Crashworthiness of Composites Structures

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\textbf{ABSTRACT}

Predictable computational tools, based on experimental and analytical methods, are developed to support the design, evaluation, and optimization of the dynamic structural response of composite airframes. Crashworthiness structural requirements such as the evaluation of survivable volume, the retention of items of mass, deceleration loads experienced by occupants, and emergency egress paths are identified by developing detailed finite element models of metallic narrow-body transport aircraft to study the crashworthiness behavior of aircraft structures during survivable impacts. At the coupon level, high speed test methods are being investigated experimentally and numerically not only for material property generation but also for material model development; a Round-Robin High Strain Rate Testing Material dynamic characterization of the in-plane tensile material properties of CMH-17 material Toray - T700G/2510 PW carbon/epoxy is conducted over a wide range of strain rates ranging between 0.01 to 250 s\textsuperscript{-1} in collaboration with four research partners. At the sub-assembly level, a finite element model of 10-ft. fuselage section of a metallic narrow-body transport is developed and used to study the energy absorbing capabilities of individual structural members. Fasteners are identified as one of the major energy absorption components. The ability of fastener modeling techniques to capture joint behavior for dynamic loading applications is investigated. Tensile testing of single load transfer specimens is conducted and results are used to verify different fastener finite element models. Tests are conducted at speeds ranging from quasi-static up to 100 in/s. At the full scale level, the 10-ft. section is validated with experimental data of a drop test conducted at the FAA technical center.
INTRODUCTION

The introduction of composite airframes warrants an assessment to evaluate that their crashworthiness dynamic structural response provides an equivalent or improved level of safety compared to conventional metallic structures. This assessment includes the evaluation of the survivable volume, retention of items of mass, deceleration loads experienced by the occupants, and occupant emergency egress paths. In order to design, evaluate, and optimize the crashworthiness behavior of composite structures it is necessary to develop experimental and numerical methods and predictable computational tools.

The advances in computational tools combined with coupon/component level testing allows for a cost-effective approach to study in depth the crashworthiness behavior of aerospace structures. A building block approach is used to assess the crashworthiness dynamic structural response of composite airframes. Current research programs are conducted at the first two levels of the building block:

- At Coupon Level: High speed test methods are being investigated experimentally and numerically not only for material property generation but also for material model development (*Dynamic Characterization of Round Robin Material*).

- At Element Level: Numerical tools used to model structural joints are being evaluated (*Modeling Fastener Joints for Crashworthiness Simulations*).

PROGRAM I – DYNAMIC CHARACTERIZATION OF ROUND ROBIN MATERIAL

Open literature reports variations in the material response of most materials when subjected to large strain rates. High strain rates occur in airplane/automobile accidents and other engineering applications such as impact or bird-strike events, plastic flow close to the tip of a fast propagating crack, high speed metal forming, etc. [1]. Before including such effect in numerical modeling of structures, appropriate constitutive equations need to be developed. Characterizing the behavior of composites under dynamic loading is not an easy task. Baselines for the stress-strain behavior of composites are generated at quasi-static to slow strain rates (<1 s\(^{-1}\)) using traditional testing machines and load sensing devices. However, at high strain rates, generating stress-strain curves represents a challenge; several test apparatus are used to account for different strain rate ranges. Hence different load measurement methods are used. In addition, there is not a standard procedure for extracting iso-strain rate curves.

The crashworthiness working group (CWG) of the CMH-17 has been conducting a round robin exercise to evaluate/compare the different numerical methods for simulating crushing behavior of energy absorption devices made of laminated composites. The first sets of simulations are limited to material properties generated at quasi-static rates. Future simulations will address the simulation of crushing behavior under dynamic loading thus requiring appropriate material constitute properties generated at representative strain rates. However, due to the wide range of test methods used by researchers in the past, no standard exists for conducting such tests but only guidelines [2]. The current investigation aims to generate rate sensitive tensile properties for the material being used by the CWG of the CMH-17 at selected strain rates up to 250 s\(^{-1}\). A secondary objective is to evaluate the test/method apparatus, specifically the load measurement method, employed by the participating laboratories.
Experimental Methods

Tensile specimens are fabricated using two material systems: 2024-T3 Aluminum and Toray T700/2510 plain weave/epoxy (F6273C-07M). Newport NB321/7781 fiberglass epoxy is used to fabricate tabs for the composite specimens. Specimens are manufactured and instrumented by NIAR/WSU and distributed to all participating laboratories. The Aluminum specimens are used as a control material to evaluate load measurement devices. Aluminum specimens are dog-bone specimens fabricated per ASTM E8 but varied to accommodate an extended tab [3, 4]. Aluminum specimens are instrumented with two Vishay strain gages: strain gage CEA-06-250UN-120 mounted on the extended tab region and another gage EP-08-125BG-120 mounted directly on the gage area. The gage on the extended tab is used to measure the load introduced to the specimen. Composite specimens are straight-tabbed specimens with rectangular cross section per ASTM D3039 with dimensions varied for high strain rate testing [5]. Laminated panels are manufactured with traditional vacuum bag prepreg lay-up and cured in autoclave. Quality control is enforced by means of TTU C-Scans and fiber volume content measurement. Specimens are fabricated in three different stacking sequences: [0°]_4, [90°]_4, and [±45°]_4. Composite specimens are instrumented with Vishay strain gages CEA-00-250UN-350 and CEA-00-125UT-350.

Tests at quasi-static rates for baseline data are conducted at NIAR/WSU using a standard 22 kip (100 kN) MTS servo-hydraulic machine and a 11 kip (48 kN) load sensor. Two type of test apparatus are used by the participating laboratories for dynamic testing: a high stroke servo-hydraulic testing machine and a tensile Split Hopkinson Pressure Bar (SHPB). The high stroke servo-hydraulic machine is used in combination with a slack inducer device that allows for the actuator to accelerate to a desired velocity. Each laboratory uses its own load sensor, set of gripping devices, connectors/adaptors, etc. In general load sensors are piezo-electric load cells. Nominal strain rates are: 0.0004, 0.01, 1, 100, and 250 s⁻¹.

Results

The quasi-static material response of the composite material is characterized. Average material properties are estimated for reference: the Modulus of Elasticity of [0°] specimens is 8.25 Msi (C.V. 4.3%), for [90°] specimens is 8.77 Msi (C.V. 5.4%), and for [±45°] specimens is 1.96 Msi (C.V. 7.3%). The tensile strength for [0°] specimens is 160 ksi (C.V. 3.9%), for [90°] specimens is 148 ksi (C.V. 2.5%), and for [±45°] specimens is 29 ksi (C.V. 6.9%). Variability based on three (3) replicates is calculated for reference purposes only.

Test results for 2024-T3 Aluminum show the stress-strain behavior of the material not to vary with increasing strain rate during the elastic regime of deformation. In addition, no major variations are seen in the failure strength of the material with increasing strain rate. However, flow stress seems to increase as a function of strain rate.

Composite materials dynamic testing results before load correction show different trends between laboratories when looking at the apparent tensile strength. Lab A, C, and D test results for [0°] and [90°] specimens show larger apparent failure strengths with increasing strain rate up to nominal strain rate 100 s⁻¹. After which there is a drop in the strength for nominal strain rate 250 s⁻¹. On the other hand, Lab B results for [0°] and [90°] specimens show a drop in apparent failure strength with increasing strain rate. Test results for [±45°] specimens from Lab A, C, and D show larger apparent
failure strengths with increasing strain rate. On the other hand, Lab B results for [±45°] specimens show an unexpected drop in apparent failure strength for nominal strain rate 1 s⁻¹. Test results after load correction from all laboratories for [0°] composite specimens do not show the material strength increasing with strain rate. Similarly, [90°] specimens do not show significant sensitivity to strain rate even though results show larger scatter when compared to [0°] specimens. Nevertheless, the strength of [±45°] specimens increases as a function of strain rate in all laboratory results. Strain rates introduced by the tensile SHPB differ from average strain rates introduced by the high stroke servo-hydraulic machine due to the different specimen geometry and the capabilities of each test apparatus. Only nominal strain rates above 100 s⁻¹ can be compared. Results obtained using a tensile SHPB do not show the material response of composite specimens in the fiber direction [0°] and [90°] to be strain rate sensitive for the evaluated strain rates. On the other hand, results for [±45°] specimens show higher strength values with increasing strain rate.

PROGRAM II – MODELING FASTENER JOINTS FOR CRASHWORTHINESS SIMULATIONS

Mechanical joining using bolts and fasteners is the most widely used joining method in aerospace industry. Metal and Composite Structures use fasteners as one of the primary joining entities to facilitate slip resistance and load transfer. The current investigation used a 10-ft fuselage section model created in a previous research program to identify the average number of fastener connections that an aircraft structure of this type may have. Twenty two thousand and twelve (22,012) fasteners were identified in a 10-ft section. Also, the model was used to study the energy dissipation characteristics of the structure during a crash event. During a 30 ft/s drop test of the fuselage section the energy dissipated through fastener joints was up to 43 % of the total energy for no cargo configurations. Given the role of fastener joints in aircraft structural integrity, it is important to identify the available numerical tools to account for this type of joints, and more importantly, which ones are suitable for crashworthiness simulations of metallic and composite aircraft structures. The size of finite element models used for crashworthiness evaluations imposes limitations to the level of detail when capturing localized effects.

The scope of the program was to define guidelines for modeling fastener joints for crashworthiness simulations. The primary objective was to evaluate how accurate existing simplified numerical techniques to model bolts/fasteners represent mechanical joints behavior under dynamic loading. Simplified techniques were compared against complex models and validated with testing. The key parameters for comparison included load transfer, energy dissipation, and computational time. savings when being part of large structures models.

Experimental Methods – Material Characterization

A material characterization was conducted to generate the material properties required for simulation of single joint specimens. The material system was Aluminum 2024-T3 Clad. Dog-bone specimens were fabricated, instrumented, and tested. In-plane tension testing was conducted per ASTM E 8 using a standard 22 kip (100 kN) MTS servo-hydraulic machine and a 5.5 kip (25 kN) load sensor. Tests were conducted at a quasi-static rate of 0.05 in/min and strain was measured using strain gages and a laser extensometer along with a Vishay 2210 signal conditioner. The material response in tension is shown in Figure 1.
Experimental Methods – Preload Measurement

The clamping force introduced by a Hi-lok fastener to the joint was characterized experimentally. Hi-lok fasteners are designed for a specific preload range. It contains a hex nut that would shear off when the load on the fastener reaches such range. When used in service, every part is fastened per industry specifications such load is properly transferred between components. Therefore, numerical models used to study load transfer and energy dissipation in crash events should account for the preload in bolted joints. Not accounting for it may change the load path and the energy absorbing characteristics of the structure.

The test specimen included two Aluminum 2024-T3 plates, a 5 Kip load cell calibrated in compression (LWO-2 Transducer Techniques), a nut (HL-70), and a pin (HL-18). Several specimens were fabricated. First, an interference fit hole was drilled in each plate. Subsequently, the preload in the Hi-lok joint was introduced by directly clamping the load cell in between the two plates as shown in Figure 3. The fastener was torqued using a torque wrench until the nut sheared off. The maximum load read by the load cell was recorded. Based on the response shown in figure 4 an average clamping force was estimated for simulation.
Experimental Methods – Load Transfer Testing

The specimens used to test the joint performance and the load transfer were single fastener dog-bone shaped specimens. The specimen was compounded with three different parts as shown in Figure 5: the main part, a transfer part, and a doubler to balance the thickness.

In-plane tension testing was conducted first at a quasi-static rate of 0.05 in/min to generate a baseline for dynamic evaluations. Load was transferred from the main part to the transfer part through the joint, while the purpose of the doubler was to avoid bending by simulating a symmetric configuration. Test apparatus used was a MTS High Stroke Rate Servo-hydraulic with a capability for dynamic loads up to 5 kip combined with a Slack Inducer Mechanism and a 22 kip strain gage based load cell. An anti-buckling fixture was used to prevent bending. Strain was measured at three different location in the specimen. Axial strain gages CEA-06-250UN-120 were used and a Vishay 2210 signal...
conditioner. The strain gages were placed to measure the strains experienced by the different parts. The test set-up and strain gage locations are shown in Figure 6.

![Test Set-up and Specimen Instrumentation](image)

Figure 6. Test Set-up and Specimen Instrumentation.

Load transfer results are shown in Figure 7 for each test conducted. Load transfer was estimated by comparing strain gage measurements at location 2 vs. location 1. The percentage load transfer is given by:

\[
\% \text{ Load Transfer} = \left[ 1 - \left( \frac{SG_2}{SG_1} \right) \right] \times 100
\]

where SG 1 and SG 2, are the strain measurements (mm/mm).
Analysis Methods

Once the joint behavior was characterized experimentally along with the average fastener preload, different simulation techniques were evaluated. The solver used in present work was LS-Dyna. However, most commercial solvers provide equivalent simulation approaches to represent mechanical joints. In addition, complex solutions have been developed by users after combining simplified methods aiming to account for localized effects.

In this research program, a solid element model of the fastener and the specimen was built to generate a baseline for simulation. Then, the joint behavior was evaluated using a shell element model of the specimen and joining methods computationally cost efficient, so that they could be used accurately in large scale aerospace structure models. First set of simulations used a complex model representing the specimen and the anti-buckling fixture using solid 3D elements and a fine mesh as seen in Figure 8. The model was built with solid elements with nominal size of 0.206 mm. Boundary conditions were defined to constrain the bottom nodes of the specimen not to move in any direction. A prescribed translational displacement in longitudinal direction was applied to the top set of nodes at a quasi-static rate. The anti-buckling fixture was also modeled using solid elements and constrained in the same way as it was tested (to avoid out of plane displacements). Different contact types were used between the specimen and the bolt shank and nut and also between the whole jointed specimen and the anti-buckling fixture.

In the shell element model, bottom nodes were contained not to move in any direction and a prescribed translational displacement in longitudinal direction was applied to the top set of nodes at a quasi-static rate. Various simplified bolt modeling techniques were evaluated using this model and compared to solid model results and validated with the experimental results. Examples of the evaluated techniques included spotweld beams, beams with an elastic patch, spider web connections, or beams with rigid links as shown in Figure 9.
Other fastener modeling approaches have been developed by Ls-Dyna users by combining simple techniques. One approach combines the simplicity of beam elements with a spider connection and a solid element modeling [6]. Null beams are modeled around the holes for contact and the bolt shank is modeled with type 9 spotweld-beam elements. Shell elements are used to model the bolt head and the nut as seen in Figure 10. Another example of bolt modeling uses a beam element at the center of the hole to model the Bolt shank. Then, another beam element is connected to the periphery of bolt hole using contact springs. Shell element patches representing the bolt head and the nut are modeled as rigid and constrained using extra nodes [7]. A schematic representation of this method appears in Figure 11. This approach with a beam model is advantageous if failure forces for bolted joint are known under different conditions.
Results

Simulation results obtained with the 3D model were compared and validated with the experimental results. Two different simulations were conducted, one taking into account the existing preload introduced by the bolt and a second one without it. The preload was introduced in Ls-Dyna using INITIAL_STRESS_SECTION option. The model with preload showed better correlation when compared to test data while the model without preload showed a 2.5% drop in load transfer as shown in Figure 12.
SUMMARY AND CONCLUSIONS

Program I – Dynamic Characterization Of Round Robin Material

Test of 2024-T3 Aluminum specimens is conducted to evaluate the capabilities of the load sensor. The material response, generated using the strain gage mounted on the tab as load measurement device, does not show sensitivity to the evaluated strain rates over the elastic regime. The load measured this way can be used for the load correction methodology since it is not being modulated by the load train effect. The effect of higher strain rates on the material response, if any, is seen as an increment in flow stress as a function of strain rate.

The quasi-static material response of the composite material is generated as a baseline for estimating the effect of nominal strain rates as high as 250 s\(^{-1}\). Before correction, the material strength in the fiber direction \([0^\circ]\) and \([90^\circ]\) seems to increase as a function of strain rate. However, there is a sudden drop above nominal strain rate 100 s\(^{-1}\). On the other hand, the strength of \([±45^\circ]\) specimens seems to increase as a function of strain rate. After load correction, the material response of composite specimens in the fiber direction \([0^\circ]\) and \([90^\circ]\) does not show significant sensitivity to the evaluated strain rate across laboratories. However, the response of the off-axis orientation \([±45^\circ]\) still shows some sensitivity to high strain rates. Regardless the difference between actual strain rates introduced by each test apparatus, the SHPB results agree with servo-hydraulic machine results after load correction; the material response in the fiber direction \([0^\circ]\) and \([90^\circ]\) does not show sensitivity to the evaluated strain rates and the material response for the off-axis orientation \([±45^\circ]\) show a moderate increment in the strength with increasing strain rate.

High stroke servo-hydraulic machines used in combination with a slack inducer device show to be suitable test apparatuses for conducting tensile testing at medium strain rates. However, the force signal measured with piezoelectric load cells is modulated by the grips, adapters, and pins present in the load train. Hence, the material response for medium strain rates is only apparent before signal
modulation correction. The load correction methodology may be applicable for strain rates as low as 1 s\(^{-1}\).

**Program II – Modeling Fastener Joints For Crashworthiness Simulations**

Several simulations of a mechanical joint were performed under different modeling techniques to evaluate and study the advantages and disadvantages between them. An experimental characterization was needed in order to define simulation parameters such as material model, preload introduced by the fastener, and boundary conditions. The quasi-static material response of the Aluminum 2024-T3 Clad was generated following tensile testing test method ASTM E 8. Preload introduced by a Hi-lok fastener was measured using a load cell calibrated in compression. Single fastener specimens were tested in-tension to evaluate the load transfer.

Simulations results for the solid elements model showed good correlation when compared to test results. The load transfer improved for the model accounting for the preload in the fastener when compared with the model without. Results without preload showed a 2.5% drop in load transfer and no computational cost savings. The shell element model was used to compare the available simplified techniques to represent a mechanical joint. Simulations using these techniques were compared to the solid model results. Although the load transfer may agree with the solid model, for some of the simplified techniques the absence of the hole meant that stress concentrations around hole were not present. Not having the hole changes the stress distribution around joining point and it may affect the failure mode of the material around the joint. It was also noted that the simplified techniques failed at locations not necessarily in the vicinity of the hole and at a later time since the absence of the hole allows more load to be transferred.

**REFERENCES**


