VALIDATION OF MATERIAL MODELS: JOINING AND ASSEMBLY SYSTEM FOR THERMOSET AND THERMOPLASTIC COMPOSITE MATERIALS

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Abstract

The objective of the Validation of Material Models (VMM) project is to validate the predictive capability of physics-based computational crash models for carbon fiber composites to enable broader use of the models in the design of automotive carbon fiber primary structural crash and energy management systems. This paper focuses on the development of the joining and assembly technology for producing the front-bumper and crush-can system. Components were joined using both adhesive and mechanical fastening, as appropriate based on the overall system design. The methods used for joining are described in detail, including the process used to select an appropriate adhesive and the process to assemble and join the components. Crash tests of the assembled crush cans were then used to compare the effect of the joining methods on the crush cans performance.

Background and Introduction

The objective of this four-year, $7 million U.S. DOE and USAMP Cooperative Agreement project is to validate and assess the ability of physics-based material models to predict crash performance of automotive primary load-carrying carbon fiber composite structures.[1] Models evaluated include Automotive Composites Consortium/USAMP-developed models from the University of Michigan (UM) and Northwestern University (NWU), as well as four major commercial crash simulation codes: LS-DYNA, RADIOSS, PAM-CRASH, and Abaqus. Predictions are being compared to experimental results from quasi-static testing and dynamic crash testing of a lightweight carbon fiber composite front-bumper and crush-can (FBCC) system which was selected for demonstration via design, analysis, fabrication, and crash testing. The successful validation of these crash models will facilitate improved design of lightweight carbon fiber composites in automotive structures for mass reductions. This paper focuses on the joining of the FBCC components, a necessary step in the manufacturing process. To that end, Joining approach and design, adhesive selection, joining procedure, and an assessment of the joining technology are described.

Both, thermoset and thermoplastic composite systems were evaluated as part of the VMM project. Full FBCCs were evaluated for the thermoset composites. These systems were composed of continuous-woven-carbon-fiber/epoxy prepreg as well as carbon fiber sheet molding compound. Further details of the thermoset FBCC can be found in the associated article "Validation of Material Models: Thermoset Composite Materials and Processing for a Composite Bumper-Beam System" in these conference proceedings. [2] Only the crush cans were evaluated for the thermoplastic composites. These systems were composed of continuous-woven-carbon-fiber/nylon prepreg sheets and chopped carbon-fiber/nylon flakes. Further details of the thermoplastic FBCC can be found in the associated article "Validation of Material Models: Development of Carbon Fiber Reinforced Thermoplastic Composites for a Front-Bumper/Crush-Can System" in these conference proceedings. [3] In both cases, all components were molded using compression molding. Adhesives for each system were selected separately with the intent of using a similar bonding procedure for each system. At the time of this paper submission, many of the results for the thermoplastic system were still pending and therefore, the primary focus of this report is on the thermoset composites.

Design of the FBCC

A schematic of the FBCC system is shown in Figure 1. The design requires the system be molded as five separate components: the bumper beam, two crush can half "A", and two crush can half "B". These components are compression molded, and then trimmed to size. Following trimming, the components must be joined. There are two types of interfaces in the FBCC. The first is the interface between the two crush can halves (Figure 2). This interface is joined using an adhesive as well as 4 rivets spaced along the interface. The interface also features a series of bumps and dimples that act as spacers for maintaining bond-line thickness as well as locating the two halves accurately relative to each other. The second interface is between the assembled crush can and the bumper beam (Figure 3). The bumper beam features a novel design comprised of receiver cups with standoffs. This interface uses only adhesive bonding.

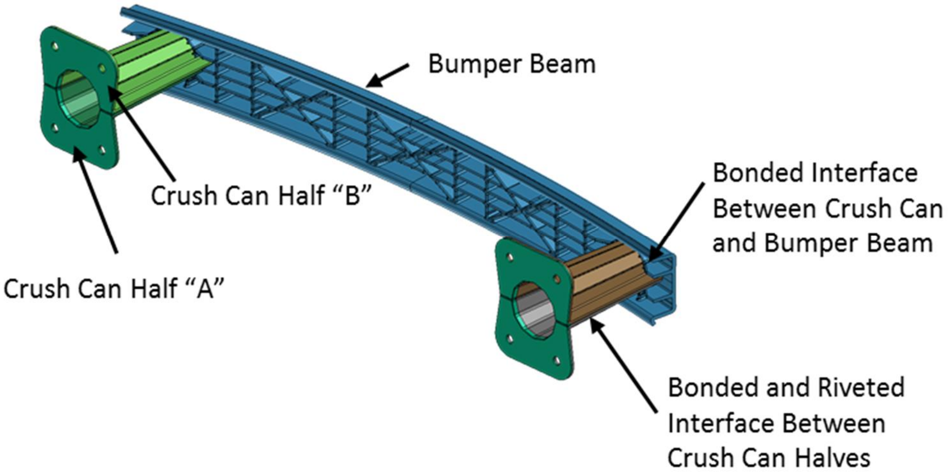


Figure 1: Schematic of the FBCC system, showing the five separate molded components and the bonded interfaces.

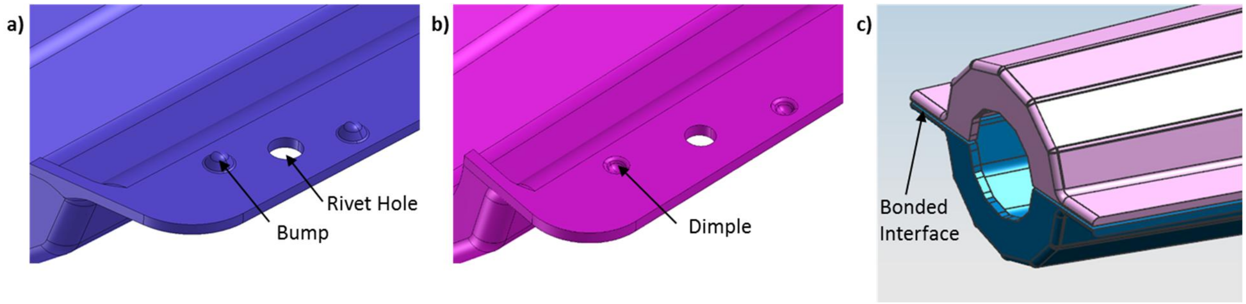


Figure 2: Details of the bonded interface for the crush can halves. a) Zoom-in of half "A" showing the bumps and rivet holes. b) Zoom-in of half "B" showing the receiving dimples and matching rivet holes. c) Schematic of the assembled crush can showing the location of the interface. Rivets are not shown.

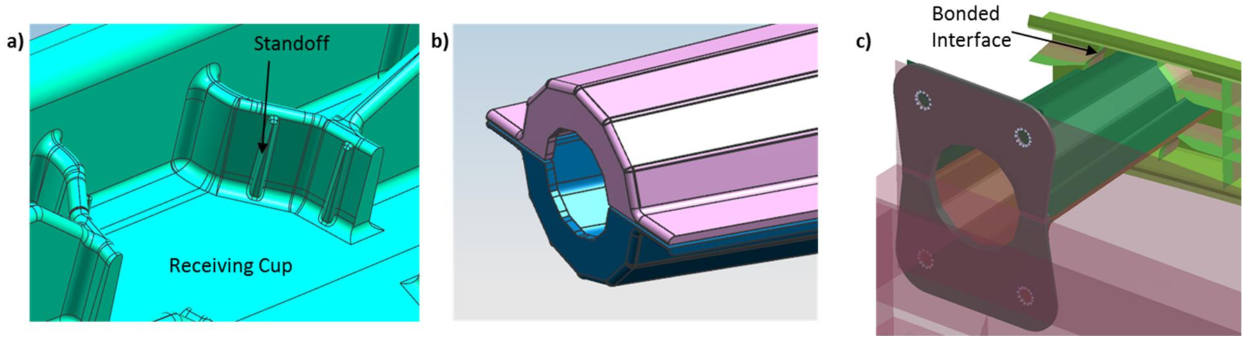


Figure 3: Details of the bonded interface for the bumper beam and crush can. a) Zoom-in of the receiving cup in the bumper beam and the standoffs. b) Zoom-in of the assembled crush can. c) Schematic of the assembled bumper beam and crush can, indicating the location of the bonded interface. No rivets are used at this interface.

Adhesive Selection

Adhesive Selection for Thermoset Composites

Three adhesives were evaluated for use in joining the thermoset FBCC system, each with distinct mechanical capabilities:

- DOW BETAFORCE® 2850S, a 2-component polyurethane (PU) adhesive, with lap shear for metal substrates of less than 11 MPa and elongation about 115%
- DOW BETAMATE® 73326/73327, a 2-component epoxy adhesive, with lap shear about 10 MPa and elongation about 13%
- DOW BETASEAL® X2500 Plus, a 2-component polyurethane (PU) adhesive, with lap shear less than 5 MPa and elongation about 150%.

The BETASEAL adhesive had the highest elongation, with relatively low strength, while the BETAMATE adhesive had very high strength and relatively low elongation. The BETAFORCE adhesive was in the middle of these other systems in terms of performance. Three types of mechanical tests were used to evaluate the performance of these adhesives, including lap shear (ASTM D1002), cleavage peel (ASTM 3807), and impact peel (modified) (ISO 11343). Two different substrates were evaluated, both composed of the same woven-carbon-fiber/epoxy prepreg used in the FBCC. The first substrate type used an 8-layer cross-ply layup, while the second substrate types used an 11-layer quasi-isotropic layup (0/90/45/-45/0/90/0/-45/45/90/0).

The results from the testing are shown in Table 1 and Table 2 for the cross-ply and quasi-isotropic layups, respectively. Based on these tests, the BETAFORCE adhesive showed the most promise due to its superior performance in cleavage peel and impact peel. In particular, the impact peel performance was deemed to be the most important because of its similarity to the failure mode expected during crash tests of the FBCC.

Table 1: Results of the adhesive testing on the thermoset system for the cross-ply configuration. (CF=cohesive failure of adhesive; FT=fiber tear (cohesive failure) of substrate; AF=adhesive failure)

	BETAMATE™ 73326M/27M	BETAFORCE™ 2850L	BETASEAL™ X2500 Plus
Chemistry	Epoxy	Polyurethane	Polyurethane
Lap Shear (MPa)	6.74 ± 0.19 100% CF	2.19 ± 1.53 100% CF	2.09 ± 0.10 100% CF
Cleavage Peel Max Load (N) Peel (N·m)	52.0 ± 18.7 0.88 ± 0.12 100% CF	131 ± 13.3 2.70 ± 0.56 100% CF	58.3 ± 12.9 1.05 ± 0.35 100% CF
Impact Peel (N/mm)	3.06 100% CF	30.3 90% CF 10% FT	11.2 35% CF 65% FT

Table 2: Results of the adhesive testing on the thermoset system for the quasi-isotropic configuration. (CF=cohesive failure of adhesive; FT=fiber tear (cohesive failure) of substrate; AF=adhesive failure)

	BETAMATE™ 73326M/27M	BETAFORCE™ 2850L	BETASEAL™ X2500 Plus
Chemistry	Epoxy	Polyurethane	Polyurethane
Lap Shear (MPa)	7.21 ± 1.17 100% CF	5.46 ± 0.27 100% CF	1.38 ± 0.10 20% CF 80% AF
Cleavage Peel Max Load (N) Peel (N·m)	70.3 ± 18.7 1.13 ± 0.29 100% CF	167 ± 36 3.17 ± 0.21 85% CF 15% FT	105 ± 12.3 2.07 ± 0.09 100% CF
Impact Peel (N/mm)	5.05 100% CF	24.8 15% CF 85% FT	19.0 65% CF 35% FT

Adhesive Selection for Thermoplastic Composites

The team is also performing a similar selection process for optimally joining the thermoplastic composites. At the time of submitting this paper, these test results are still pending and are part of the future work planned in the project.

FBCC Joining Procedure

The objective of developing a joining procedure for the FBCC was to provide structurally strong interfaces within a fast cycle time usable for full-scale production. The following joining procedure was used:

1. Machine rivet holes during trimming of the molded parts.
2. Joining the crush can halves according to the procedure detailed in Figure 4. An additional step is required only for the thermoplastic cans where an extra primer is applied.
3. Join the assembled crush cans to the bumper beam using the procedure detail in Figure 5. For this step, a custom bonding fixture was used (Figure 6) to accurately locate the parts being assembled and provide repeatable pressure during adhesive cure.

While this procedure did successfully achieve geometrically-accurate and repeatable joining of the components, it is too slow for full scale production. Future improvements to the procedure would include selection of a faster curing adhesive or use of higher temperature to speed up cure of the adhesive at each stage.

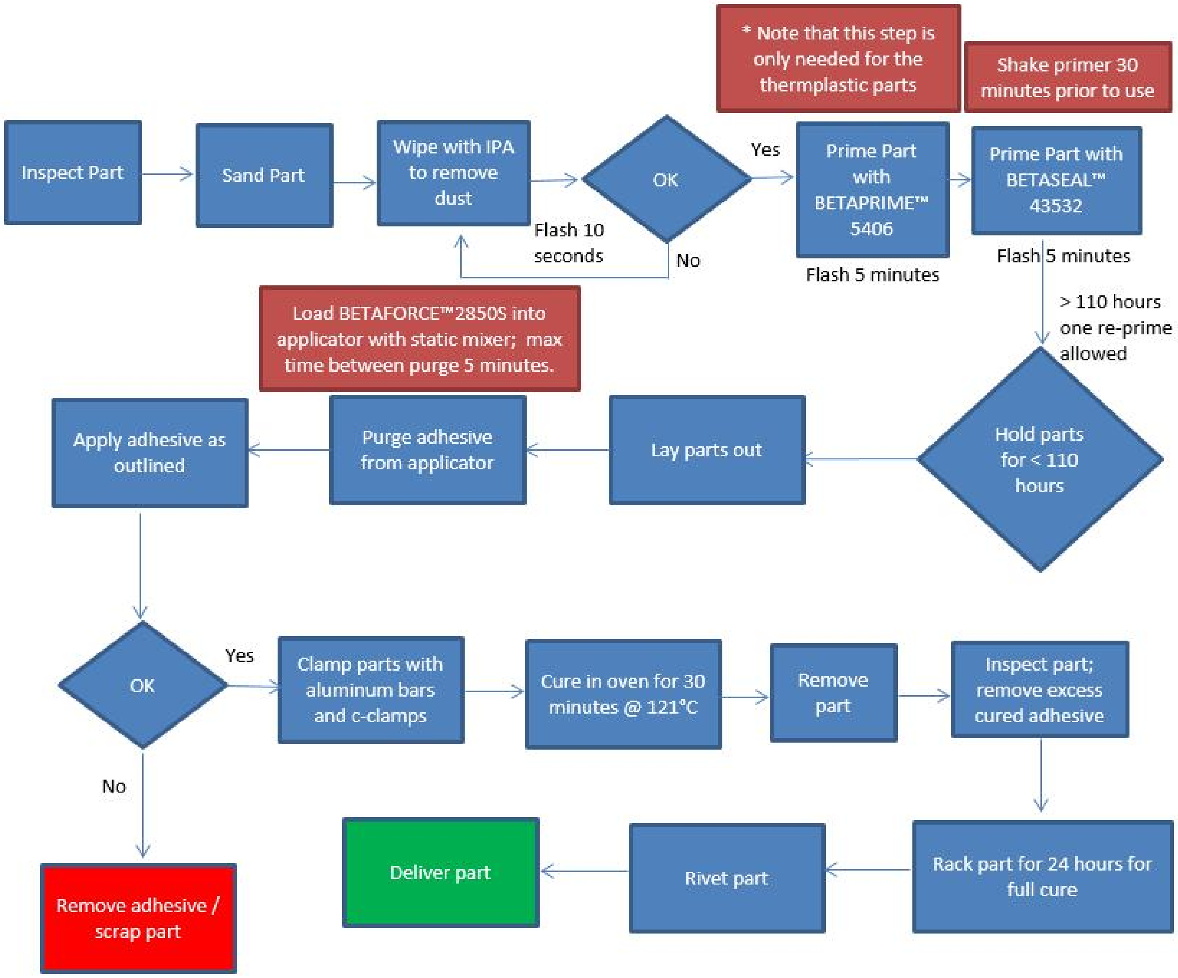


Figure 4: Flow chart of the bonding procedure for joining the crush can halves.

Figure 5: Flow chart of the bonding procedure for joining the crush can and bumper beam.

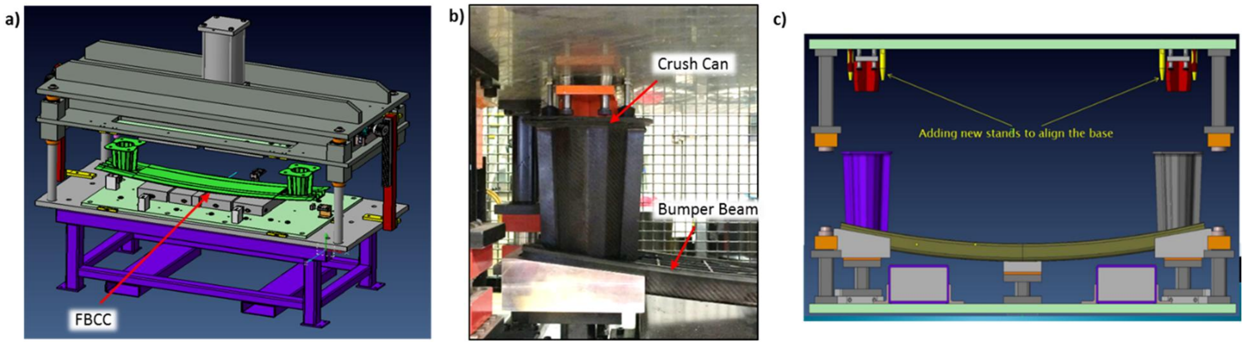


Figure 6: The fixture used to join the assembled crush can and bumper beam. a) Schematic of the press and fixture showing the location of the FBCC. b) A zoomed-in photograph of the actual FBCC components in the press. c) Pins were added to the fixture to ensure the holes for mounting the FBCC to the crash test sled were properly aligned.

Analysis of Crush Can Joining Methods

Several tests were used to assess the selected joining method prior to full-scale FBCC crash testing. The focus of the effort was to assess the joining method used for the crush can halves. The bond between the bumper beam and the crush cans was assumed to be less critical, since most of the load is transferred between the parts by direct contact. This is particularly true in full-frontal impact, which is considered the most important crash mode evaluated in this program.

Drop Tower Testing of Adhesively Bonded Tubes

While tooling for molding of the FBCC components was being manufactured, the team conducted multiple drop tower tests on carbon fiber composite hat-section tubes to evaluate the adhesive under a similar loading scenario. The geometry of these tubes is shown in Figure 7. The tubes are composed of a hat-section channel and a plate, which are adhesively bonded together. Both, cross-ply and quasi-isotropic layups were evaluated with the BETAFORCE adhesive. The tubes were potted into an aluminum block fixture, and then tested in a drop tower, where a flat plate with a mass of 74.5kg was dropped from a height of 0.98m. Figure 8 shows the damage to both the cross-ply and quasi-isotropic layups. The primary damage mode of the tubes was crush of the composite, composed of many small fiber, matrix, and interface fractures. However, large-scale delamination was observed in the samples. In the cross-ply sample, the delamination was primarily within the plate and therefore was not attributed to the adhesive. In contrast, in the quasi-isotropic sample the delamination was at the interface with the adhesive. The difference can be attributed to the difference in delamination resistance between the two layups. In both cases, however, no catastrophic failures occurred during this testing that indicated issues with the adhesive.

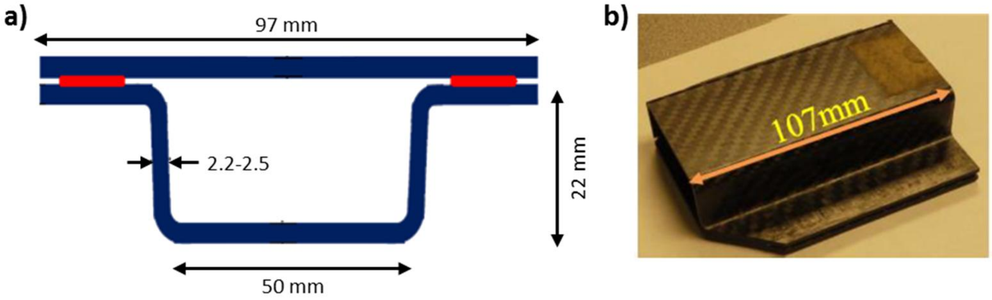
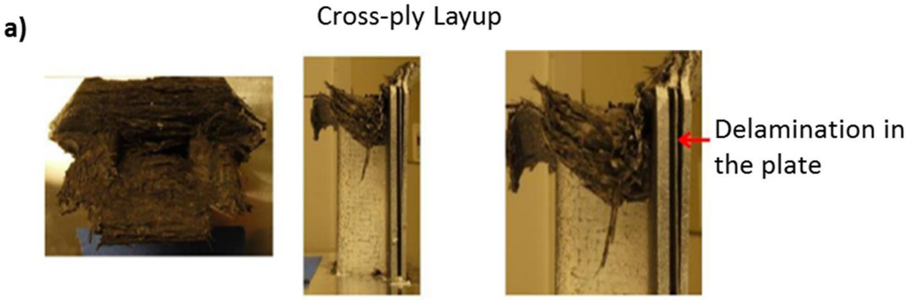


Figure 7: a) Schematic of the geometry of the tube sample. b) Photograph of the sample.



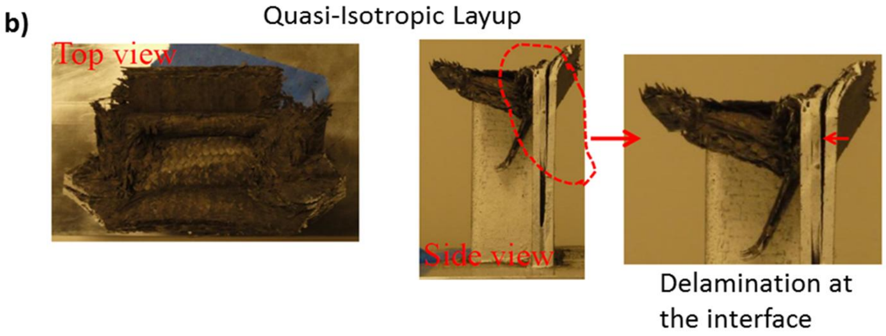


Figure 8: Images of the samples after testing for a) the cross-ply composite layup and b) the quasi-isotropic layup.

Crash Testing of Assembled Crush Cans

The effect of the bonding condition for joining the two halves of the crush can was further examined using crash tests. An image of the setup, including a crush can before and after testing is shown in Figure 9. We examined four conditions:

- Polyurethane (PU) adhesive (BETAFORCE™ 2850L) with no rivets,
- PU adhesive with 4 rivets per side,
- PU adhesive with 5 rivets per side, and
- Epoxy adhesive (BETAMATE™ 73326M/26M) with 4 rivets per side.

For testing, an 1145 kg sled was crashed into the cans at 4.85 m/s. Results of the testing are shown in Figure 10 and Table 3. The failure mode in all cases was axial crush. In most cases the crush initiated from the impacted side of the crush can, though in a few cases the crush initiated at the back side. However, in these cases no difference was seen in overall performance. No large-scale delamination was observed, such as those found in drop tower testing of the bonded tubes. Qualitatively, there are no visible difference between the four conditions in the force-time plot. There was a very slight drop in the total impulse absorbed and average crush load by the crush can with no rivets. However, the max crush load was the same in all cases. There is no discernable difference between the PU and epoxy adhesive. Based on these results, we decided to use 4 rivets per side with PU adhesive. The use of rivets was chosen as a conservative design, particularly for off-axis impacts, which were not evaluated here.

Figure 9: (Left) A crush can mounted on the wall prior to crash testing. (Right) The crush can after the test.

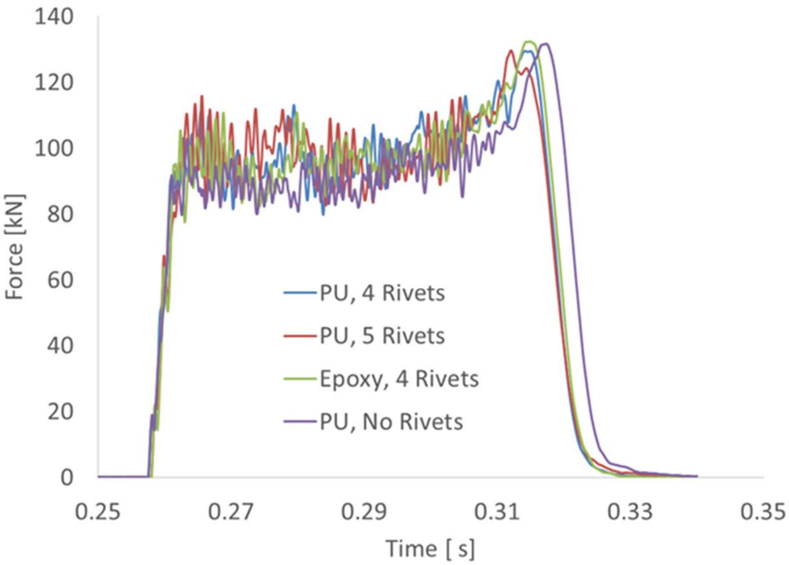


Figure 10: Force vs time plots for each testing configuration.

Table 3: Summary of results from crash testing.

Sample	Max Crush Load [kN]	Average Crush Load [kN]	Impulse Absorbed [kN*s]
PU, No Rivets	131	94.8	6.08
PU, 4 Rivets	129	100	6.1
Epoxy, 4 Rivets	132	99.4	6.08
PU, 5 Rivets	129	101	6.1

Summary and Conclusions

In this portion of the VMM project, a method for joining the components of the FBCC system was developed and validated. Key activities included selection of an appropriate adhesive, development of the joining procedure, and evaluation of the joined parts. Overall, the team was successful in the development of this procedure, and early results are promising as to the performance of the joined interfaces during crash testing of the parts. Importantly, the adhesive operated effectively during crash testing of individual crush cans. Currently, analysis for full-scale thermoset FBCC crash testing is underway. Early observations indicate that the joining procedure is effective but could be optimized for mass production by automation and the use of a faster cure cycle.

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