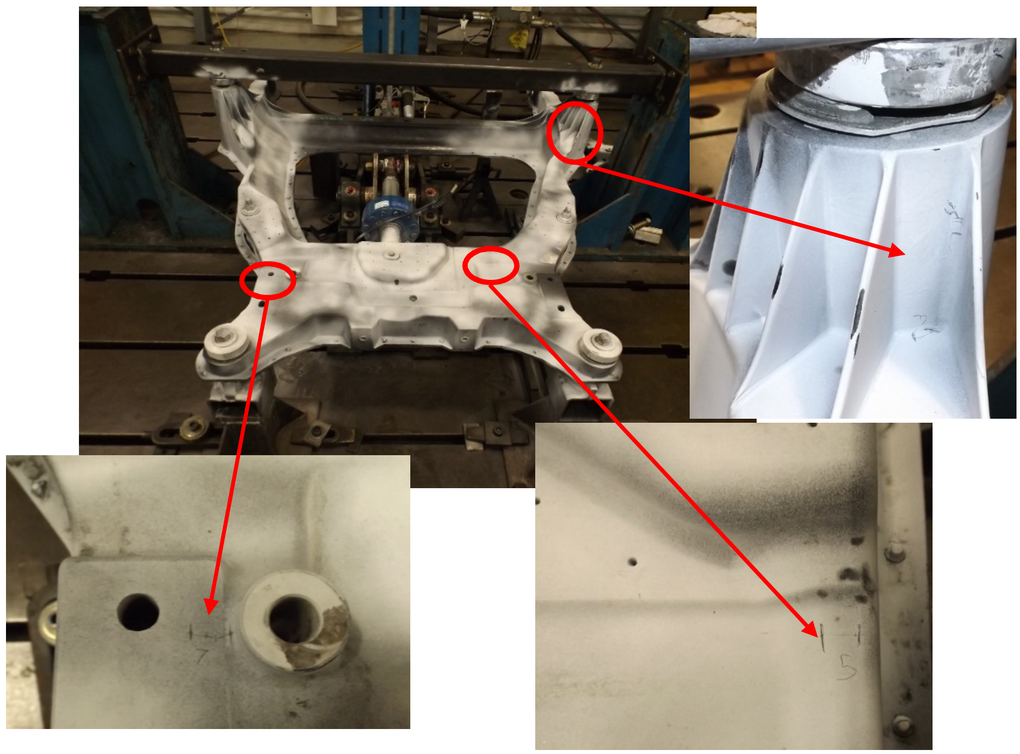

Figure 9: roll restrictor test cracks - CF subframes

Front Lower Control Arm Fatigue Test

Test Procedure

The subframes were secured to a fixture which was rigidly bolted to the bedplate. A longitudinal and a lateral actuator were connected to the ball joint stud of the left and right lower control arms shown in Figure 10. Loads were applied into the subframe by block cycles. Inspections were made periodically throughout the test to look for cracks in the subframe.

A calibrated Flextest controller was used to control the load of all four hydraulic actuators. Loads were applied in a sinusoidal wave based on the block cycles generated from production Fusions' GEDL control arm load events.

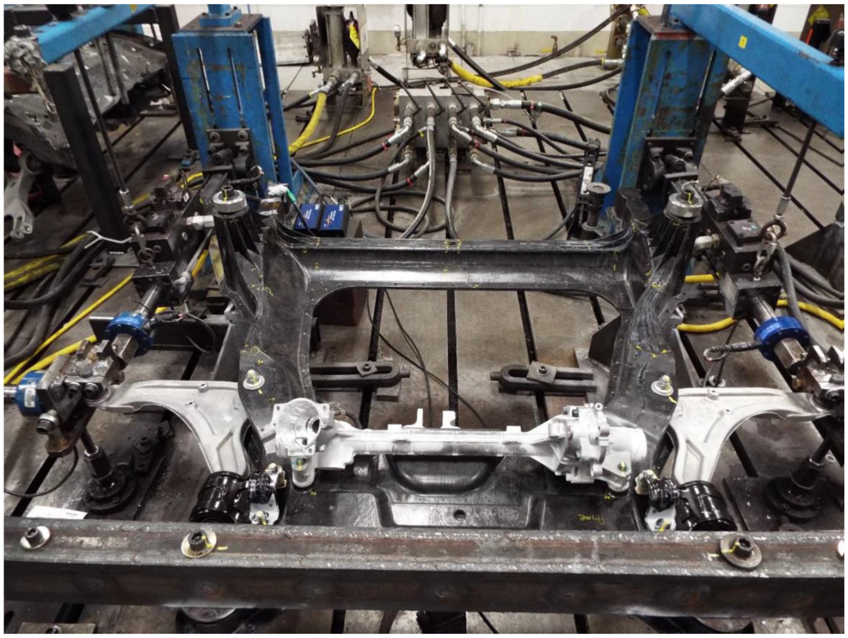

Figure 10: control arm test setup

Test Results

The steel subframe was tested through two baseline-loading cycles (two lives). Cracks were detected before completing the second baseline loading cycles (Figure 11)

Figure 11: control arm test cracks – steel subframe

The CF subframe was also tested for two baseline cycles.

For the three carbon fiber composite subframe samples, multiple small cracks were detected. Some initiated at the early loading blocks. Most of the cracks were around the front body mounts. Propagations were observed as the test progressed. Selected cracks are shown in Figure 12. The subframes survived the two baseline loading cycles without losing its load carrying capacity.

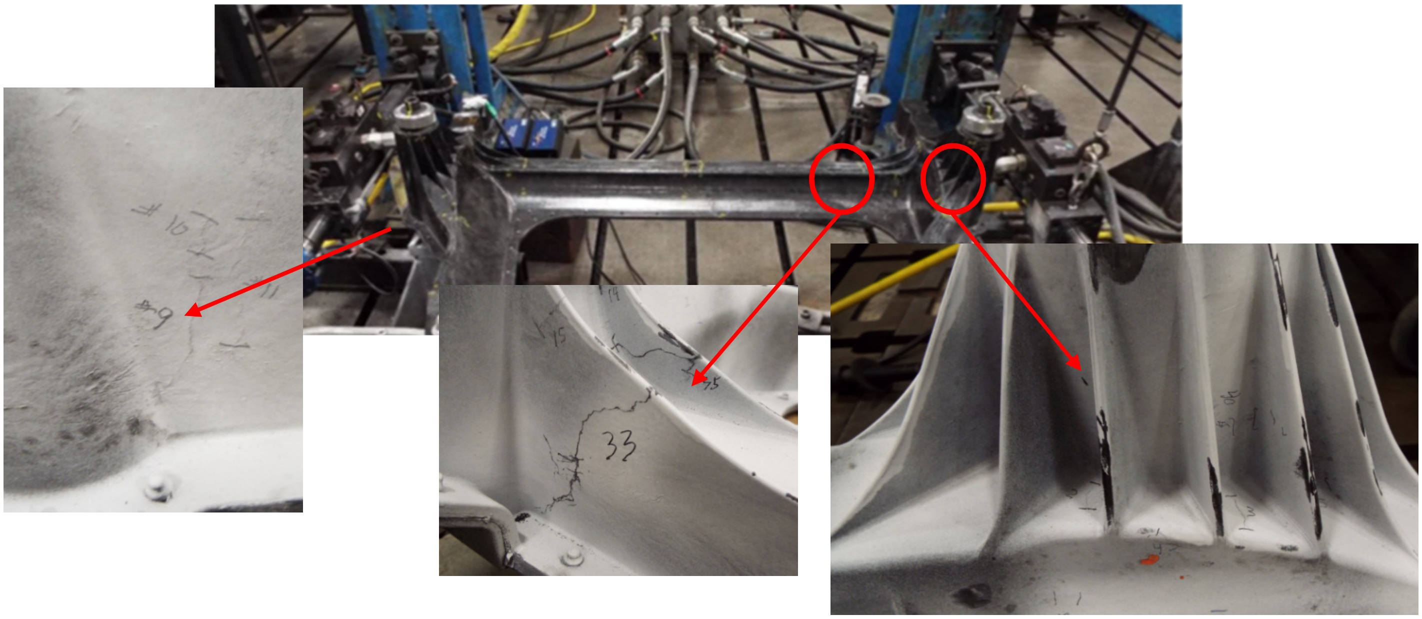

Figure 12: control arm test cracks –CF subframe

Stabilizer Bar Fatigue Test

Test Procedure

The CF subframe was mounted level to the bedplate as shown in Figure 13. The subframe was loaded through the stabilizer bar brackets and bushings. The test load was applied 90 degrees to level using a production stabilizer bar. Lower control arm bushings and a roll restrictor were bolted in place, and a steering gear was mounted to each frame tested.

Sinusoidal Block cycle test loads were applied. The two actuators were run 180 degrees out of phase at 2.0 Hz with the two baseline lives and four over stress loading blocks generated from production Fusions' GEDL stabilizer bar load events.

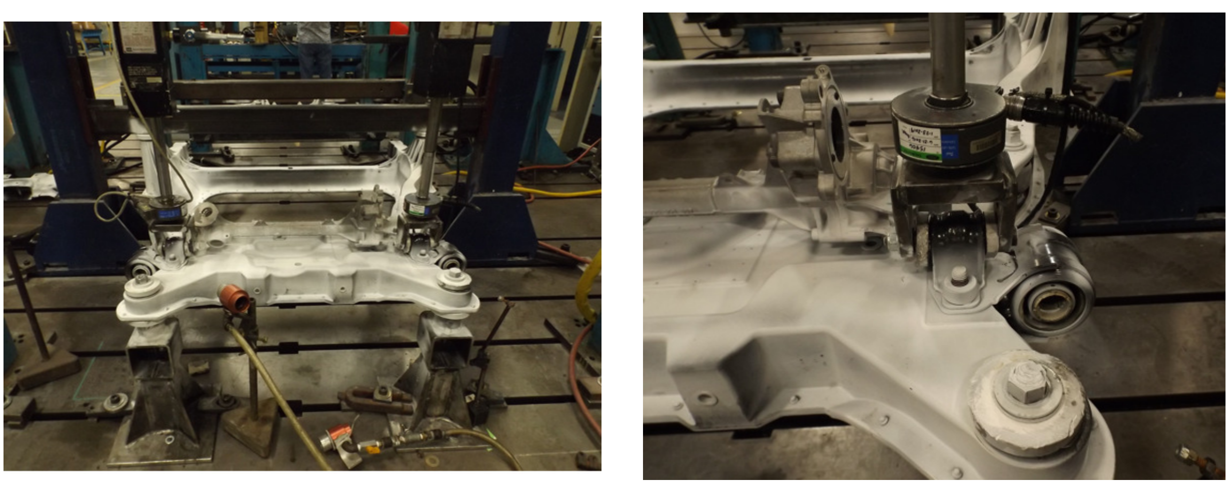

Figure 13: stabilizer bar test setup

Test Results

One steel subframe was tested through two baseline-loading cycles (two lives) and four over stress cycles. There was no damage detected.

For the three CF subframe samples, cracks initiations were detected close to the finish of second baseline cycles. More small cracks were observed through over stress loading. Several cracks were around the front body mounts and other cracks were scattered throughout the subframe. Most cracks did not propagate. Selected cracks are shown in Figure 14. The subframes successfully passed the two baseline loading cycles and four over stress cycles without losing its load carrying capacity.

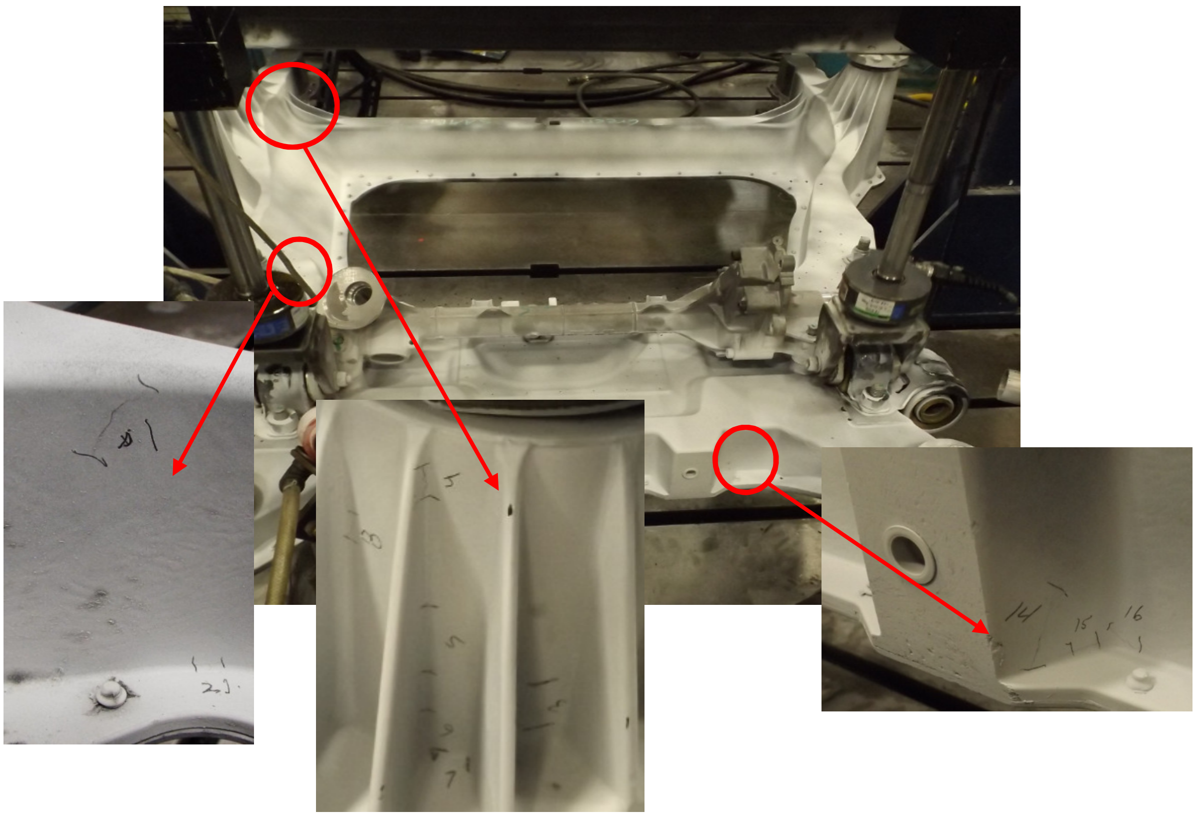

Figure 14: stabilizer bar test cracks –CF subframe

Steering Gear Fatigue Test

Test Procedure

The CF subframe was mounted level to the bedplate as shown in Figures 15. The subframe was loaded through a steering gear housing using simulated tie rod ends. The load axis was 6 degrees forward and 6 degrees down at outer tie rod ball joints, 26 mm from the ends of the housing. Lower arm bushings and a roll restrictor were placed in their respective locations and bolted into place.

The two actuators were run 180 degrees out of phase such that when the Left Hand load cell was in tension, the Right Hand load cell was in compression. Block cycle loads were applied with two baseline lives and eleven over stress generated from production Fusions' GEDL steering load events.

Figure 15: steering gear test setup

Test Results

One steel subframe was tested through two baseline-loading cycles (two lives) and eleven over stress cycles. There was no damage detected.

Multiple crack initiations were detected on each of the three CF subframe samples before the completion of second baseline cycles. Cracks were at or close to the steering gear attachment joint. The cracks did not propagate much. Selected cracks are shown in Figure 16. The subframes passed the two baseline loading cycles and eleven over stress cycles without losing its load carrying capacity.

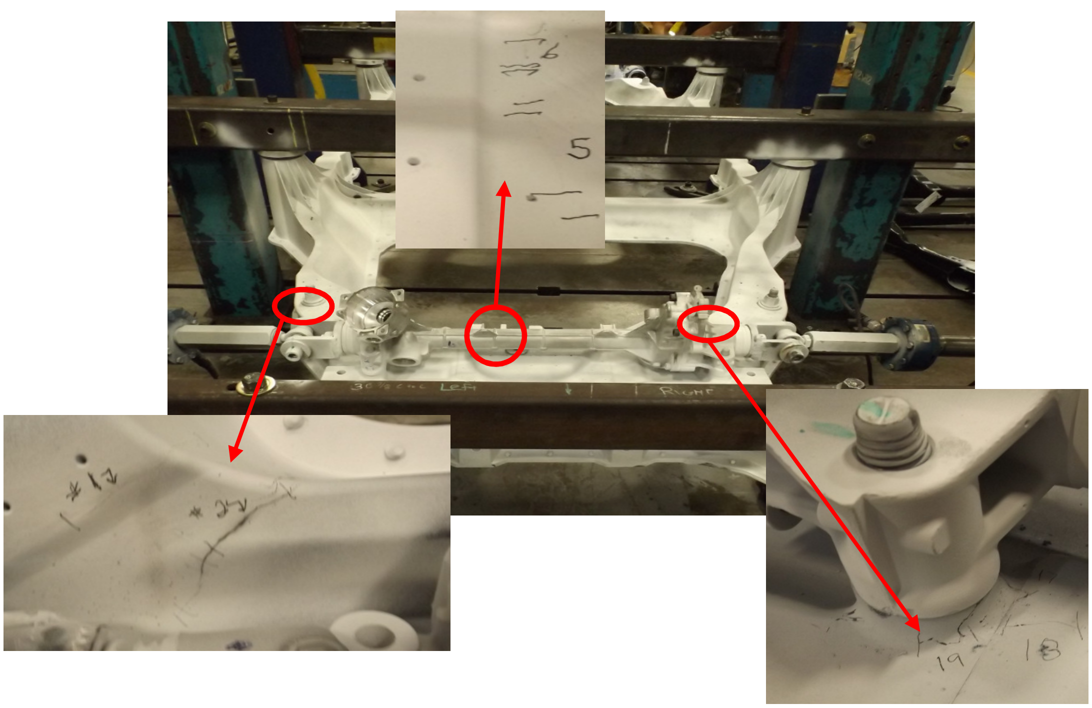

Figure 16: steering test cracks – CF subframe

Vehicle High Cycle Durability Test

A carbon fiber composite subframe was installed in a production Fusion and tested at Ford Michigan Proving Ground. The test followed the Ford procedure which is one of several tests required for passenger cars, crossovers and utility vehicles. The test emphasizes accelerated vehicle body and chassis systems and component durability based on customer correlated public road usage [8].

The vehicle was inspected daily through the three month test duration. The inspections evaluated part condition and visually inspected the paint marks on the subframe joints to detect possible bolted fastener movements.

The vehicle durability test results were contrary to the component fatigue tests. Scattered small cracks were not observed through the test. Few cracks were detected. The crack on the front body mount was found at the very early stage of the test. It propagated and stabilized at about 25% of the test duration. Other cracks were recorded at about 50% of the test duration. They remain the same lengths until the end of the test. The cracks are shown in Figure 17.

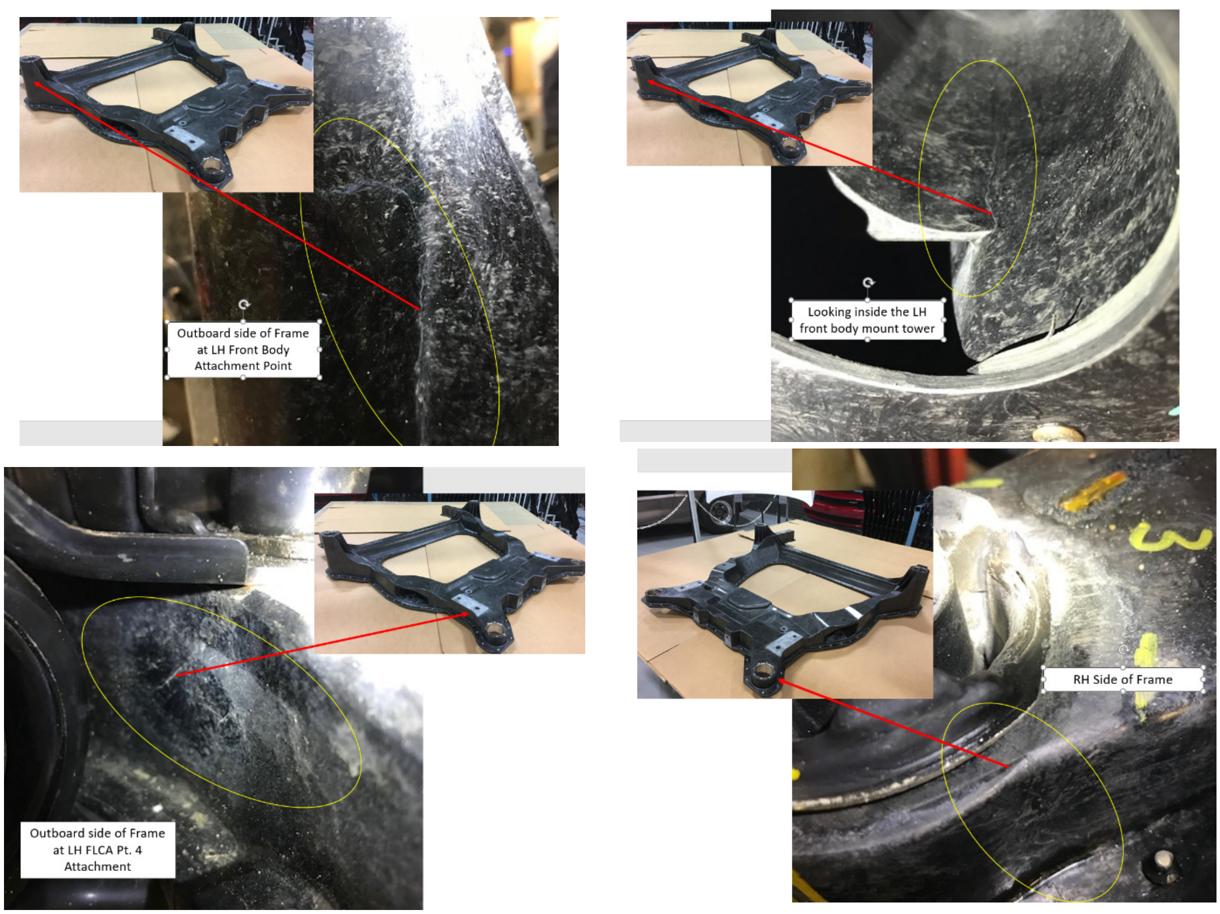

Figure 17: cracks – vehicle durability test

The vehicle completed required test conditions and cycles. No degradation of functions was detected. The post-test inspection, Figure 18, did not find visible movement of fasteners. The Fusion vehicle with a CF composite subframe successfully passed the proving ground durability test.

Figure 18: CF subframe – post vehicle durability test

Carbon Fiber Subframe Component Strength Tests

The strength tests were conducted to evaluate the load carrying capacity of the CF subframe. Three loading conditions were designed. Fixtures were built for each of the tests. The subframe was secured at the four body mounts shown in Figure 19. The subframes were loaded under quasi-static loads up to failure occurred and compared with the surrogate vehicle's GSS loads (Global Suspension Strength) at the loading joints.

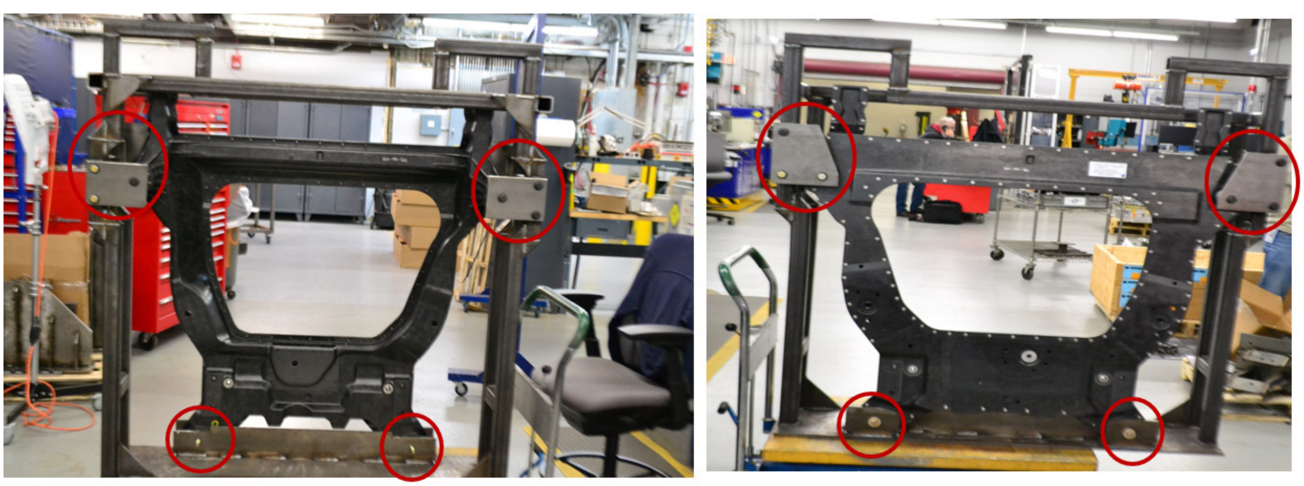

Figure 19: CF subframe – Strength test fixture

CAE simulations were done before the tests to predict failure locations and peak loads. CAE simulation results also helped to choose load cells for the tests. ABAQUS was used for CAE simulations.

Roll Restrictor Strength Test

Test Setup

For the roll restrictor test, a steel tube was used to represent the roll restrictor bushing. The load was applied in the vehicle's longitudinal direction shown in Figure 20.

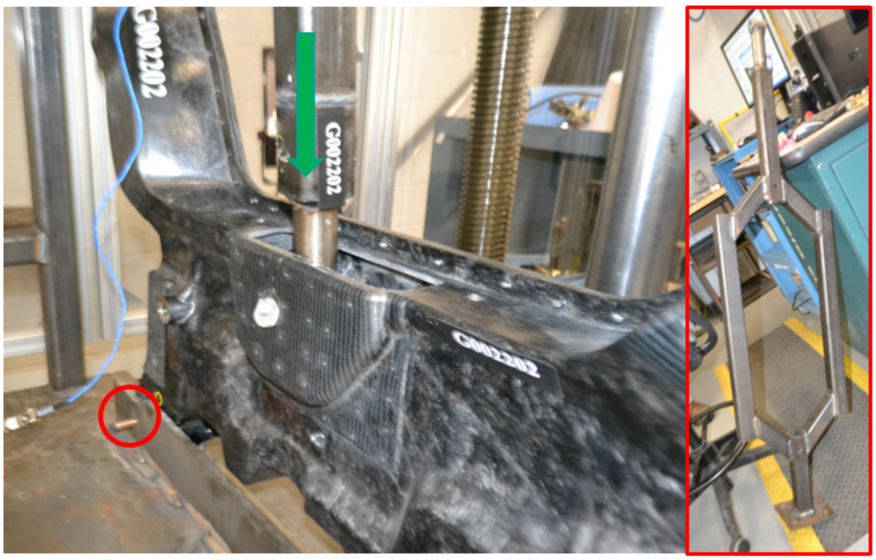

Figure 20: Strength test – roll restrictor loading

Test Results

The failure started at the loading location. The bolt hole of the roll restrictor was damaged. The bolt was bent and the nut was broken shown in Figure 21. The force curve is shown in Figure 22. The peak load is about 80 kN.

Figure 21: strength test – roll restrictor loading damage

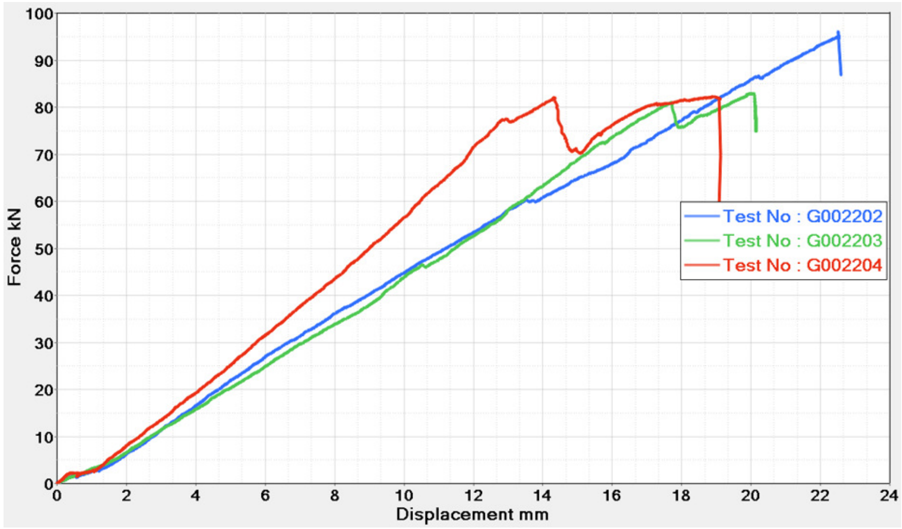

Figure 22: Strength test – roll restrictor loading force deflection plot

Test and CAE Comparison

The test results were compared with CAE predictions. The ABAQUS simulation predicted high stress area at the edge of the bolt hole that is the same location showing failure in the tests (Figure 23). The peak load predicted by the simulation is higher than the failure load of the test.

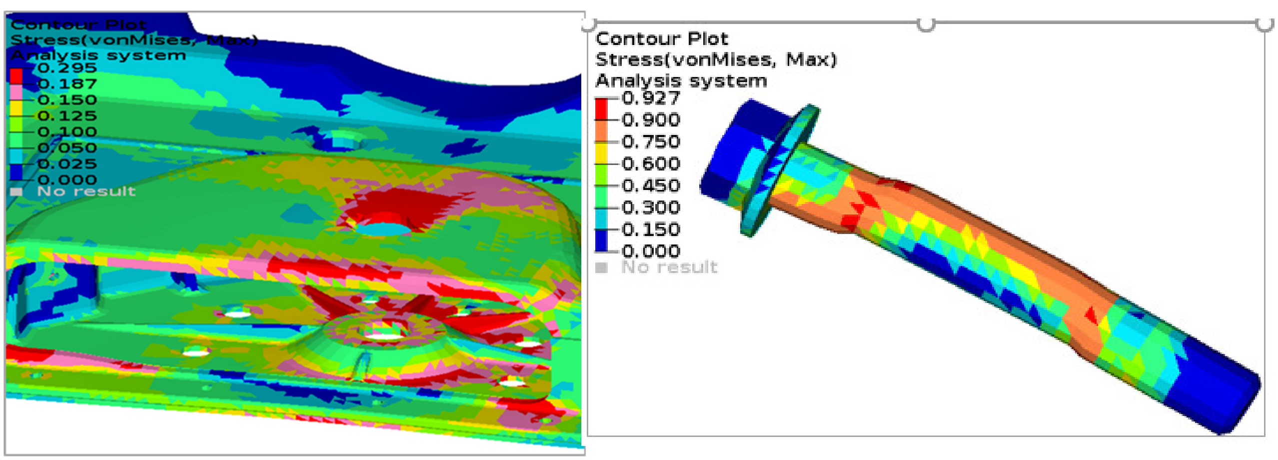

Figure 23: Strength test – roll restrictor loading CAE failure locations

Control Arm Front Joint Strength Test

Test Setup

For the control arm front joint test, a steel tube was used to represent the control arm bushing. The load was applied in the vehicle's lateral direction shown in Figure 24.

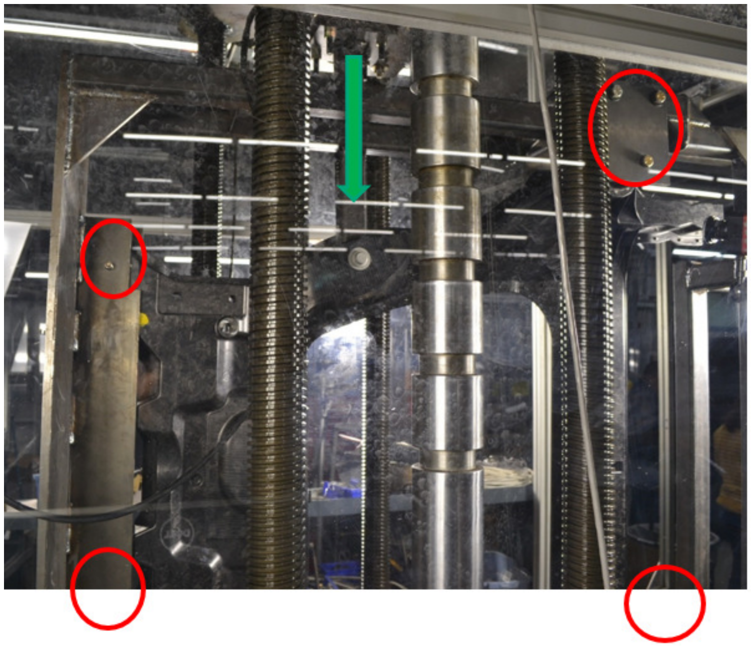

Figure 24: Strength test – control arm front joint loading

Test Results

The damage started near the loading location. There was a crack on the opposite side of the loading point. Figure 25 shows cracks on the subframe. The force curve is shown in Figure 26. The peak loads of the test are higher than 58 kN, the GSS resultant load at this hard point.

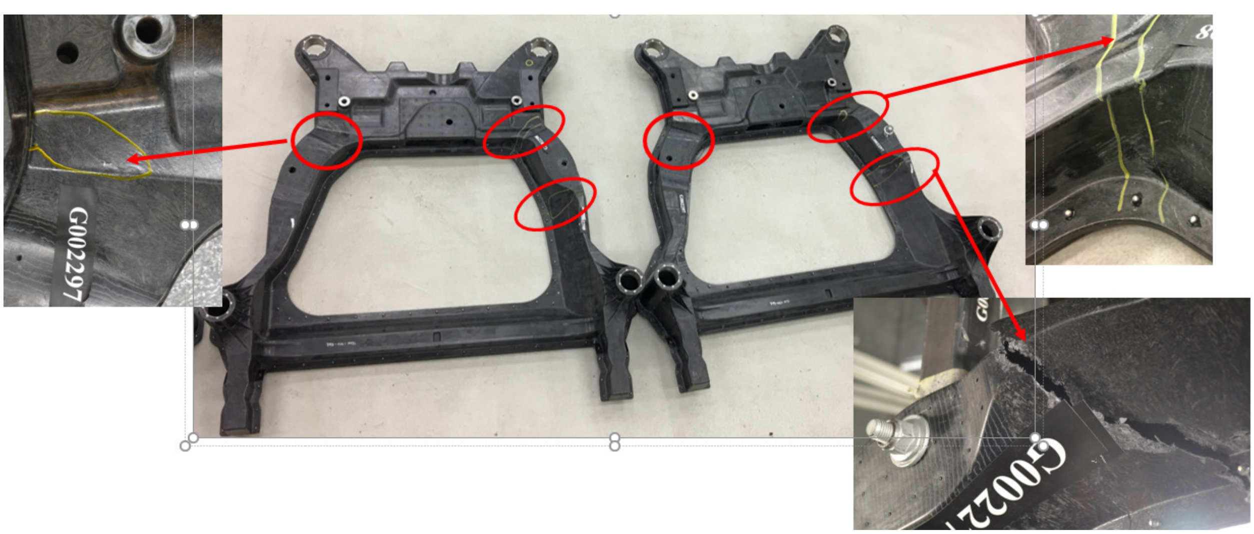

Figure 25: strength test – control arm front joint loading damage

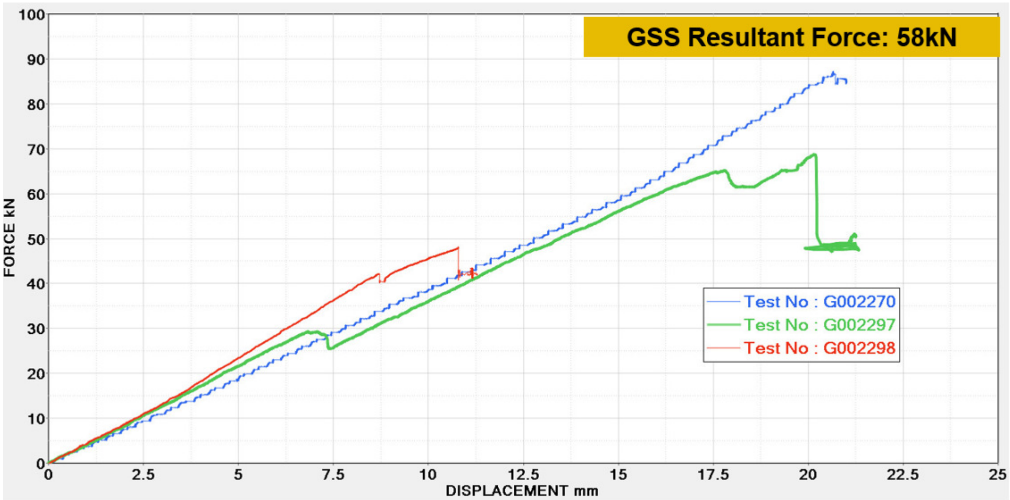

Figure 26: strength test – control arm front joint force deflection plot

Test and CAE Comparison

The test results were compared with CAE predictions. The ABAQUS simulation predicted high stress areas near the loading point that are the same locations showing failures in the tests (Figure 27). The CAE simulation did not catch the crack on the opposite side of the loading point. The peak load predicted by the simulation is higher than the failure load of the test.

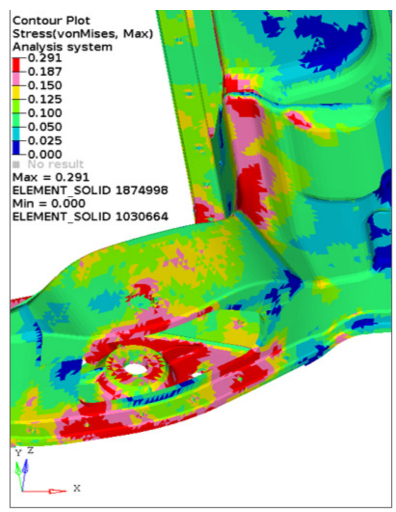

Figure 27: Strength test – control arm front joint loading CAE failure locations

Control Arm Rear Joint Strength Test

Test Setup

For the control arm rear joint test, A "U" bracket was used to represent the control arm bushing bracket. The load was applied to the lateral direction of the vehicle shown in Figure 28.

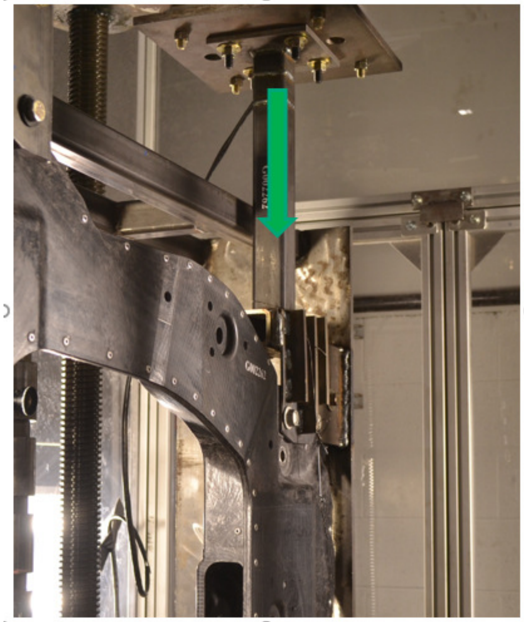

Figure 28: Strength test – control arm rear joint loading

Test Results

The damage started near the loading location. Figure 29 shows cracks on the subframe. The force curve is shown in Figure 30. The peak loads of the test are much higher than 35 kN, the GSS resultant load at this hard point,

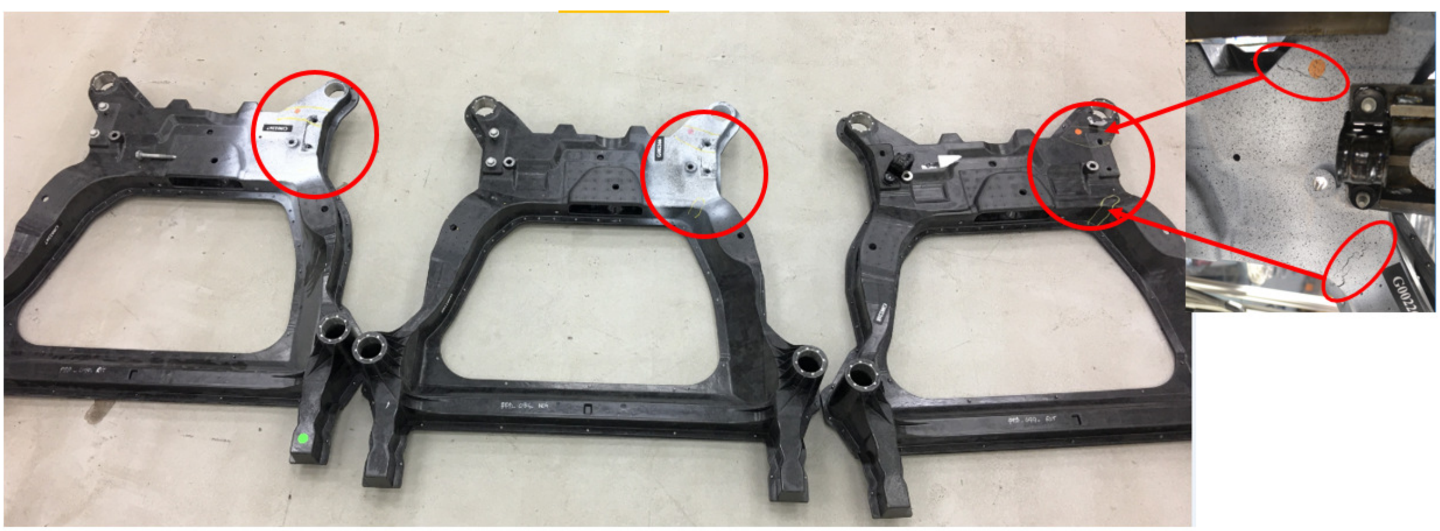

Figure 29: strength test – control arm rear joint loading damage

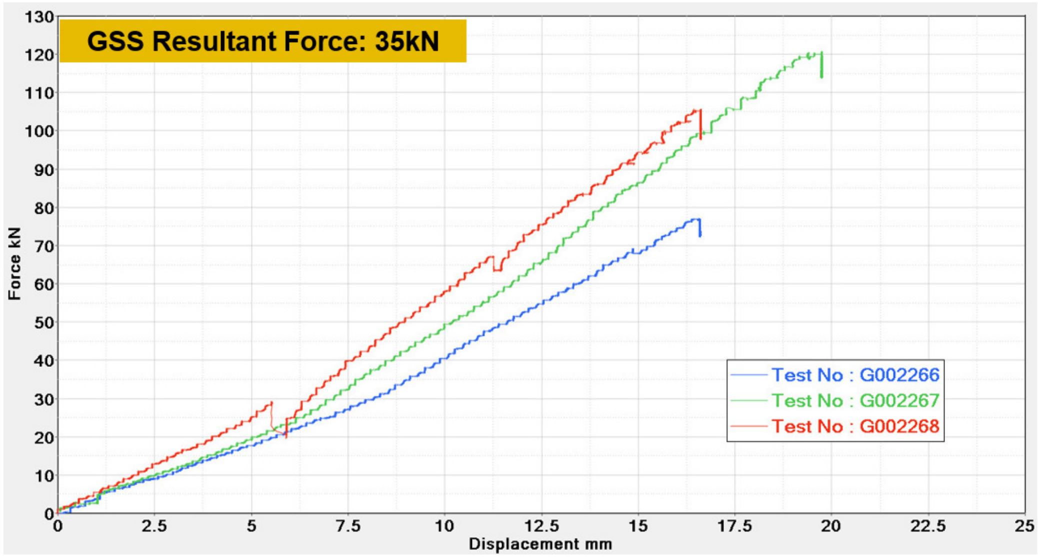

Figure 30: strength test – control arm rear joint force deflection plot

Test and CAE Comparison

The test results were compared with CAE predictions. The ABAQUS simulation predicted the high stress area near the rear body mount that is the same location showing a crack in the tests (Figure 31). The CAE simulation did not catch the crack between the control arm front and rear joints. The peak load predicted by the simulation is higher than the failure load of the test.

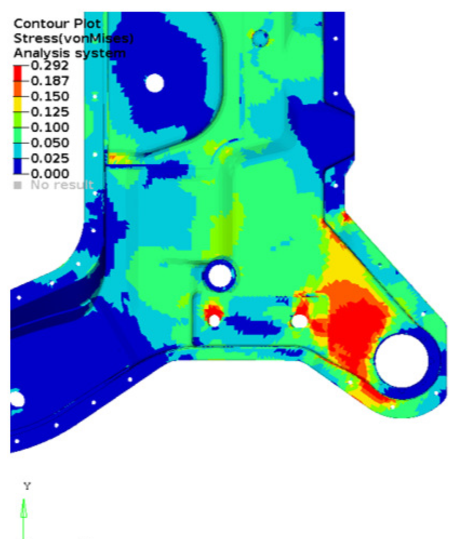

Figure 31: Strength test – control arm rear joint loading CAE failure location

Vehicle Special Event Tests

The proving ground special event test is intended to examine the effect on suspension, steering and affected body components, when subjected to shock loading as experienced when driving over curbs and braking into potholes. This procedure is part of a set of tests which evaluate the effect of severe driving maneuvers to a worldwide passenger cars, CUV's, Mustang, police cars and small sport utility vehicles [9].

The test results stated that the Fusion with a CF subframe passed the Level One test. No damage was observed at the completion of the Level One test. The vehicle did not pass the Level Two test. The subframe was damaged at one of the braking into pothole runs. The post-test photo is shown in Figure 32.

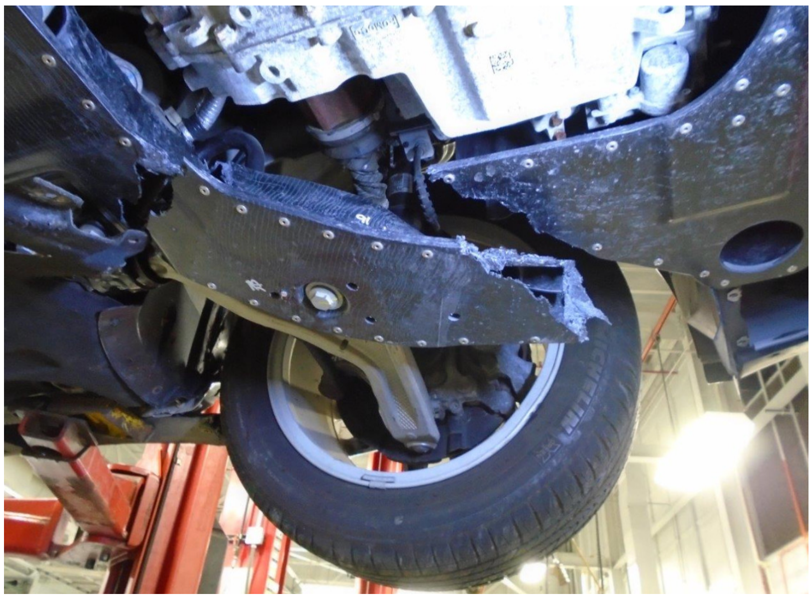

Figure 32: CF subframe – post vehicle special event test

The CAE driven design process did not simulate this dynamic loading event. This damage was not anticipated based on our knowledge with steel subframes and early development of other lightweight research subframes. We learned from this incident that a CAE procedure is necessary to analyze the response of CF chassis components under underbody impact loading.

Summary

A carbon fiber composite research subframe was developed based on Ford Fusion's package space. The prototype subframe was compression molded with EpicBlend SMC, a chopped 50k industrial-grade carbon fiber with a modified vinyl ester resin. EpicBlend CFS-Z with 0º/90º NCF, was co-molded with the chopped EpicBlend SMC material. The design was CAE driven. CAE design iterations demonstrated that the CF subframe met stiffness, durability and bolt load retention performance requirements.

Both component and vehicle tests were conducted to verify the design and build of this industry first CF composite subframe.

Component fatigue tests produced multiple cracks on the subframe. Most of the cracks are small. The cracks stabilized at certain points of the tests. All tests passed the required two lives loading cycles without losing load carrying capacity. CAE simulations did not correlate with test results.

The vehicle high cycle durability test was successful. It produces less than five cracks. The cracks propagated and stabilized as the test progressed. The vehicle maintain all functions through the test. No fastener torque loss was observed after the test. CAE simulations did not correlate with test results.

Component strength tests were completed with satisfied results. The peak loads exceeded the GSS loads at all tested hard points. CAE predictions captured most failure locations. CAE predicted peak loads were higher than test loads.

The Vehicle special event Level one test was completed. The vehicle did not pass the Level Two tests.

One of the challenges of the CF subframe design was the material input for CAE simulations. More efforts are needed to create material models for CF composite analyses.

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