# FAME Bracket Reliability Analysis

## User Tutorial for the FAME Bracket Reliability Analysis Tool

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Institute for Software Integrated Systems
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## 1.0 Summary

A bracket reliability analysis tool has been developed that performs fatigue analyses to derive damage or remaining life at a desired probability level for a class of brackets. The class was angle brackets with gussets with varying angle and gusset wall thicknesses. This tool is also applicable to a general (user defined geometry) design. In this case the user would have to provide a maximum stress in the bracket that was seen over the entire mission history (e.g., by performing finite element analyses of the general bracket) that helps to define an allowable stress factor (ASF) for the bracket. Damage parameter maps for different ASF values that were generated for stainless steel 17-4PH and Aluminum 6061-T6 are used in the bracket design tool to generate the damage at a given level of probability. The tool has been integrated with META-CyPhy version 14.03.

## 2.0 Motivation

Fatigue failure is a common occurrence in brackets that support the engine and drive train assemblies to the hull of an ACV due to driving on mission terrains for these vehicles. Hence a bracket design and verification tool was developed that performs fatigue analyses of the bracket to derive damage at a desired probability level for a class of brackets. Since the developing of multi-dimensional damage parameter maps for all different shapes of brackets (i.e., parameterizing and varying height, width, depth, thickness, material, etc) was not feasible, an allowable stress factor (ASF) for a bracket was used to index the damage-parameter maps. ASF is defined as the yield stress of the material divided by the maximum von Mises stress due to the largest force in the mission history. ASF defines a "level of conservatism" or an implied safety factor of the design of the bracket. An ASF for a given material of a bracket will have a single damage value at a given probability level. However, a single ASF value would be associated with a family of bracket geometry parameters. Physics-based models coupled with dynamic simulation were used to predict the dynamic shock and vibration at the brackets under a typical operating environment. Dynamic models help speed up the product development cycle and ensure system performance. Multi-body dynamics (MBD) models are used early in the product design cycle to accurately simulate system level platform dynamics prior to building costly physical prototypes, or even higher fidelity system level finite element models. MBD models help design engineers to effectively analyze and optimize the performance for the dynamic environment of mechanical systems.

# 3.0 Background

## 3.1 Caveats

Brackets are forged or extruded and did not contain welds. Brackets with welds could have failure at the welds due to their reduced fatigue capability. The fastener holes to attach the brackets to the hull or to the transmission and engine assembly were not considered in the stress analyses since the preload in the fasteners and the use of appropriate washers would prevent a stress concentration at the holes due to bracket forces.
Other assumptions are:

- Seed Design for suspension layout
- 35 tons Gross Vehicle Weight (mass properties based on Creo model or estimated from uniform density box)
- Suspension spring/damping characteristics obtained from the public domain
- Constant vehicle speed
- Rigid vehicle hull
- Power Pack mounting bracket stiffness provided by ACEI, based on engineering expertise.

## 3.2 Backend Workflow

The backend workflow, invisible to the user, is as follows:

1. An MBD simulation model of a seed design vehicle (SDV) based on the Official Gamma Seed was developed. The SDV included springs that represented the brackets that attached the engine and transmission assemblies to the hull.
    - Gather mass properties from the SDV CAD model (or estimated assuming uniform density box)
    - Create MBD model based on CAD model of SDV and its components.
    - Determine suspension spring/damping characteristics.
    - Determine mounting bracket location & stiffness.
    - Select terrain/obstacle profiles.
    - Determine reasonable vehicle speed(s).
    - Run dynamic simulations.

- Post-process result for acceleration/force time histories at points-of-interest including power pack mounting brackets for the current effort.
- Mission force history was defined by concatenating the bracket force histories that were generated from MBD simulation of the SDV being driven over: Perryman 3, 12? high half round bump, 30? step down, and 96? wide trench crossing.
- Bracket force histories were derived from DADS simulations of SDV using DADS software.
- A class of angle brackets for 2 materials and 3 angle dimensions and varying angle and gusset thicknesses were defined.
- For each bracket design, linear static Finite Element (FE) analyses were performed to derive the maximum stress in the brackets due to highest force in the bracket mussion history.
- An allowable stress factor for each bracket was calculated by dividing the yield stress of the material by the maximum stress in that bracket.
- An outcome of the FE analyses were the bracket stiffness in the three directions. Stiffnesses were represented via springs in the DADS vehicle simulation analyses.
- The ACEI fatigue failure simulation model was modified to generate damage parameter maps for given values of ASF, for a given material of the bracket due to the bracket force mission histories derived from the DADS simulations.
- ASF equations bracket thicknesses at and tg were derived by curve fitting the bracket FE analyses results. Bracket stiffness equations were also derived in a similar fashion.
- In the bracket design and verification tool, the ASF is calculated using the equations for the geometry and material of the bracket and enter the damage parameter maps.

### 3.3 Simulation Setup

Bracket force histories, which were used for the damage simulations, were derived from MBD simulations of the SDV using DADS software. Mission force history was defined by concatenating the bracket force histories that were generated from Perryman 3, 12' High half round bump, 30' step down, and 96' wide trench crossing DADS simulations of the SDV.

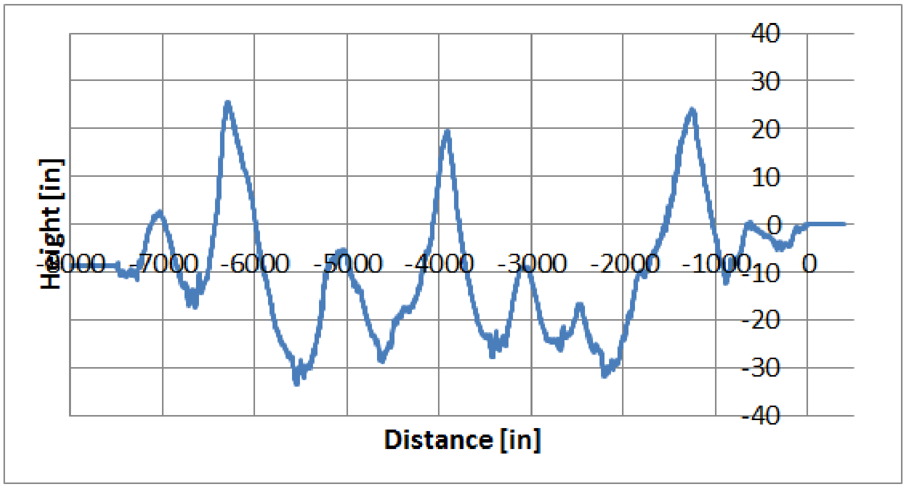
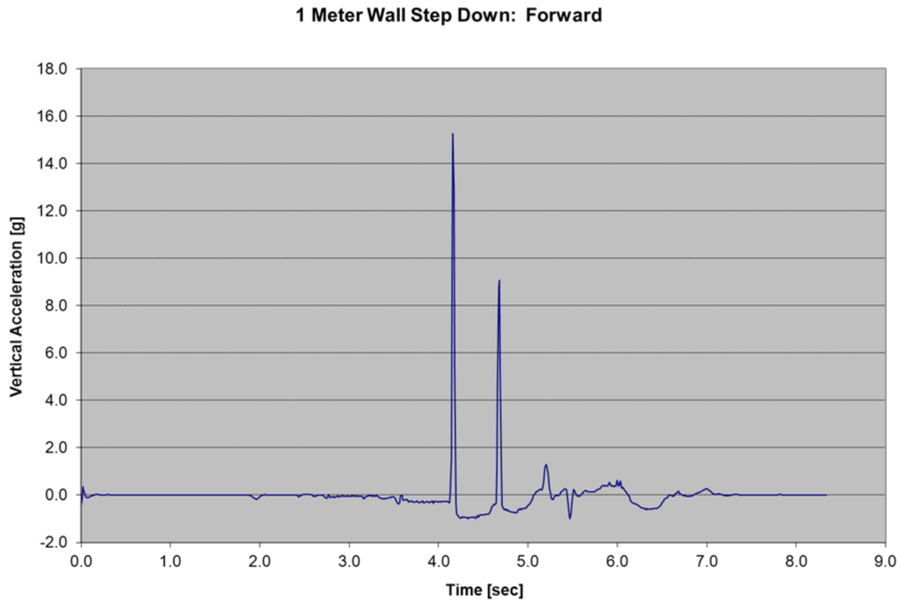



**Figure 1: Perryman 3 Course.**



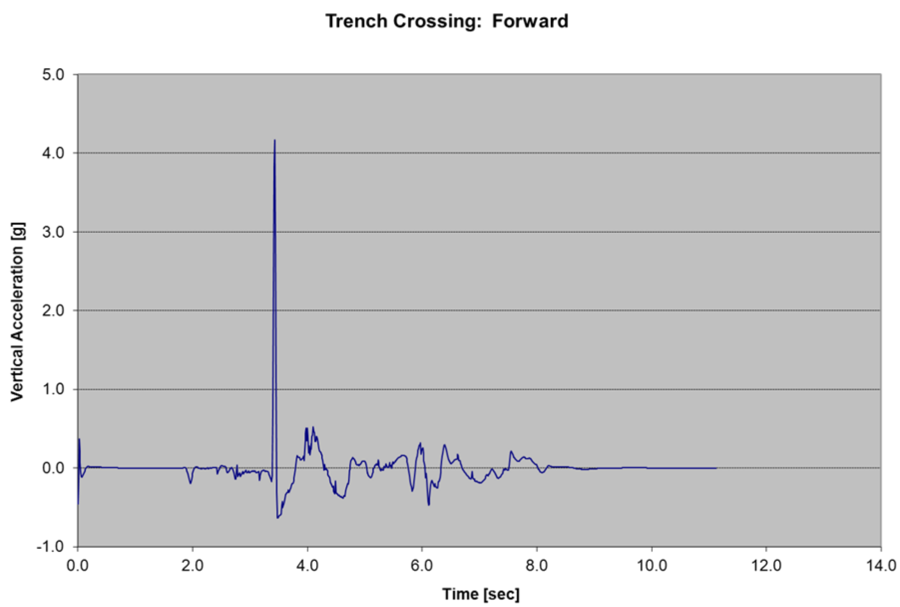




**Figure 2: Sample acceleration time histories for trench crossing and 1 meter wall step down**

From the histories of the four brackets that support the engine and transmission assembly, the Front Left (FL) bracket histories were chosen to define the mission since they had the highest force peaks. One mission was defined to be a distance of 28,800 miles based on 1200 hour operation FANG challenge requirement. In the history, the 28 second Perryman 3 was repeated for the full duration (212826 times) and the wall step up, step down, and trench crossing events were repeated every 10 miles (2880 times).

### 3.4 Technical Details

The fatigue model generates damage parameter maps at different probabilities of occurrence for a component given its cyclic load history, geometry, material properties and the uncertainties. The fatigue model is based on strain vs. life (e vs.N) behavior of the material due to cyclic loads. The inputs to the fatigue model are the bracket force history, the material data and the governing parameters for the component. Monte-Carlo (M-C) loops are performed for the number of random trials to derive the damage at desired probabilities of occurrence for a set of parameter values. In a single M-C trial, damage is derived by the following steps. The input bracket load history is first transformed to a stress time history using a load-to-stress transformation described by the bracket geometry or ASF. Next, the stress range and number of cycles are identified using the rainflow counting technique. If the stress range of a cycle is above the yield strength, the total strain, e, will include the elastic and plastic strain. Neuber's rule is used to transform the elastic stress to a total strain range using the stress-strain curve for the material. Walker relation is then used to correct the total strain range to account for the mean strain of the cycle. The damage due to total strain is derived using the strain vs. life model. Finally, the total damage due to each cycle is accumulated using Miner's rule to find the damage due to the entire force history.

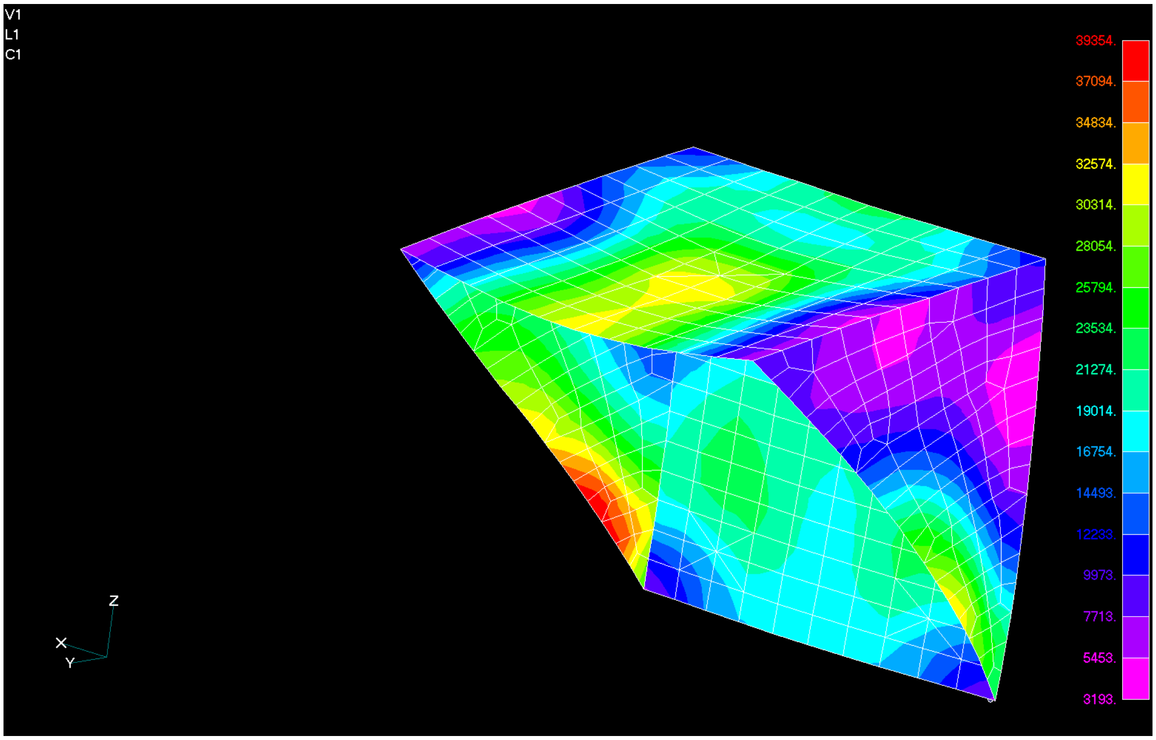



**Figure 3: Sample von Mises stress contour of a 4 x 4 x 4 bracket is shown above. Maximum stress of 39.4 ksi due to the largest force of 18300 lbs and the yield stress for 17-4PH is 170 ksi. Hence the ASF = 170/39.4 = 4.31.**

The Stainless steel 17-4PH H900 and Aluminum 6061-T6 materials properties used in the bracket damage simulations are from MIL-HNDBK-5J and ACEI material's data files. The stress rupture properties given in Table 1 are the yield strengths for alloys. The A and B "basis" values for these materials (from published literature) were used to derive the mean, standard deviation, and the coefficient of variations for the yield stress and describe the strength uncertainty. The total strain vs. life data are used in the bootstrapping materials model approach to capture fatigue life uncertainty implied by the data set.

| | LIFE (Number of Missions) | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Probability | Allowable Stress Factor (ASF) | | | | | | | | | | |
| of Failure | 1.00 | 2.00 | 3.00 | 4.00 | 5.00 | 6.00 | 7.00 | 8.00 | 9.00 | - | - |
| **0.0001** | 1.54E-03 | 6.18E-02 | 3.37E-01 | 9.34E-01 | 1.75E+00 | 4.02E+00 | 7.96E+00 | 1.19E+01 | 1.96E+01 | 0.00E+00 | 0.00E+00 |
| **0.0002** | 1.74E-03 | 7.08E-02 | 3.95E-01 | 1.24E+00 | 2.36E+00 | 5.41E+00 | 9.84E+00 | 1.63E+01 | 2.72E+01 | 0.00E+00 | 0.00E+00 |
| **0.0003** | 1.95E-03 | 7.36E-02 | 4.59E-01 | 1.36E+00 | 2.75E+00 | 6.56E+00 | 1.22E+01 | 1.98E+01 | 3.25E+01 | 0.00E+00 | 0.00E+00 |
| **0.0004** | 2.06E-03 | 7.89E-02 | 4.81E-01 | 1.45E+00 | 3.53E+00 | 7.97E+00 | 1.34E+01 | 2.29E+01 | 3.99E+01 | 0.00E+00 | 0.00E+00 |
| **0.0005** | 2.14E-03 | 8.32E-02 | 5.15E-01 | 1.54E+00 | 4.04E+00 | 8.79E+00 | 1.47E+01 | 2.69E+01 | 4.41E+01 | 0.00E+00 | 0.00E+00 |
| **0.0006** | 2.18E-03 | 8.81E-02 | 5.40E-01 | 1.63E+00 | 4.38E+00 | 9.41E+00 | 1.61E+01 | 2.93E+01 | 4.84E+01 | 0.00E+00 | 0.00E+00 |
| **0.0007** | 2.28E-03 | 9.20E-02 | 5.54E-01 | 1.74E+00 | 4.68E+00 | 1.00E+01 | 1.74E+01 | 3.23E+01 | 5.44E+01 | 0.00E+00 | 0.00E+00 |
| **0.0008** | 2.33E-03 | 9.53E-02 | 6.02E-01 | 1.84E+00 | 4.96E+00 | 1.04E+01 | 1.89E+01 | 3.40E+01 | 5.83E+01 | 0.00E+00 | 0.00E+00 |
| **0.0009** | 2.36E-03 | 9.72E-02 | 6.20E-01 | 1.92E+00 | 5.19E+00 | 1.07E+01 | 2.04E+01 | 3.57E+01 | 6.18E+01 | 0.00E+00 | 0.00E+00 |
| **0.001** | 2.42E-03 | 9.94E-02 | 6.43E-01 | 2.06E+00 | 5.33E+00 | 1.17E+01 | 2.18E+01 | 3.69E+01 | 6.42E+01 | 0.00E+00 | 0.00E+00 |
| **0.002** | 2.88E-03 | 1.17E-01 | 8.08E-01 | 2.80E+00 | 7.54E+00 | 1.67E+01 | 3.11E+01 | 5.46E+01 | 9.21E+01 | 0.00E+00 | 0.00E+00 |
| **0.003** | 3.17E-03 | 1.29E-01 | 9.18E-01 | 3.28E+00 | 9.36E+00 | 1.97E+01 | 3.79E+01 | 7.10E+01 | 1.18E+02 | 0.00E+00 | 0.00E+00 |
| **0.004** | 3.38E-03 | 1.38E-01 | 1.02E+00 | 3.68E+00 | 1.05E+01 | 2.30E+01 | 4.49E+01 | 8.48E+01 | 1.40E+02 | 0.00E+00 | 0.00E+00 |
| **0.005** | 3.54E-03 | 1.45E-01 | 1.09E+00 | 4.05E+00 | 1.16E+01 | 2.59E+01 | 5.23E+01 | 9.56E+01 | 1.62E+02 | 0.00E+00 | 0.00E+00 |
| **0.006** | 3.69E-03 | 1.52E-01 | 1.16E+00 | 4.36E+00 | 1.28E+01 | 2.85E+01 | 5.79E+01 | 1.09E+02 | 1.81E+02 | 0.00E+00 | 0.00E+00 |
| **0.007** | 3.84E-03 | 1.58E-01 | 1.24E+00 | 4.69E+00 | 1.38E+01 | 3.13E+01 | 6.28E+01 | 1.18E+02 | 2.01E+02 | 0.00E+00 | 0.00E+00 |
| **0.008** | 3.98E-03 | 1.64E-01 | 1.31E+00 | 4.99E+00 | 1.47E+01 | 3.42E+01 | 6.78E+01 | 1.28E+02 | 2.21E+02 | 0.00E+00 | 0.00E+00 |
| **0.009** | 4.12E-03 | 1.70E-01 | 1.37E+00 | 5.32E+00 | 1.57E+01 | 3.62E+01 | 7.29E+01 | 1.40E+02 | 2.40E+02 | 0.00E+00 | 0.00E+00 |
| **0.01** | 4.25E-03 | 1.75E-01 | 1.42E+00 | 5.59E+00 | 1.67E+01 | 3.86E+01 | 7.84E+01 | 1.48E+02 | 2.56E+02 | 0.00E+00 | 0.00E+00 |
| **0.02** | 5.14E-03 | 2.19E-01 | 1.92E+00 | 7.99E+00 | 2.45E+01 | 6.05E+01 | 1.27E+02 | 2.53E+02 | 4.37E+02 | 0.00E+00 | 0.00E+00 |
| **0.03** | 5.83E-03 | 2.53E-01 | 2.32E+00 | 1.01E+01 | 3.17E+01 | 7.93E+01 | 1.73E+02 | 3.47E+02 | 6.12E+02 | 0.00E+00 | 0.00E+00 |
| **0.04** | 6.42E-03 | 2.81E-01 | 2.67E+00 | 1.20E+01 | 3.82E+01 | 9.83E+01 | 2.19E+02 | 4.37E+02 | 7.82E+02 | 0.00E+00 | 0.00E+00 |
| **0.05** | 6.93E-03 | 3.07E-01 | 2.99E+00 | 1.39E+01 | 4.50E+01 | 1.17E+02 | 2.64E+02 | 5.30E+02 | 9.70E+02 | 0.00E+00 | 0.00E+00 |
| **0.06** | 7.45E-03 | 3.30E-01 | 3.33E+00 | 1.57E+01 | 5.16E+01 | 1.34E+02 | 3.09E+02 | 6.27E+02 | 1.15E+03 | 0.00E+00 | 0.00E+00 |
| **0.07** | 7.90E-03 | 3.55E-01 | 3.64E+00 | 1.75E+01 | 5.79E+01 | 1.53E+02 | 3.56E+02 | 7.23E+02 | 1.34E+03 | 0.00E+00 | 0.00E+00 |
| **0.08** | 8.38E-03 | 3.77E-01 | 3.93E+00 | 1.91E+01 | 6.40E+01 | 1.71E+02 | 4.00E+02 | 8.26E+02 | 1.53E+03 | 0.00E+00 | 0.00E+00 |
| **0.09** | 8.85E-03 | 4.00E-01 | 4.22E+00 | 2.08E+01 | 7.09E+01 | 1.90E+02 | 4.45E+02 | 9.32E+02 | 1.73E+03 | 0.00E+00 | 0.00E+00 |
| **0.1** | 9.29E-03 | 4.23E-01 | 4.52E+00 | 2.25E+01 | 7.73E+01 | 2.09E+02 | 4.95E+02 | 1.04E+03 | 1.95E+03 | 0.00E+00 | 0.00E+00 |
| **0.2** | 1.36E-02 | 6.43E-01 | 7.55E+00 | 4.07E+01 | 1.50E+02 | 4.35E+02 | 1.07E+03 | 2.33E+03 | 4.52E+03 | 0.00E+00 | 0.00E+00 |
| **0.3** | 1.85E-02 | 8.96E-01 | 1.12E+01 | 6.30E+01 | 2.43E+02 | 7.39E+02 | 1.85E+03 | 4.17E+03 | 8.39E+03 | 0.00E+00 | 0.00E+00 |
| **0.4** | 2.47E-02 | 1.20E+00 | 1.56E+01 | 9.16E+01 | 3.67E+02 | 1.15E+03 | 2.96E+03 | 6.90E+03 | 1.42E+04 | 0.00E+00 | 0.00E+00 |
| **0.5** | 3.28E-02 | 1.60E+00 | 2.14E+01 | 1.30E+02 | 5.40E+02 | 1.72E+03 | 4.60E+03 | 1.11E+04 | 2.30E+04 | 0.00E+00 | 0.00E+00 |
| **0.6** | 4.34E-02 | 2.12E+00 | 2.92E+01 | 1.84E+02 | 7.92E+02 | 2.60E+03 | 7.19E+03 | 1.75E+04 | 3.72E+04 | 0.00E+00 | 0.00E+00 |
| **0.7** | 5.79E-02 | 2.86E+00 | 4.07E+01 | 2.67E+02 | 1.19E+03 | 4.04E+03 | 1.14E+04 | 2.84E+04 | 6.20E+04 | 0.00E+00 | 0.00E+00 |
| **0.8** | 7.94E-02 | 3.97E+00 | 5.96E+01 | 4.07E+02 | 1.90E+03 | 6.71E+03 | 1.95E+04 | 4.99E+04 | 1.12E+05 | 0.00E+00 | 0.00E+00 |
| **0.9** | 1.16E-01 | 6.04E+00 | 9.91E+01 | 7.27E+02 | 3.58E+03 | 1.33E+04 | 4.11E+04 | 1.07E+05 | 2.50E+05 | 0.00E+00 | 0.00E+00 |
| **1** | 7.78E-01 | 5.29E+01 | 1.47E+03 | 1.91E+04 | 2.34E+05 | 5.15E+05 | 2.80E+06 | 1.79E+07 | 3.43E+07 | 0.00E+00 | 0.00E+00 |

**Table 1: Sample Damage-Parameter Map for 17-4PH900 Steel Bracket.**

## 4.0 Tutorial

This tool allows you, as a system designer or design tester, to explore the reliability consequences of different bracket design choices, and to assess the probability of catastrophic fatigue failure of the bracket as a result of mission stress. Specifically, the tool will help you discover answers to the following questions:

- What is the probability of fatigue failure in my bracket if it is used to support the engine in the Seed Design Vehicle (SDV), where the vehicle is run for 1200 hours over the terrain profile described above?
- If I make changes to the dimensions or the material of the bracket, what difference does that make?

## 4.1 Installation

The tool comes packaged with META-CyPhy version 14.03. Please follow download and installation instructions for CyPhy to set it up.

## 4.2 Additional Downloads

Download the example FAMEBracketFatigue.xme file to run this tutorial. This is an empty dummy design. The specifics of the Seed Design are hard-coded into the back-end. In the future, design details will be directly imported from MetaLink and Mass and CAD Assembly test benches.

## 4.3 Tool Use

### Step 1: Open Example File

Double click the FAMEBracketFatigue.xme file to open it in CyPhy-GME. Click on Create a Project File and save your project.

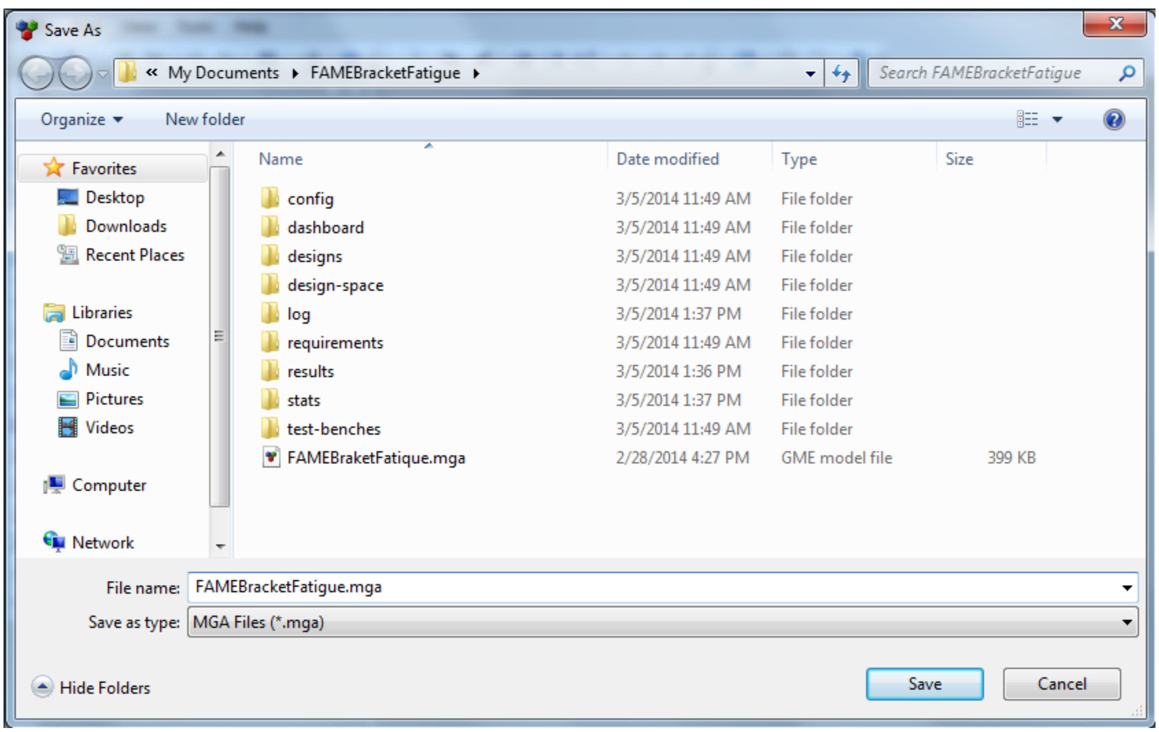



**Figure 4: Save Project File.**

## Step 2: Open Test Bench

Expand the project in the GME Browser pane, select Testing, then select TestBench4.

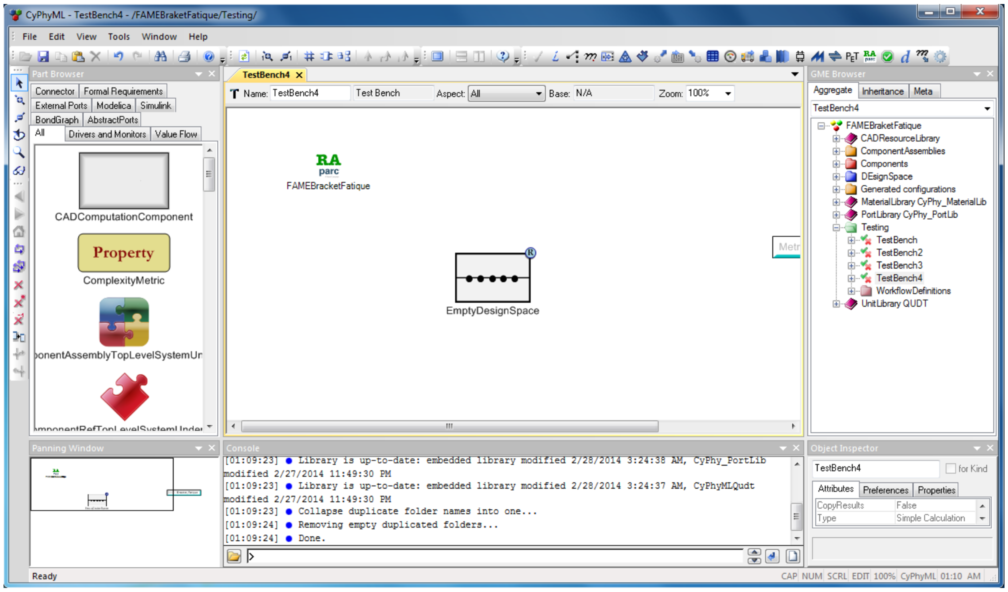



**Figure 5: Open Test Bench.**

## Step 3: Run CyPhy Master Interpreter

Click on the CyPhy Master Interpreter button to open up test bench dialog box.

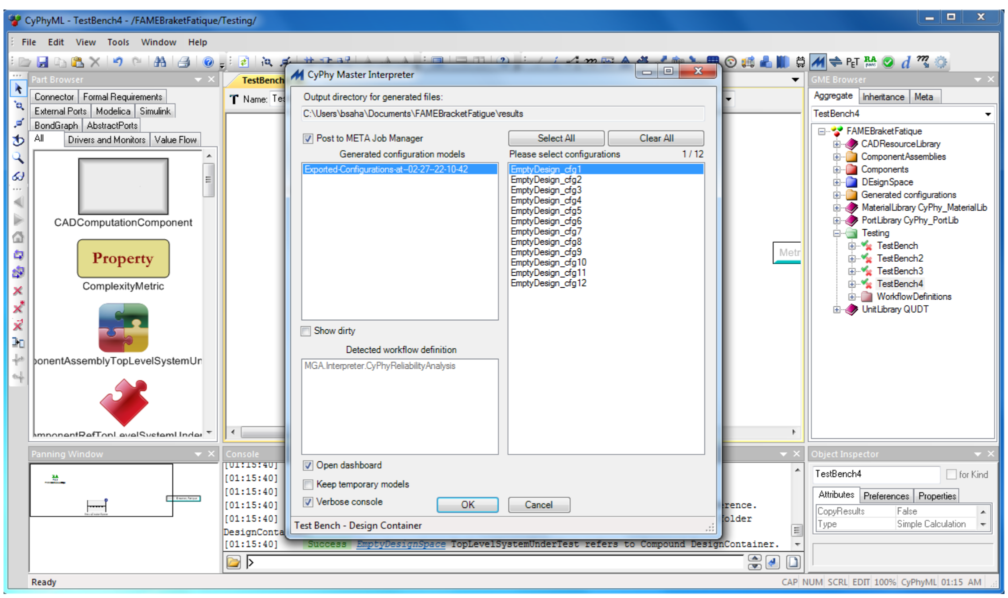



**Figure 6: Test Bench Dialog Box.**

Since we are experimenting with an empty design, the configurations are exactly the same. Select any one (or multiple), make sure you check Post to META Job Manager, and click OK.

### Step 4: Set Bracket Configuration

Running the CyPhy Master Interpreter will open up a Bracket Configuration dialog box. The settings in this dialog box will apply to all configurations selected in the previous step.

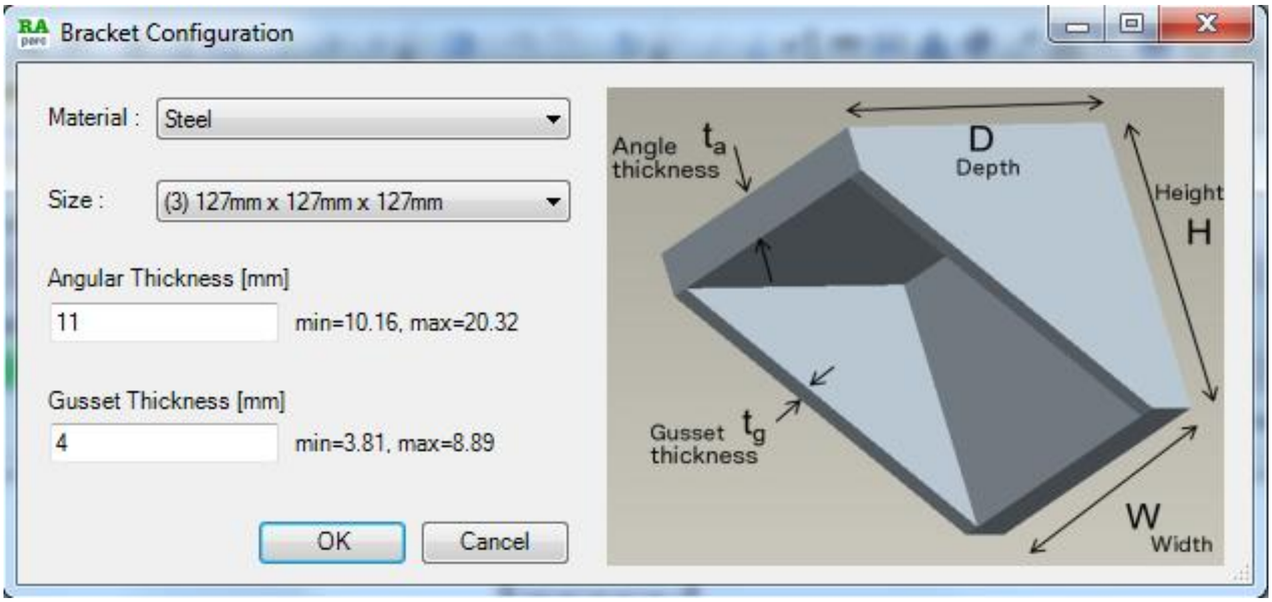



**Figure 7: Bracket Configuration Dialog Box.**

The choices available to you are:

| ID | Name | Possible Values | Input type | Explanation |
|---|---|---|---|---|
| 1 | Material Type | {1,2} | Menu selector | 1: Steel (default) |
| | | | | 2: Aluminum |
| 2 | Size | {1,2,3} | Menu selector | 1: 76.2mm x 76.2mm x 76.2mm (default) |
| | | | | 2: 101.6mm x 101.6mm x 101.6mm |
| | | | | 3: 127mm x 127mm x 127mm |
| 3 | Angular Thickness (ta) | Steel: [10.16mm, 20.32mm] | Numeric input | These ranges are checked when user input is provided. Range shows in red when out-of-range input is provided. |
| | | Aluminum: [17.78mm, 22.86mm] | | |
| 4 | Gusset Thickness (tg) | Steel: [3.81mm, 8.89mm] | Numeric input | These ranges are checked when user input is provided. Range shows in red when out-of-range input is provided. |
| | | Aluminum: [12.7mm, 17.78mm] | | |

**Table 2: List of bracket parameters and possible values.**

### Step 5: Run JobManager

Once the JobManager Configuration window pops up, make sure that Remote Execution is unchecked, then click Run.

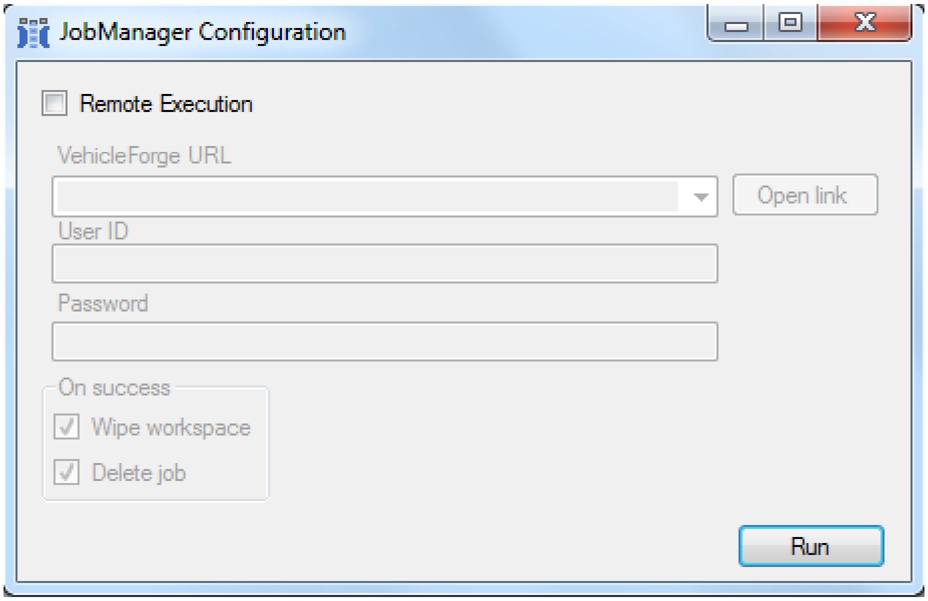



**Figure 8: JobManager Configuration Dialog Box.**

Wait until the JobManager indicates that the test bench has successfully run.

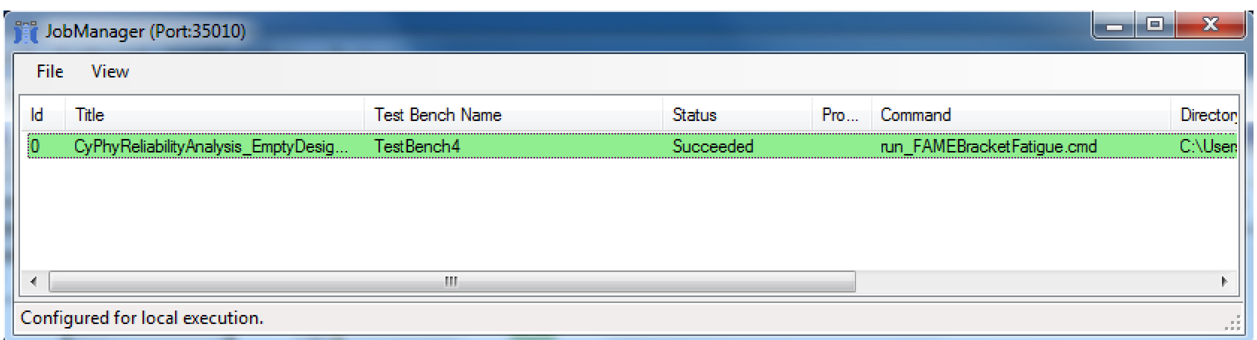



**Figure 9: JobManager Success Notification.**

In order to evaluate several different bracket designs, you can repeat steps 2 through 4, each time selecting a different design configuration and a corresponding bracket configuration. All bracket fatigue computations will be done w.r.t. the Seed Design.

### Step 6: View Dashboard

Once you have run all the configurations that you want to, refresh the Design Space Analyzer Dashboard in the Chrome browser. The browser window opens up on its own. If you have closed it, you can open up the index.html file in the project folder. The Dashboard will load all the configurations run.
The example below shows 4 configurations. The metric values shown are probabilities of fatigue failure after 1200 hours of typical mission usage (Perryman 3 course with obstacles). The metric should be between 0 and 1, with smaller numbers being better.

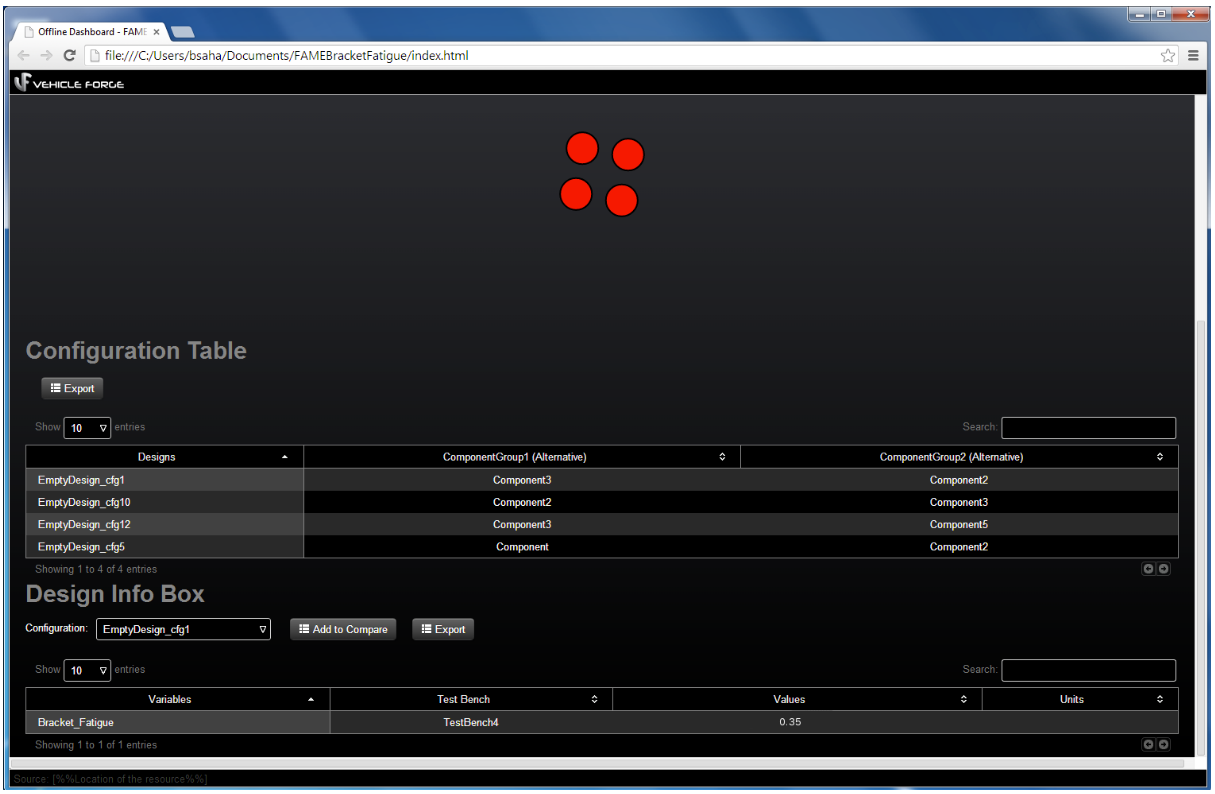



**Figure 10: Design Space Analyzer Dashboard (dummy values shown here).**

You can also select multiple configurations to compare their reliability numbers side-by-side.

## 5.0: Development Path

Currently this tool is meant as a technology demonstration as well as integration exercise with CyPhy. After mid-Gamma, we will extend this capability to custom designed brackets within custom vehicle designs. Where possible, effects of bracket failure will be integrated with dynamics. The focus will be on maturation of this technology and validation.