VALIDATION OF MATERIAL MODELS FOR CRASH TESTING OF CARBON FIBER COMPOSITES: PHYSICAL CRASH TESTING

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Abstract

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 primary load-carrying carbon fiber composite automotive structures. 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 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 significant mass savings.

This paper details the methodology and findings of the dynamic crash testing of both the steel and the carbon fiber composite FBCCs. Steel FBCCs were used to establish test protocols for six load cases. In addition, results obtained from steel FBCC tests were used to establish the crash performance targets required for designing a carbon fiber composite FBCC. Load cases used for the steel FBCCs were used to test the carbon fiber composite FBCCs so that the crash performance of these systems can be compared. Test results thus obtained will be used to compare with the CAE predictions to establish current CAE capability in predicting crash responses of carbon fiber composite structures.

Background

The capability of finite element models in predicting high-speed, crash events, specifically in the automotive sector is of great value. Simulations reduce resources from working hours, parts and vehicles to lab equipment. However, in order to improve and validate the accuracy and quality of predictive models, physical testing is still required.

The Validation of Material Models (VMM) project objective is to validate the predictive capability of computational crash models for carbon fiber composites. Specifically, a commercially available automotive front bumper crush can was chosen for evaluation. Six crash mode load cases were chosen: full frontal at 15.6 m/s (35mph), 40% frontal offset at 13.4 m/s (30 mph), frontal 10” diameter pole at 8.94 m/s (20 mph), 30° frontal angular at 8.94 m/s (20 mph). In addition, two low speed tests were chosen based on low speed damageability of frontal center and quarter at 4.47 m/s (10 mph). These test conditions were chosen primarily for the ability in utilizing the energy absorption capabilities of the FBCC when loaded in frontal, compressive modes while the pole and angular tests were conducted to evaluate the effect of off axis loads of shear and tension.

Tests were conducted only using the FBCC. Some of the modes were developed from existing regulatory and public domain test protocols. The full frontal impact is based on the New Car Assessment Program (NCAP) full frontal barrier protocol[2]. The 40% frontal offset is based on the Insurance Institute for Highway Safety's (IIHS) Moderate Overlap Frontal Crashworthiness Evaluation[3]. The lower speed midpoint impact is based on the Research Council for Automobile Repairs Low-Speed Structural Crash Test Protocol[4]. The pole and angular tests were based off anachronistic proposed test protocols not adopted in the regulatory or public domains.

The steel FBCC is comprised of two conical crush cans welded to a sweeping bumper as shown in Figure 1. The crush cans are high-strength low-alloy steel (HSLA 350) and the bumper is martensitic 1300 steel.

Figure 1: Steel FBCC

The composite carbon fiber composite crush cans were composed of 12 layers, woven in a quasi-isotropic configuration. The bumper was composed of 24 layers, also woven in a quasi-isotropic configuration[5]. The crush cans and bumper were joined using polyurethane-based adhesive[6]. The resin used is 42% weight, 3K woven carbon fiber and 2x2 twill, specifically: MTM®54FRB-42%-3KHS-2X2T-199-1270. The design slightly differed in appearance and shape compared to the steel system[7]. Figure 2 illustrates these structural differences using a computer aided draft (CAD). Special attention was given to maintain the same footprint of the crush can to assure similar mounting strategies for testing.

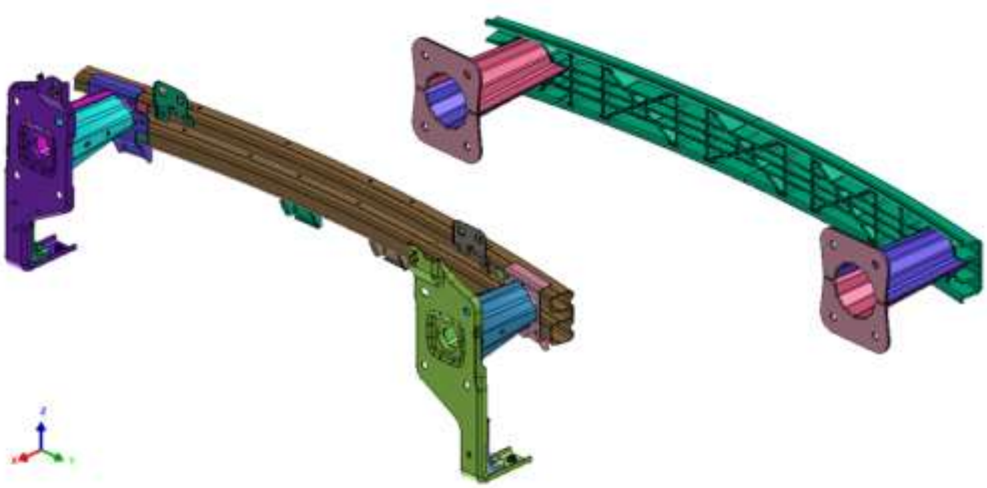


Figure 2: CAD models of steel FBCC (L) and carbon fiber composite FBCC (R).

Methods

In order to carry out testing for this program, a proper vendor needed to be identified. Wayne State University (WSU), Detroit, MI was chosen. WSU, specifically, the department of Bioengineering, has a high speed deceleration sled that has a proven track record in automotive and military high speed impacts. A deceleration sled is hydraulically controlled and comprises of a primary and secondary sled. The primary sled is fixed to the ground using in ground rails and is connected to the hydraulics. The secondary sled is mounted onto the primary sled with guide rails. Once the hydraulic is pressurized to a given setting, it is released prescribing a force to the primary sled. At this point, the primary and secondary sleds are coupled to one another, traveling along a prescribed axis from the in ground rails. As they approach a load wall, here made of at least concrete and steel, the primary sled is stopped by 'snubbers' or large breaking springs. At this point, the secondary sled is in free flight to a prescribed initial velocity. Here, the target velocities set forth by the program and describe previously. Depending on the load case, the FBCC is mounted on the secondary sled and when not mounted on the sled, it's mounted on the load wall. Figure 3 provides an example picture of the primary and secondary sled while Figure 4 provides an example picture of the snubbers.

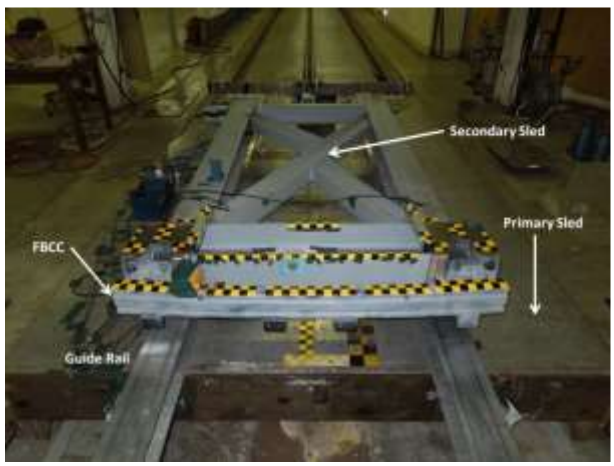


Figure 3: Front view of the primary and secondary sled. Notice the FBCC is fixed to the secondary sled and the guide rail. The small blue box to the left is the data acquisition system.

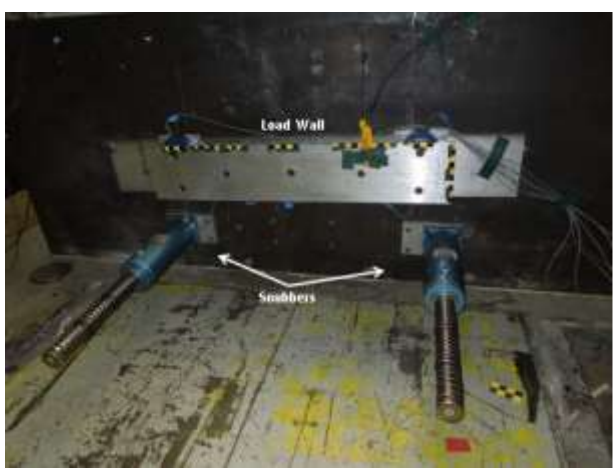


Figure 4: Front view of the load wall and snubbers. In this particular case the load wall is instrumented with load cells.

The primary sled was instrumented with three arrays of tri-axial accelerometers capable of measuring accelerations in the x, y and z directions with x being the principal direction of force and the prescribed travel of the sled along the in ground guide rails. These accelerometers have a full scale capacity of 200 Gs and were sampled at 20 kHz. Three arrays were used for redundancy in case one or two accelerometers were to break or provide questionable data. The acceleration was used to calculate the force generated by multiplying the mass of the sled or mass of sled plus the mass of the FBCC depending on configuration.

A data acquisition system (TDAS) was mounted on the primary sled for the accelerometer arrays, while a second TDAS system was mounted on the floor near the load wall, for those test conditions when load cells were used.

As previously mentioned, six load cases were studied. Full frontal, frontal offset, pole, angular, low speed midpoint and low speed quarter. A minimum of five tests per load case were targeted. Figure 5 presents a schematic of the overhead and frontal profiles of the full frontal and frontal offset tests. In the full frontal, load cells were placed on the load wall as another form of redundancy. Load cells had a full capacity 22680 kilograms and sampled at 20 kHz. For the full frontal, the FBCC was mounted on the secondary sled while the frontal offset, the FBCC was mounted on the load wall and orthogonal about the track line. This was done to protect and maintain structural integrity of the sled and tracks in case off axis loading, specifically shear occurred.

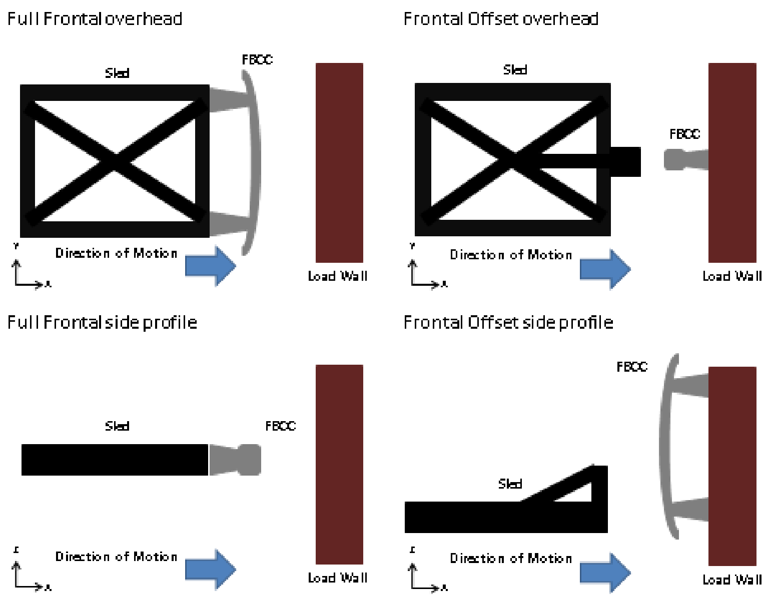


Figure 5: Full frontal and frontal offset overhead and side test configurations.

Figure 6 provides schematics for the pole and angular test conditions. In the pole test, load cells were used on the load wall. No load cells were used for the angular for fear of considerable shear loads. Note that for the angular test, because of shear loading, the orientation of the FBCC on the load wall was similar to that of the frontal offset.

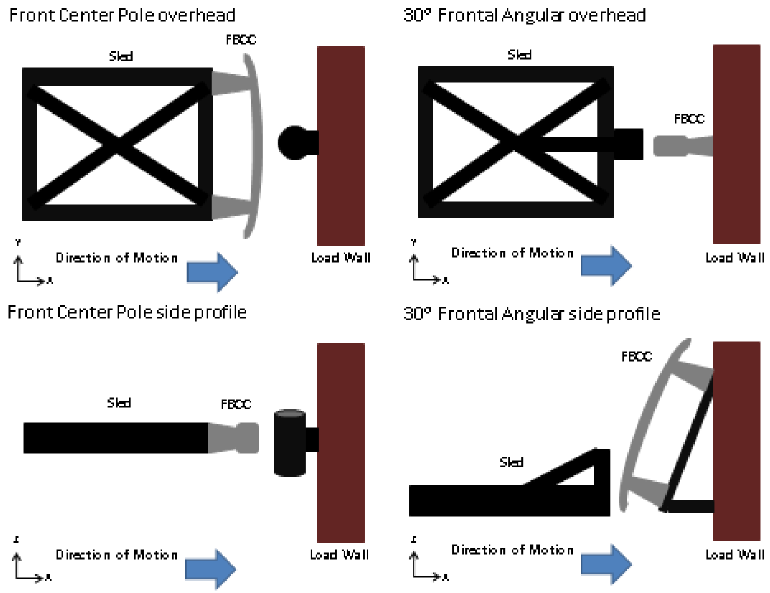


Figure 6: Frontal pole and angular overhead and side test configurations

In Figure 7, the schematics for the low speed midpoint and quarter impacts are depicted. In both cases, load cells were used on the load wall. Once more, due to the shear component, the quarter impact was mounted vertically.

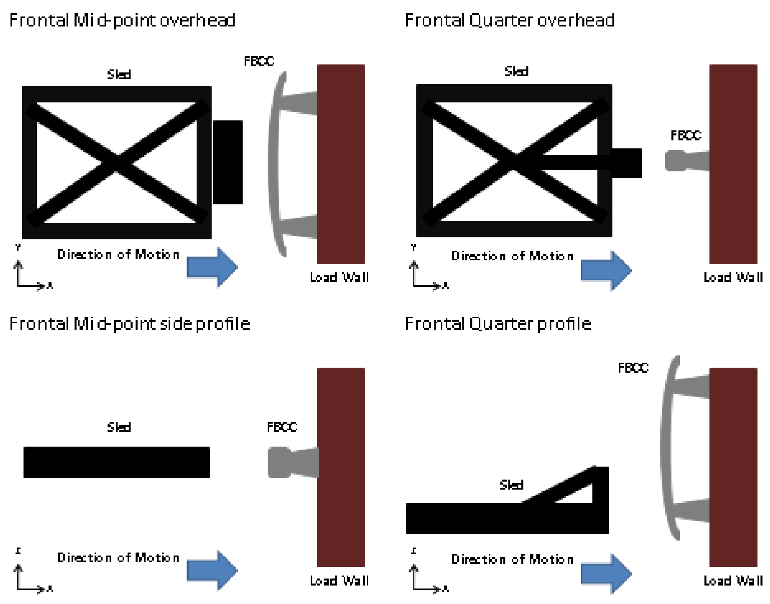


Figure7: Midpoint and quarter low speed impacts overhead and side test configurations

A contact switch was placed on the target striking surface. For instance, in the case of the full frontal, it was placed on the load wall where the FBCC would contact it. This started TDAS as well as high speed cameras. For all load cases, high speed cameras were positioned overhead and to the left and right of the sled contact region and sampled at minimum 1 kHz. Cameras were used to measure displacement of the sled as a form of redundancy in case integration of the accelerometers was unavailable.

All post-processing of data obtained in all modes was subject to the Society of Automotive Engineers (SAE) J211: Instrumentation for Impact Tests[8]. The steel testing was subject to previous publications if further edification is needed[9-12]. Carbon fiber composite testing followed the same protocol.

Results

The redundant measures matched well to one another. In the first example below, the force comparison of the sled acceleration multiplied by the sled mass is compared to the load cells in the time domain (Figure 8). In the second example, the high speed video sled displacement as a function of time is compared to the double integration of the sled accelerometers (Figure 9). The provided examples are from a full frontal steel test.

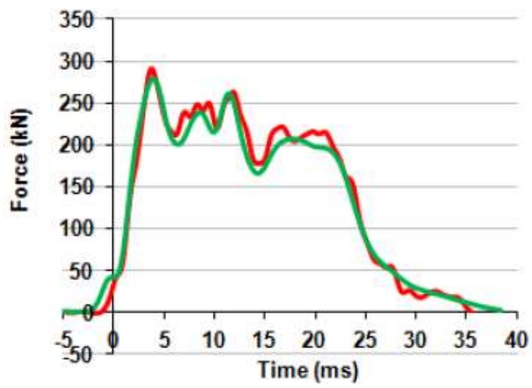


Figure 8: Force comparison of redundant measures of the load cell from the load wall (green) and the acceleration derived force (red).

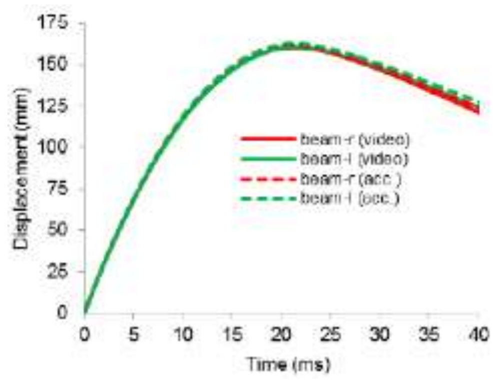


Figure 9: Sled displacement comparison using high speed video (solid line) and the integrated acceleration (dotted line).

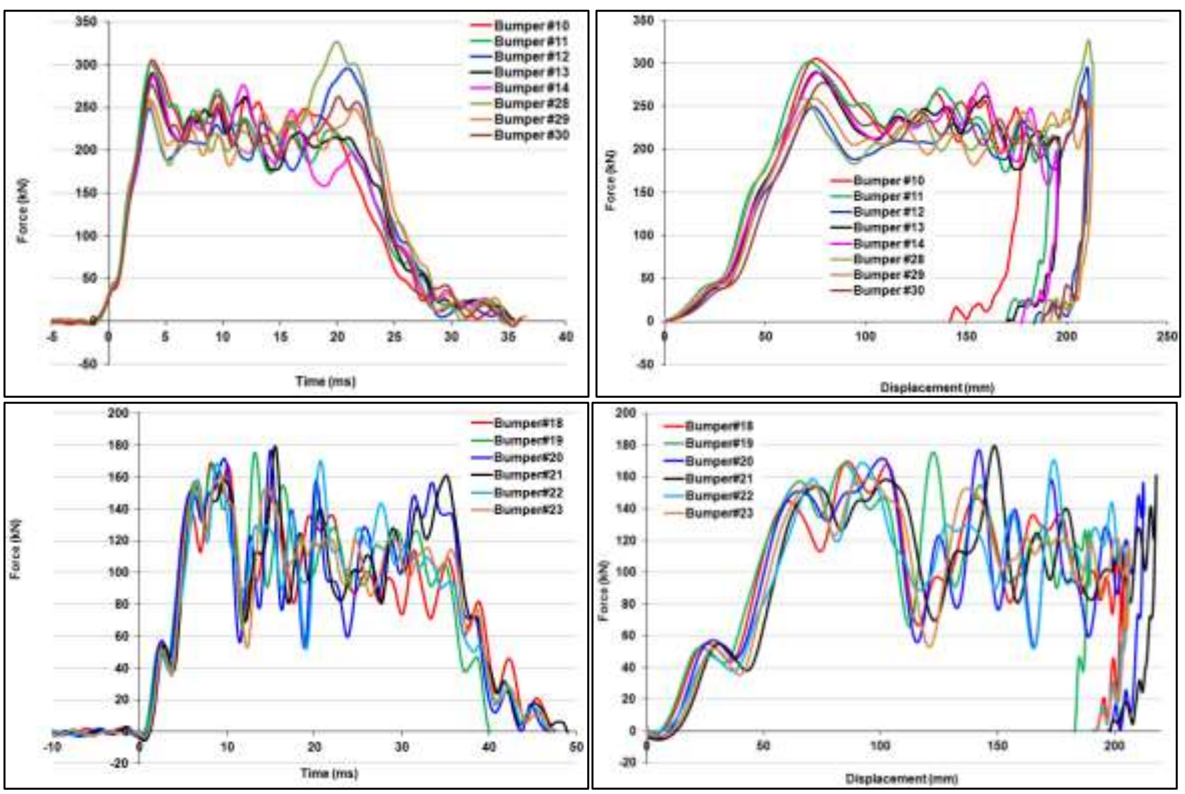
Steel FBCC Results

Table 1 provides the mass, final speeds and energy calculated with standard deviations of each load case. Mass of the sled changed between a horizontal setup (full frontal, pole, low speed midpoint) to a vertical setup (frontal offset, angular, low speed quarter) due to the nature of the test configuration (see Figures 5, 6 and 7). It's important to note that the velocities for the frontal offset and pole were less than the suggested values of 13.4 and 8.94 m/s, respectively. Another aspect to look at in Table 1 is the high repeatability in test velocity as well as energy calculated. The highest coefficient of variation in impact velocity was the low speed midpoint at 0.031.

Table1: Summary of steel FBCC testing for all load cases

Crash Mode	Mass (kg)	Impact Velocity (m/s) (S.D.)	Energy (KJ) (S.D)
Full Frontal	302.87	15.63 (0.15)	35.92 (1.75)
Frontal Offset	321.34	11.87 (0.17)	18.93 (0.67)
Frontal Pole	306.00	6.42 (0.04)	6.00 (0.14)
Frontal Angular	321.34	9.07 (0.08)	12.72 (0.22)
Low Speed Midpoint	302.30	4.48 (0.14)	12.76 (0.26)
Low Speed Quarter	326.40	4.23 (0.12)	2.14 (0.16)

Force-time and force-deflection curves were generated for all tests within each load case and are overlayed in Figure 10 below (Figure information on next page). Both the force-time and force-displacement plots for each load case showed excellent repeatability.



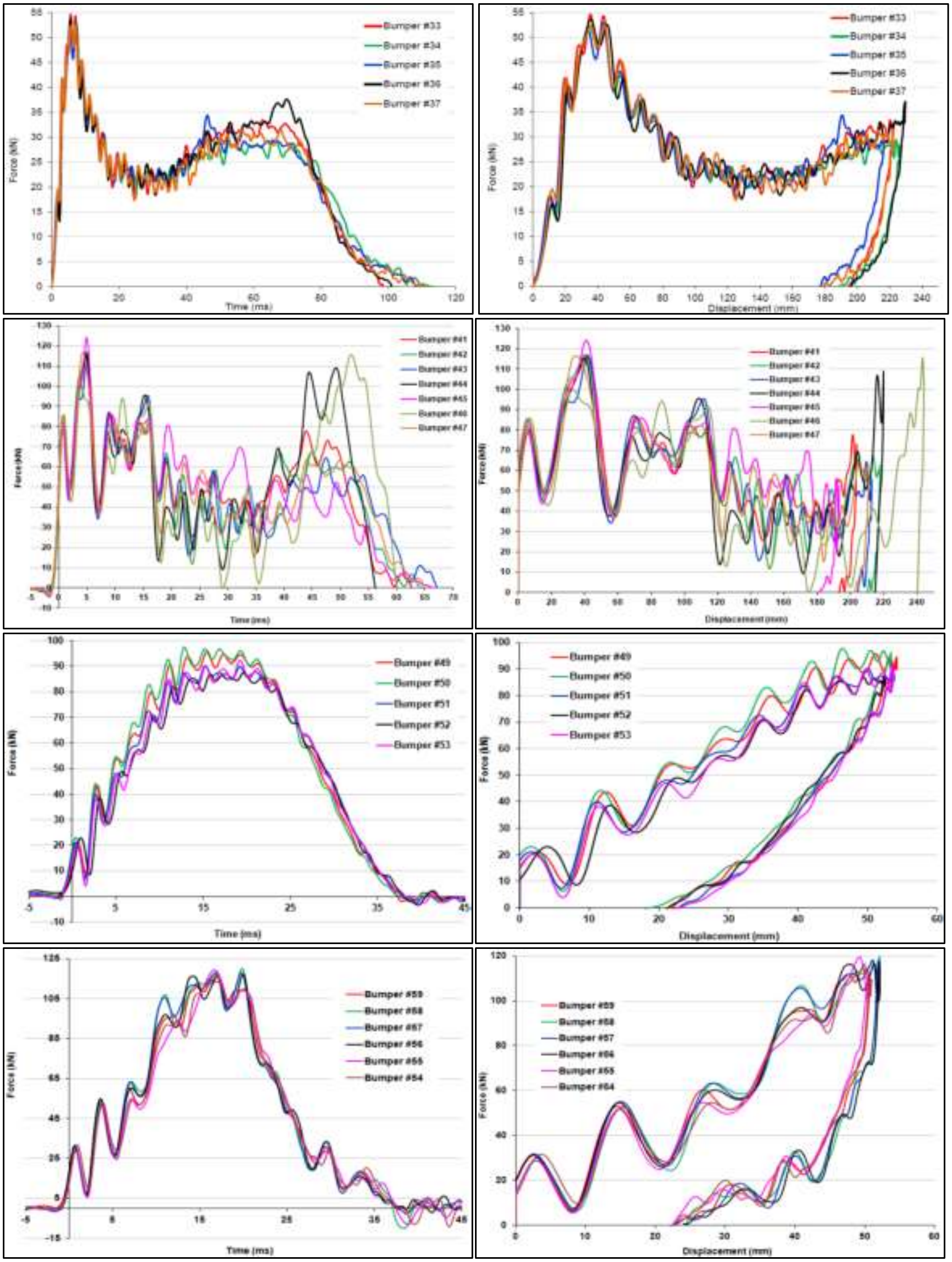


Figure 10: Force-time (L) and Force-deflection (R) overlays for all steel crash modes. In this figure, rows are organized from top to bottom as full frontal, frontal offset, pole, angular, low speed midpoint and low speed quarter.

Carbon Fiber Composite FBCC Results

Table 2 provides the mass, impact velocity and energy calculated with standard deviations of each load case. Similar to that of the steel testing, the mass of the sled changed depending on orientation (horizontal/vertical) and whether the FBCC was mounted on the sled or the load wall (Figures 5, 6 and 7). Modifications were made to the sled for repair following steel testing, which accounts for the mass variation between steel and carbon fiber composite tests under the same load case. Again the same set up was followed from the steel testing. Impact velocities were lower than steel for frontal offset, pole and angular. Only one angular test was included in the results and will be further discussed in the discussion section of this paper. The carbon fiber composite FBCC showed good repeatability but higher coefficient of variation with the highest coefficient of variation in impact velocity being the frontal offset at 0.216.

Table 2: Summary of carbon fiber composite FBCC testing for all load cases

Crash Mode	Mass (kg)	Impact Velocity (m/s) (S.D.)	Energy (KJ) (S.D)
Full Frontal	300.00	15.30 (0.24)	33.17 (1.54)
Frontal Offset	323.00	9.16 (1.98)	13.10 (4.50)
Frontal Pole	306.00	2.54 (0.16)	1.06 (0.17)
Frontal Angular	323.00	5.19	4.11
Low Speed Midpoint	302.30	4.56 (0.02)	3.15 (0.04)
Low Speed Quarter	326.40	4.21 (0.26)	2.42 (0.23)

Force-time and force-deflection curves were generated for all tests within each load case and are overlayed in Figure 11. Both the force-time and force-displacement plots for each load case showed good repeatability.

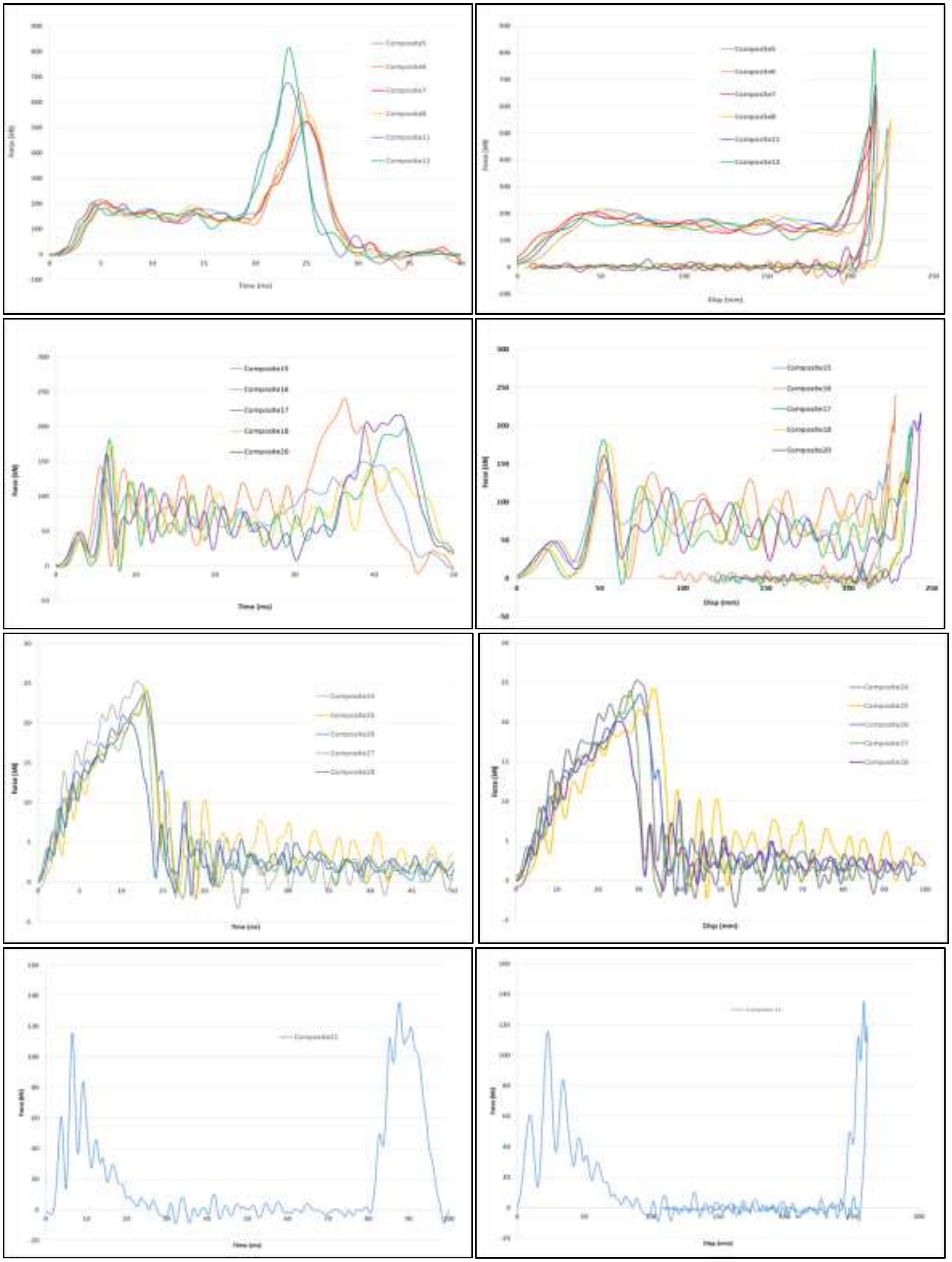


Figure 11: Force-time (L) and force-deflection (R) for all carbon fiber composite crash modes. In this figure the first four rows represent, from top to bottom, the full frontal, frontal offset, pole and angular.

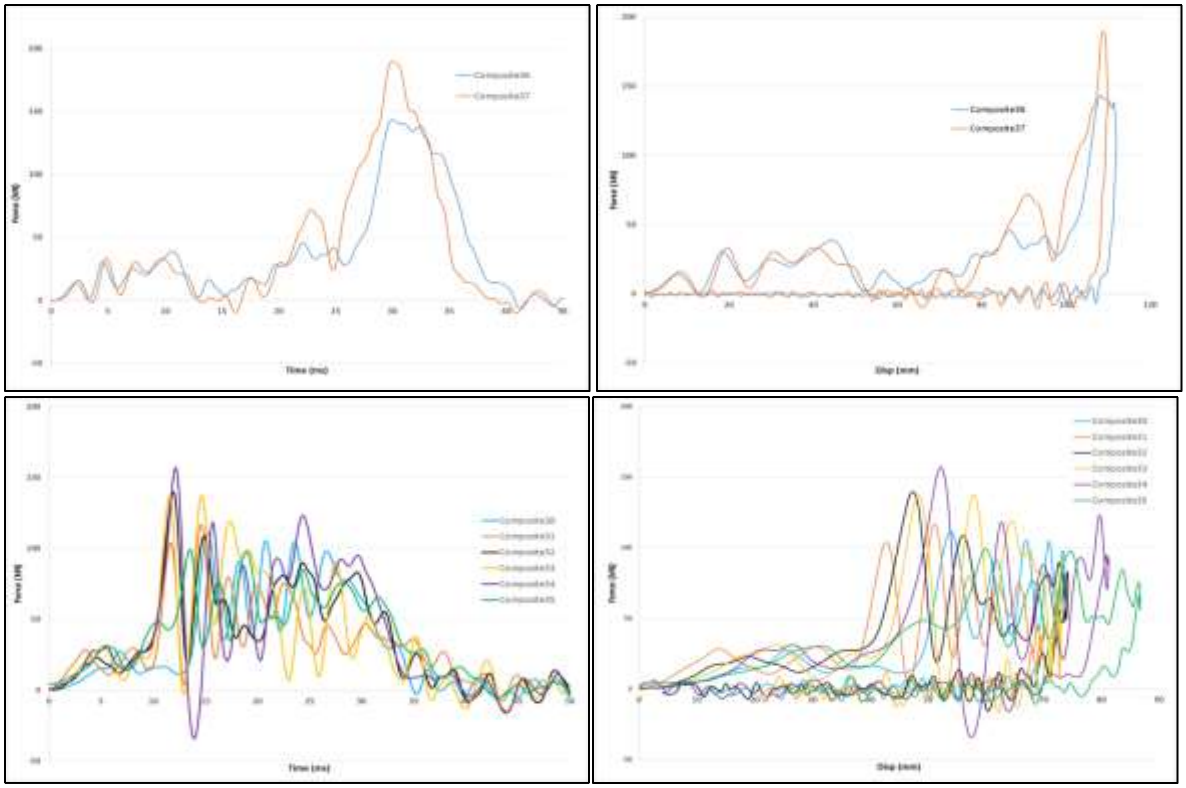


Figure 11 continued: Force-time (L) and force-deflection (R) for remaining carbon fiber composite crash modes of low speed midpoint and low speed quarter, respectively by row.

Discussion

The steel test series was used to establish a test procedure that was robust and repeatable. It was to establish a baseline of boundary conditions and objective measurements to provide to the design team with reliable data. Due to the consistent force-time and force-deflection histories in combination with the low coefficient of variation in impact velocities, this was obtained.

The full frontal carbon fiber composite FBCC test had an average load of approximately 200 kN followed by a large spike late in the time-history. Upon reviewing film analysis, the entire crush can underwent progressive crush until the bumper loaded the front portion of the sled, which caused the late spike in the force-time history. Additionally, the bumper cracked at the midpoint, but appeared to not have an effect on the load bearing capacity of the system.

The frontal offset had an average force of approximately 100 kN followed by a late spike in force of 200 kN. Film analysis showed that the oscillations found in the force-time history were due to lateral shake of the FBCC away from the contact location of the 40% overlap. That crush can underwent progressive crush until the beam bottomed out to the load wall, which accounts for the late force peak. Additionally, the non-struck crush can detached from the back of the bumper, a possible adhesive bond separation.

The pole test peak load was approximately 25 kN around 15 ms and drops off quickly. Reviewing film showed that early in the event, the bumper cracks in half at the midpoint. Later in the event, the bumper shears off of both front portions of the crush cans. The failure between the crush can and bumper was likely due to insufficient bond strength of adhesive.

Only one angular test is reported here. During practice runs, the original 8.94 m/s target led to complete separation of both crush cans from the bumper and from the load. Reducing the speed approximately to 5 m/s, provided a small window of interaction yielding a peak of 100 kN in the first 15 ms until the bumper separated from the load wall and crush cans. The crush cans sheared from the load wall while the crush can look as if the bond failed to the bumper. This test and the results will likely be very difficult to be used in any validation of crash codes as there's roughly 10 to 15 ms of contact data followed by complete separation.

The front low speed midpoint test resulted in small constant initial load for a long duration with a late peak of 15 kN after 30 ms. This is counterintuitive and upon film analysis, the bumper cracked at the midpoint and the inboard sides of each crush can and the cans separated from the bumper. This was certainly not the design intent as the FBCC takes no load at the beginning of the event. Like the angular test, this will be very difficult to validate a commercial crash code.

The low speed quarter impact straightened the bumper but there was no progressive crush in the impact crush can. In fact, the crush occurred where the crush can meets the mounting plate. The oscillations in the force-time and force-displacement curves are due to the separation of the non-struck crush can and the separation of it and the bumper. This tendency of the crush can to crush in the back in this test was prevalent. If a sample was available and tested where progressive crush was present, the oscillation would be minimized and the force ramp up would look similar to the full frontal or frontal offset tests.

In full frontal, frontal offset and the low speed quarter practice tests, crushing of the crush can rearward of the bumper took place, presenting possible instabilities of the crush can, joining, material or the design.

Conclusions

A steel FBCC was used to create a test protocol for six load conditions producing redundant, reliable, reproducible and consistent data. This data was used to aid in design and manufacturing of a carbon fiber composite FBCC. When tested under the same loading conditions, the carbon fiber composite FBCC performed similarly when compared to steel in the full frontal and frontal offset tests. Breaking of the bumper and joint failure of the crush can to the bumper in the pole test yielded unexpected results. The data is reliable up until the bumper cracks. Unfortunately, that stretch is likely the only time range that would be used to validate a commercial crash code. The angular modes resulted in very little interaction between the sled and FBCC, with complete separation of the crush cans from both the load wall and bumper. This test will likely not be of value in the validation portion of this project. The low speed midpoint bumper cracked at the crush cans and at the midpoint and resulted in unwanted energy absorption and will likely not be of value in the validation portion of this project. The low speed quarter showed crush of the crush can rear of the bumper but did hold load and will be of value in validating the commercial codes. This portion of the project was pure testing. At this time, the correlation between these physical tests and commercial crash codes is underway.

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