

2017 Bearcats Baja SAE – Testing and Analysis

A Baccalaureate thesis submitted to the
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Bachelor of Science

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by

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2017 Bearcats Baja SAE – Testing and Analysis

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INTRODUCTION

Abstract

Baja SAE is a collegiate design competition, organized by the Society of Automotive Engineers (SAE), in which seniors build and race a mini Baja car. The cars are powered by a ten horsepower Briggs and Stratton engine that is standard for every team. SAE Baja also fulfills many students' senior capstone project. Baja SAE takes students from the design phase all the way through manufacturing and assembly. A new primary objective for the 2017 team was to design and implement a test plan to test the physical capabilities of the 2016 and 2014 car frame to determine any improvement in structural strength with the new design. As a secondary objective the data analysis will allow for finite element analysis to be tuned to represent the live, non-destructive dynamic testing for future designs.

Problem Statement

The 2016 SAE Baja car frame is to be physically tested to determine potential modes of failure during operation in order to evaluate the structural strength of the design. Dynamic testing will help to determine the capabilities of the frame; while understanding the limits of the frame, the dynamic testing will assist in the re-design of the Baja car to improve the capabilities for future designs. FEA models may be validated and tuned to represent the true structural stresses in the frame for future estimations.

Research

FEA Fixed Geometry

A necessary assumption to be made when calculating stress & deformation estimations using finite element analysis is the fixed geometry of the component. The fixed geometry is a location or locations of the design that experience zero stress and deformation and all other elements deform about. Determining the proper geometries to fix is necessary as improper assumptions lead to false estimations and false data. Considering the application of dynamic testing of the frame, selecting the fixed geometry was a challenge. Ultimately, 8 joint locations were selected as recommended by the SolidWorks Education SAE Frame analysis.

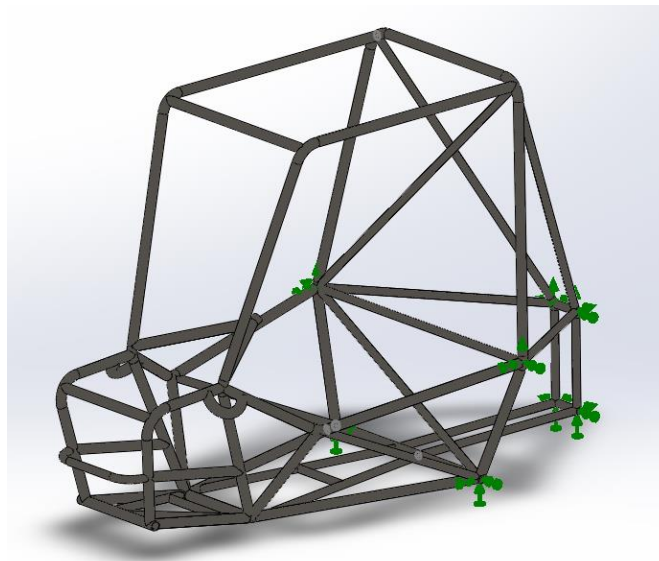


Figure 1 – Fixed Geometry locations selected for analysis. These 8 points were determined via the recommendations by SolidWorks Education SAE

Force & Load Cell Transducers

In order for the structural strength of the Baja frame to be calculated, a force must be introduced into the frame. The tests to be performed on the Baja car are dynamic in nature, and a way to record these forces is necessary to analyze data between the cars and for the tuning of the FEA. In vehicle chassis/frame testing, these force sensors have traditionally been mounted to the suspension. For this application, the upper suspension mounting bolts will be manufactured to record the forces introduced into the frame.

Three forces are to be measured orthogonally in the axial, lateral and vertical directions of the frame.

Design

Bolt Load Cell

To record the forces introduced into the frame, the upper suspension mounting bolts are to be manufactured into load cells. For this application axial, lateral and vertical forces are desired as the car operates in a three-dimensional space. Since strain gauges measure the strain across the grid of the film, the actual forces need to be calculated using a derived equation.

$$\sum F = F_X + F_Y + F_Z$$

Analysis only considers tension and compression of the bolt $\therefore F_Y \& F_Z = 0$

$$\therefore \sum F = F_X$$

$$\sum M = M_X + M_Y + M_Z$$

Analysis does not consider bolt torque $\therefore M_X = 0$

$$\therefore \sum M = M_Y + M_Z$$

Using the relationships:

$$\sigma_{tensile} = \frac{F_X}{A_{bolt}} \quad \& \quad \sigma_{bending} = -\frac{1}{I} x [(c_Y * M_Z) - (c_Z * M_Y)]$$

$$\sigma_{total} = \sigma_{tensile} + \sigma_{bending} = \frac{F_X}{A_{bolt}} + \frac{c_Y * M_Z}{I} - \frac{c_Z * M_Y}{I}$$

Using matrix algebra:

$$\sigma_T = \begin{bmatrix} \frac{1}{A_{bolt}} & \frac{c_Y}{I} & -\frac{c_Z}{I} \end{bmatrix} * \begin{bmatrix} F_X \\ M_Z \\ M_Y \end{bmatrix}$$

Using the equation derived for total stress, it is possible to calculating the force in the axial direction, and the moments about the lateral and vertical axis. Considering the objective, three outputs are desired. So, this equation must be applied three times for

three separate instances. As such, three strain gauges are required. For this design, three strain gauges are to be placed 120° apart around the circumference of the bolt. The three orthogonal axes can be defined using this method.

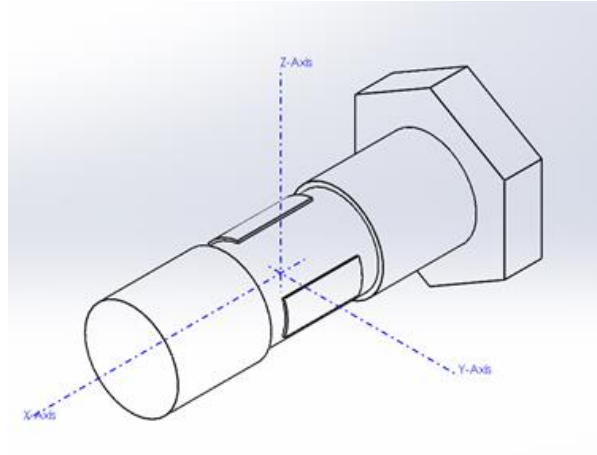


Figure 2 – Bolt force sensor design. Squares on the bolt represent strain gauges and axes can be defined.

Applying the equation for total stress three times:

$$\begin{bmatrix} \sigma_{T,1} \\ \sigma_{T,2} \\ \sigma_{T,3} \end{bmatrix} = \begin{bmatrix} \frac{1}{A_{bolt,1}} & \frac{c_{y,1}}{I} & -\frac{c_{z,1}}{I} \\ \frac{1}{A_{bolt,2}} & \frac{c_{y,2}}{I} & -\frac{c_{z,2}}{I} \\ \frac{1}{A_{bolt,3}} & \frac{c_{y,3}}{I} & -\frac{c_{z,3}}{I} \end{bmatrix} * \begin{bmatrix} F_X \\ M_Y \\ M_Z \end{bmatrix}$$

Letting G equal the matrix of constants:

$$G = \begin{bmatrix} \frac{1}{A_{bolt,1}} & \frac{c_{y,1}}{I} & -\frac{c_{z,1}}{I} \\ \frac{1}{A_{bolt,2}} & \frac{c_{y,2}}{I} & -\frac{c_{z,2}}{I} \\ \frac{1}{A_{bolt,3}} & \frac{c_{y,3}}{I} & -\frac{c_{z,3}}{I} \end{bmatrix}; \text{ where } c_Y \text{ \& } c_Z = r_{bolt}$$

Finally:

$$\begin{bmatrix} F_X \\ M_Y \\ M_Z \end{bmatrix} = G^{-1} * E * \begin{bmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \end{bmatrix}$$

Using the derived equation with three strain inputs, it is possible to calculate the force in the axial direction and the moment about the lateral and vertical axes. Assuming the bolt is constrained by the mounting tabs, and the distance from the measurement point

and the tab constraint, the lateral and vertical forces can be calculated using the relationship $Force = Moment / Distance$.

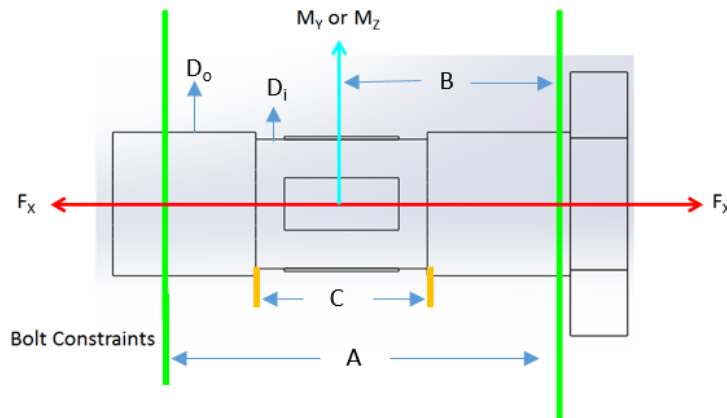


Figure 3 – Dimensional guide for the dimensions of a bolt

Where:

Bolt Gauging				
	2014 Car		2017 Car	
	Rear	Front	Rear	Front
Size:	5/16 - 18 x 2	3/8 - 16 x 2.25	M8 x 65	3/8 - 16 x 2.25
Dim A (in):	1.275	1.170	1.750	1.170
Dim B (in):	0.638	0.585	0.875	0.585
Dim C (in):	0.625	0.625	0.625	0.625
D _o (in):	0.309	0.371	0.308	0.371
Rad. Removed (in):	0.030	0.030	0.030	0.030
D _i (in):	0.249	0.311	0.248	0.311

Figure 4 – Dimension for each bolt. The dimensions correlate to figure 3

Dimension “A” is the distance between the mounting tabs, dimension “B” is half of dimension A, also the center of the strain gauge and dimension “C” is the length of the material removed from the bolt later described in the manufacturing process.

As a secondary measurement to measure the forces in the frame, a PCB accelerometer was used to measure the G’s of acceleration in the axial, lateral and vertical directions. The accelerometer will be placed in under the driver seat, which provides protection from the elements.

Finite Element Analysis & Strain Gauge Locations

Finite Element Analysis (FEA) was used to determine the locations of high stress. As discussed in the research section, 8 points were selected for the fixed geometry. The FEA estimations that resulted from this fixed geometry provided 12 unique locations, 6 symmetrically on the left and right side of the car.

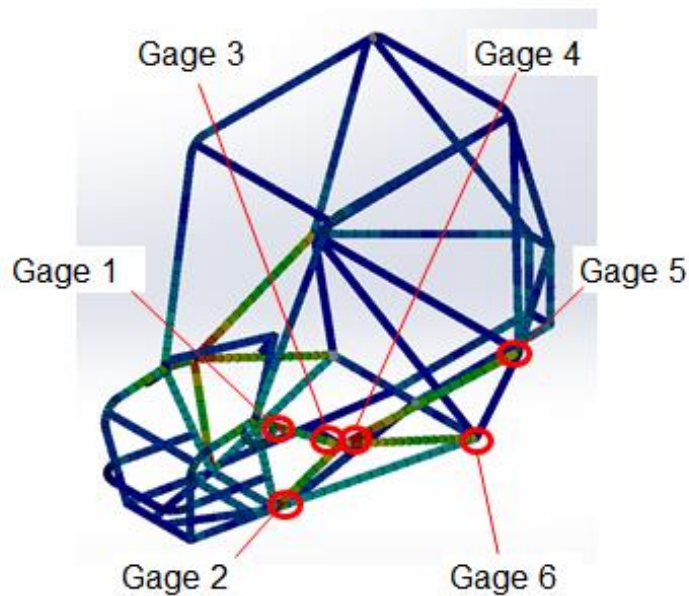


Figure 5 – 6 strain gauge locations on the left side of the frame. 6 are equivalently placed on the right side of the frame for a total of 12 unique locations.

The force inputs were considered at 3 G's, as the estimation results proved to be non-destructive. The force inputs were applied at 15° for an assumption, as if the car were dropping from a platform. This turned out to be an accurate assumption.

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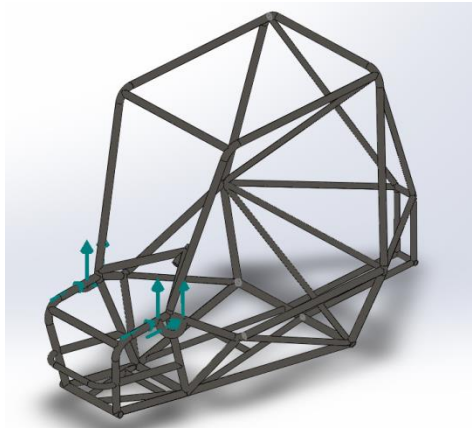


Figure 6 – Forces applied to the frame are vertically and axially applied. 3G's were applied at 15 degrees.

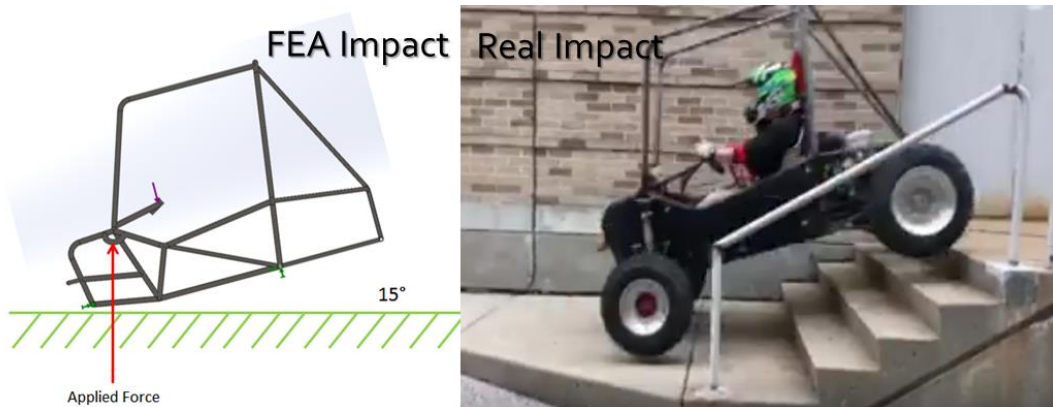


Figure 7- Comparison of the angle of force application that was assumed to an actually 3 foot drop

Data Acquisition Equipment

In order to record the data, the Somat eDaq data recorder was used. Considering the application, the Baja car requires a data recorder that has a sealed enclosure to protect the sensitive hardware from terrain debris: mud, water, dirt, rocks, sticks and other contaminants on the ground that are shot into the vehicle cab. The Somat eDaq fits this first major requirement, while also capable of high channel synchronous recording capabilities. The test plan detailed required at least 24 strain channels to be recorded at once, and the Somat eDaq provides the capabilities to record this as well as many more should more data be required for more phases of testing. The Somat eDaq intelligently stores the recorded data so that data processing and data analysis is much more organized. The software used in this application was Test Control Environment (TCE) v3.90. Other than initially starting the test, the Somat eDaq unit is stand-alone in that it requires no assistance to measure and record data other than a power source.

Manufacturing

Bolt Load Cell

The bolt load cells were manufactured by removing material around the circumference around the bolt. This provided clearance for the strain gauge to be epoxied to the bolt and to be wired, without the application of the bolt interfering with the measurements of the strain gauge. It was determined to remove 0.030" of material from the bolt, as this was the most material that could be removed from the bolt while ensuring that the bolt diameter was greater than the ANSI specified minor diameter. Slots were also cut into the bolt heads so that the wires could be run through the head and not get pinched off once the bolt was installed to mount the suspension.

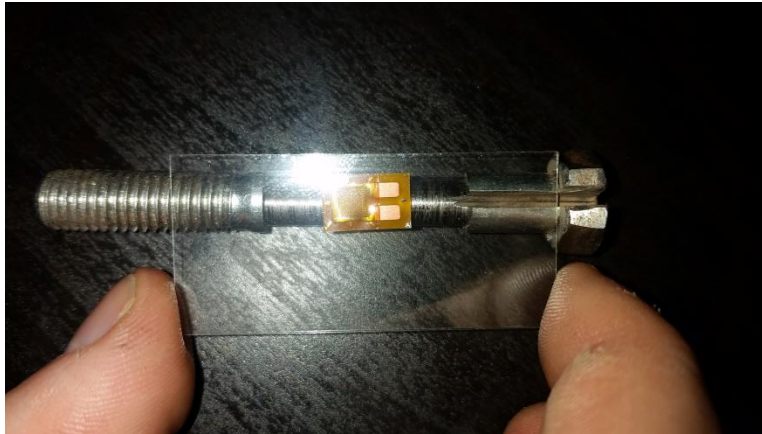


Figure 8 – Example of the manufactured bolt

Strain Gauge Application

The strain gauge locations highlighted in the FEA needed to be prepared before the strain gauge was epoxied down. Using 120 grit sandpaper on a Dremel, the paint was removed until the bare metal was shown in each location. Once the bare metal was available, 320 grit and Micro-Measurements Conditioner A were used to sand in circular patterns for approximately 1-2 minutes per location as further prep. For the final surface preparation, Micro-Measurements Neutralizer 5A was used before bonding. This is the recommend surface preparation for steel surfaces. Once a surface was prepared, the strain gauge was located and oriented before it was epoxied. After the strain gauge is located, Micro-Measurements Catalyst-C was applied the surface and strain gauge and allowed to dry for 30 seconds. Once the catalyst dries, Micro-Measurements M-Bond 200 adhesive is applied to the strain gauge. The strain gauge is then immediately

applied to the prepared surface and then cures under slight finger pressure and head for 2 minutes. Once the strain gauge is bonded, Micro-Measurements Gagekote # 8 is applied to the strain gauge surface to protect it. 30 gauge lead wire is soldered to the strain gauge and runs to the data recorded.

Conclusions

Final Conclusions

Initially, the test plan was very strong in design. All key locations had strain gauges applied, and the force sensors were going to work in theory. However, with the failure of the bolt force sensors, the testing plan fell through. The secondary method of recording force with the accelerometer provide data, however, the data was not accurate. 12 g's was recorded at one point, and if a 12 g force was actually applied to the frame, it would fail catastrophically. So, it was impossible to develop a trend line between the forces the car frame experiences vs the structural stresses seen. The accelerometer placed on the 2014 car failed and provided very inaccurate data, so even a comparison between the 2016 and 2014 frame was impossible with a common variable.

With testing time limited to less than a week, adjusting the test plan was an impossible task, so the initial test plan was pushed forward.

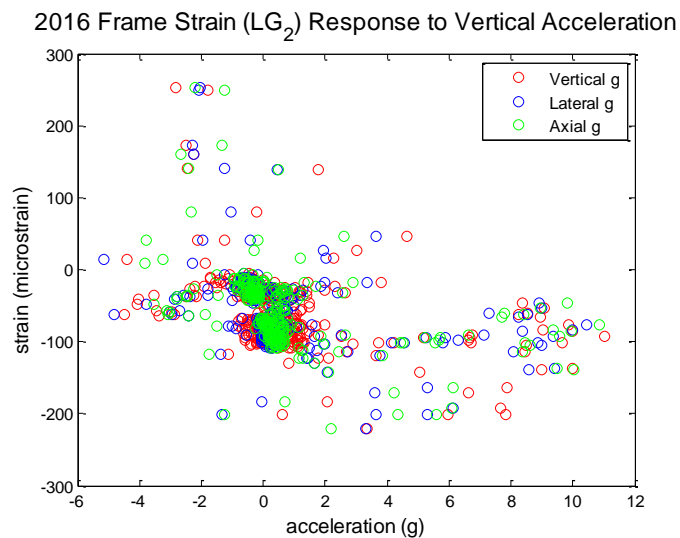


Figure 9 – Example of a strain vs acceleration plot. Poor response is seen as no trend can be determined in this scatter plot.

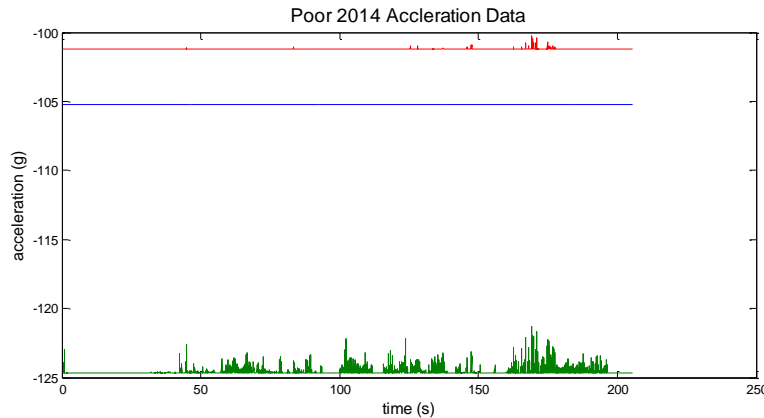


Figure 10 – Data plot of the failed accelerometer

Recommendation – Force Transducer/Load Cell

Unfortunately, the force sensing bolt design failed in the end. The strain gauges purchased for the experiment were too large to have three strain gauges placed around the circumference of the bolt. With no time to correct this issue and purchase smaller strain gauges, this design idea was scrapped in order to record data. The secondary force sensor, the accelerometer, needed to perform the function of measuring force data. As discussed in the final conclusions, this idea was also flawed. The measurement in g's is not a proper way to create a trend line, as can be seen in Appendix A, which contains the data. The dynamic testing experiment is highly reliant on a proper force sensor, and without it, the strain data means practically nothing for the application.

For future testing iterations, a major focus on a working force sensor is necessary. As a subsidiary, the entire car needs to complete before dynamic testing occurs. For this experiment, the car was extremely late in being complete so testing was rushed with no time to fix this issue.



Recommendation – Strain Gauges & FEA

Strain gauges have the inherent problem of only measure the strain located on the grid of the strain gauge – a small area. If the strain gauge is misplaced by even 1 millimeter, the strain measurement could results in data that is much smaller than the physical model experiences. If the FEA simulations are not precise enough, the strain gauge

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locations are not optimized. This occurred majorly in this application, as the FEA was not precise enough.

The FEA meshing considered the elements around the entire circumference around the tubing, rather than individual elements on the tubing itself. Stronger FEA software, better user knowledge of FEA and stronger processing hardware could provide much more accurate FEA simulations to determine more precise strain gauge locations.

In the figure below, the strain gauge is much smaller than the FEA elements. This caused a major flaw in the actual placement of the strain gauge, even if the location was close according to the FEA.



Figure 11 – Demonstration of strain gauge size vs FEA element size

Recommendation – Static Testing

This test plan determined that dynamic testing should be used to validate the FEA. For future testing, it is recommended that static testing is performed on the frame in order to validate the FEA. Static testing is much more controlled, rather than being reliant on the terrain that the car is being tested on. With the control the static testing has available, the FEA can be tuned much more accurately.

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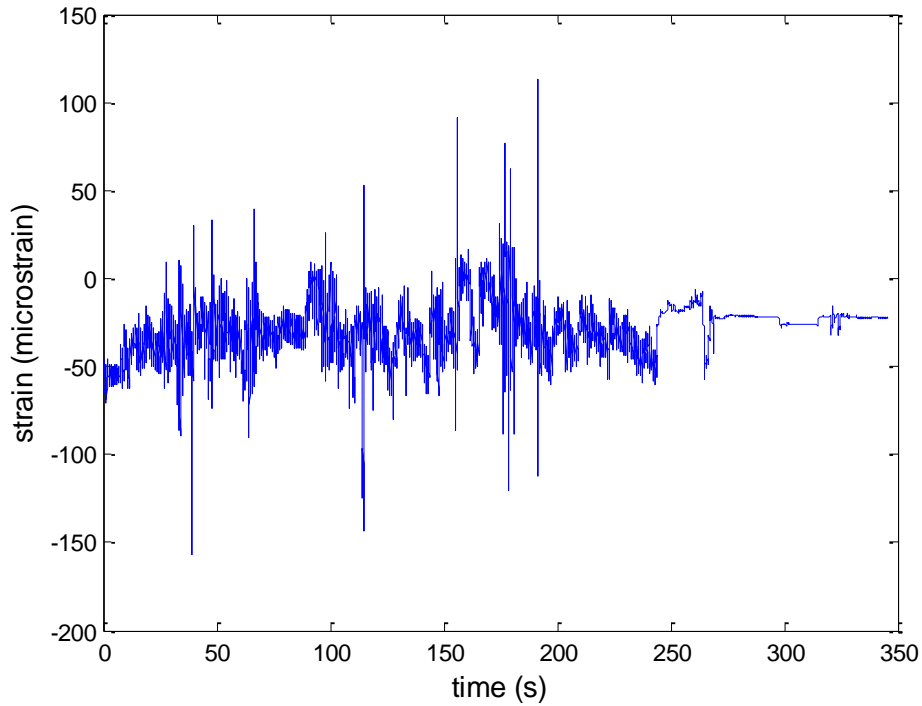
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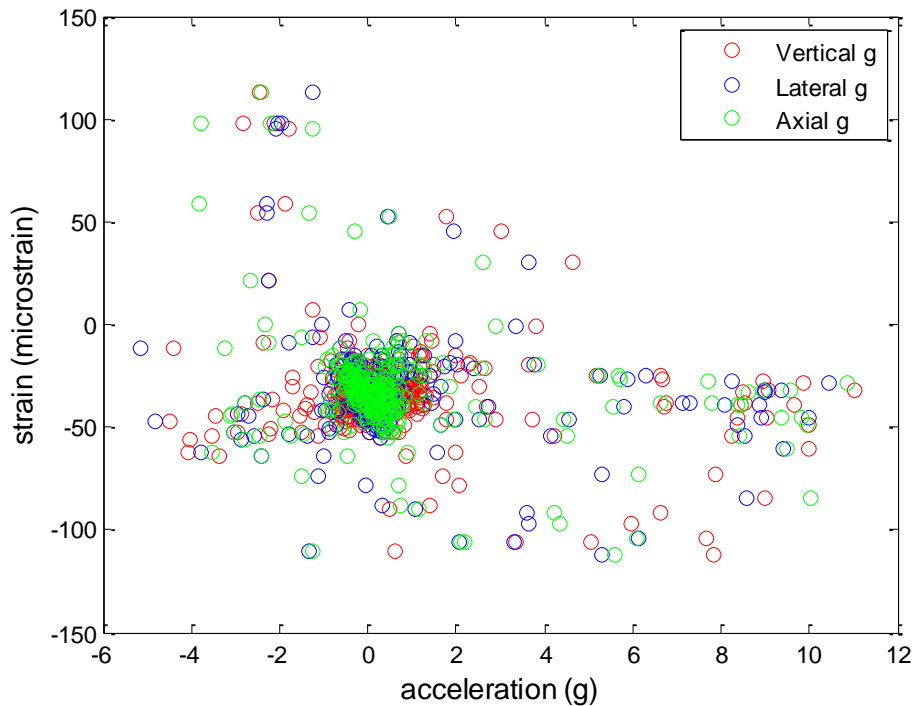
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APPENDIX A – Data, Strain vs Force plots

2016 Frame Strain (LG₁) Response



2016 Frame Strain (LG₁) Response to Vertical Acceleration

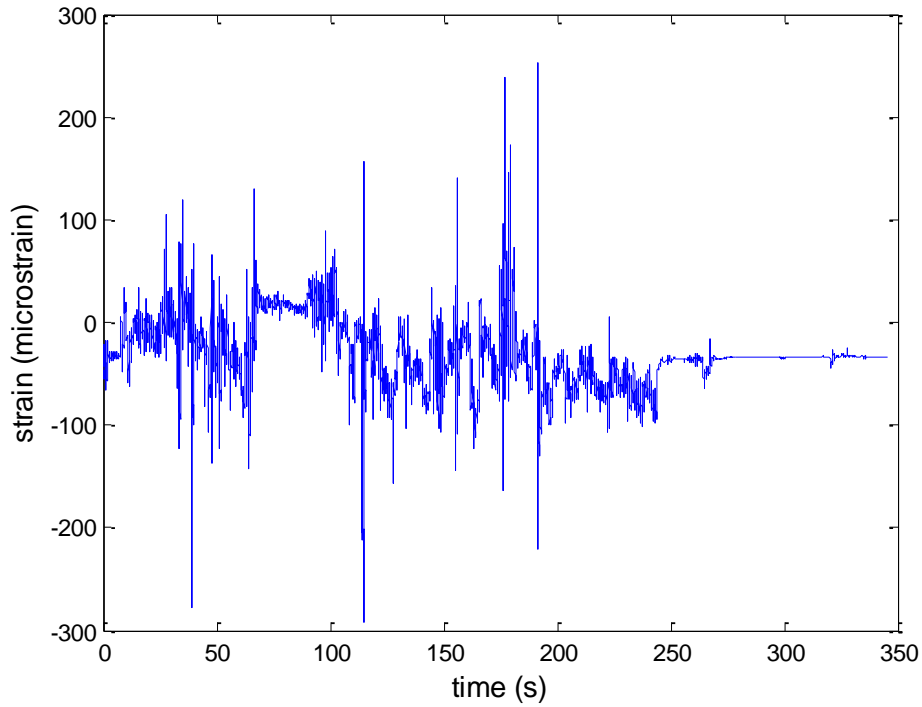


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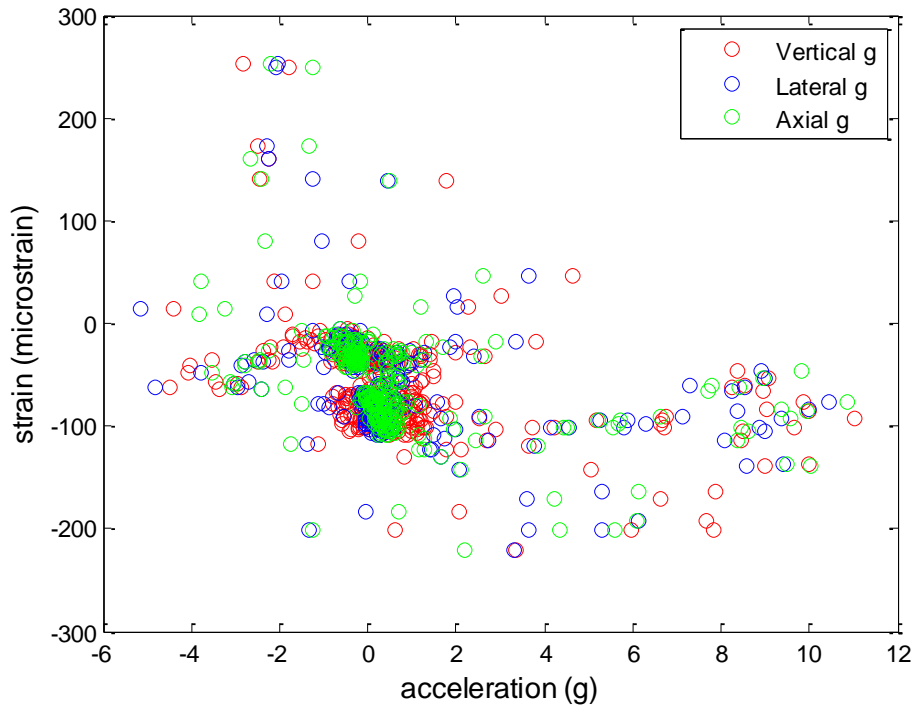
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2016 Frame Strain (LG₂) Response



2016 Frame Strain (LG₂) Response to Vertical Acceleration

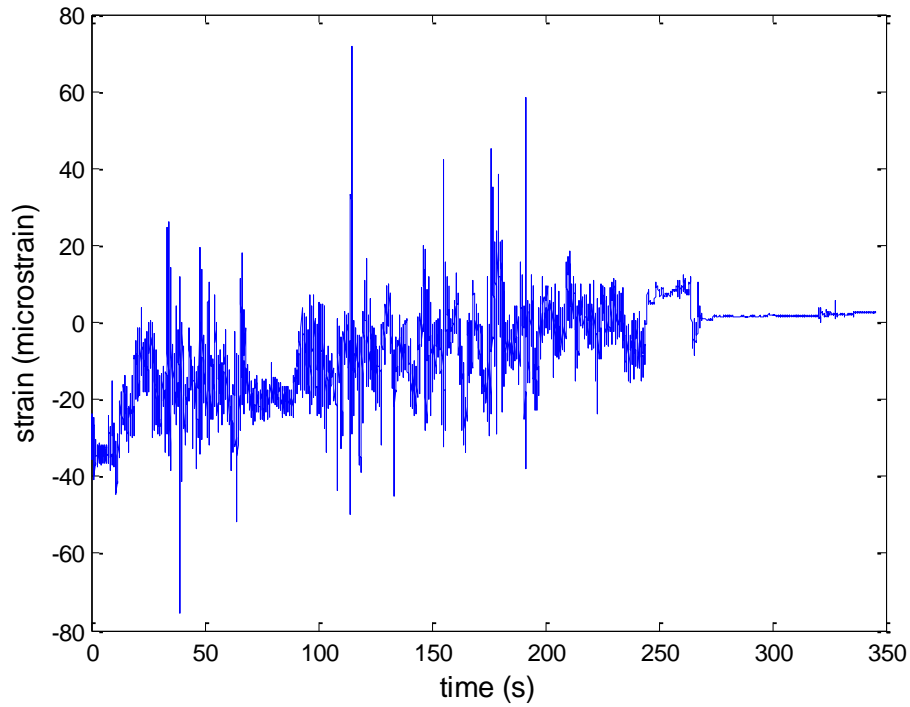


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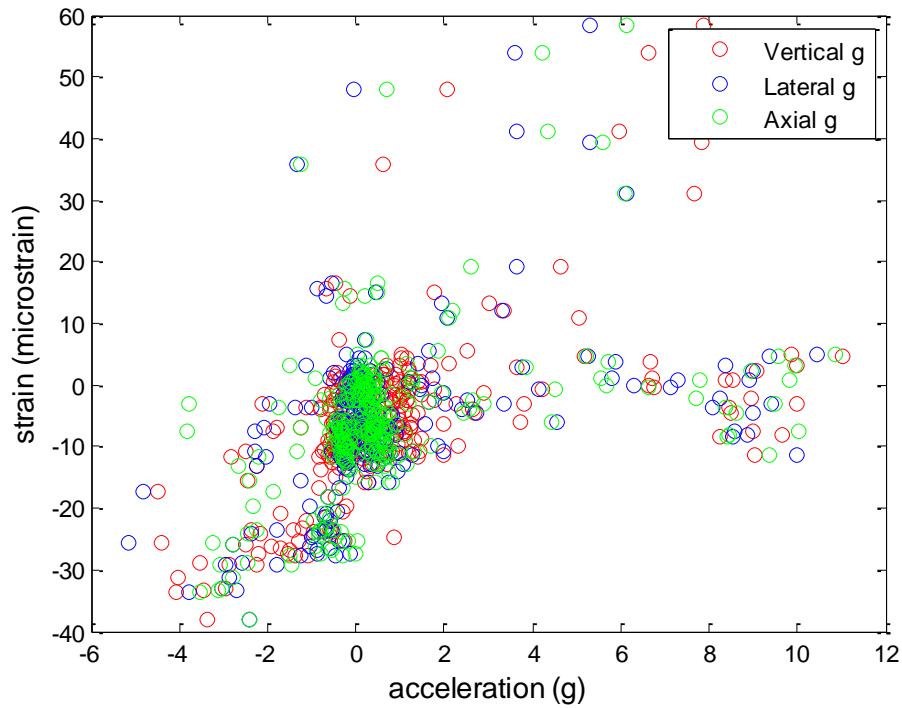
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2016 Frame Strain (LG₃) Response



2016 Frame Strain (LG₃) Response to Vertical Acceleration

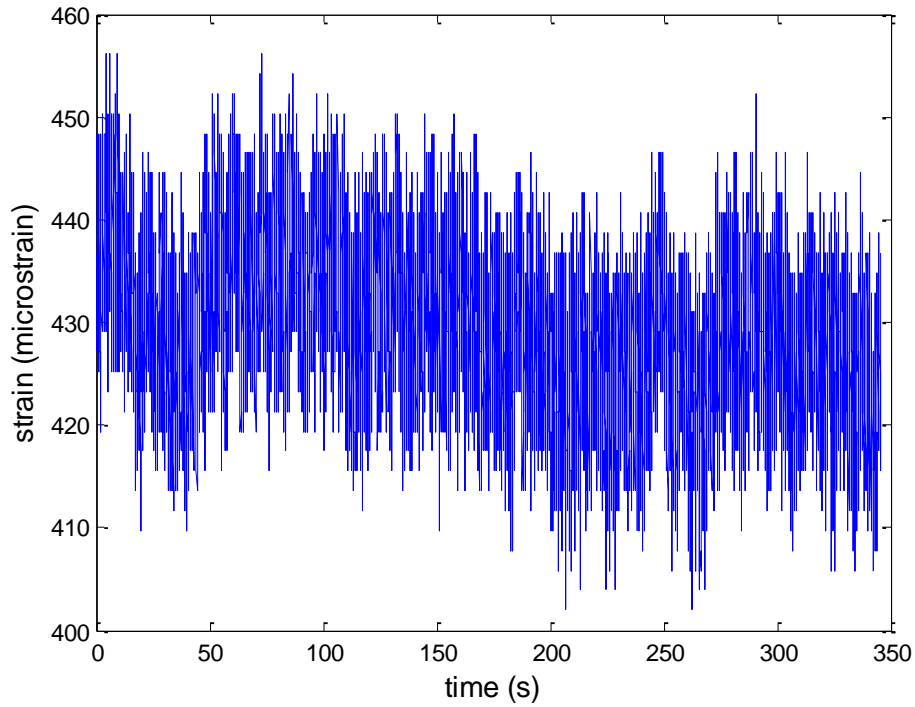


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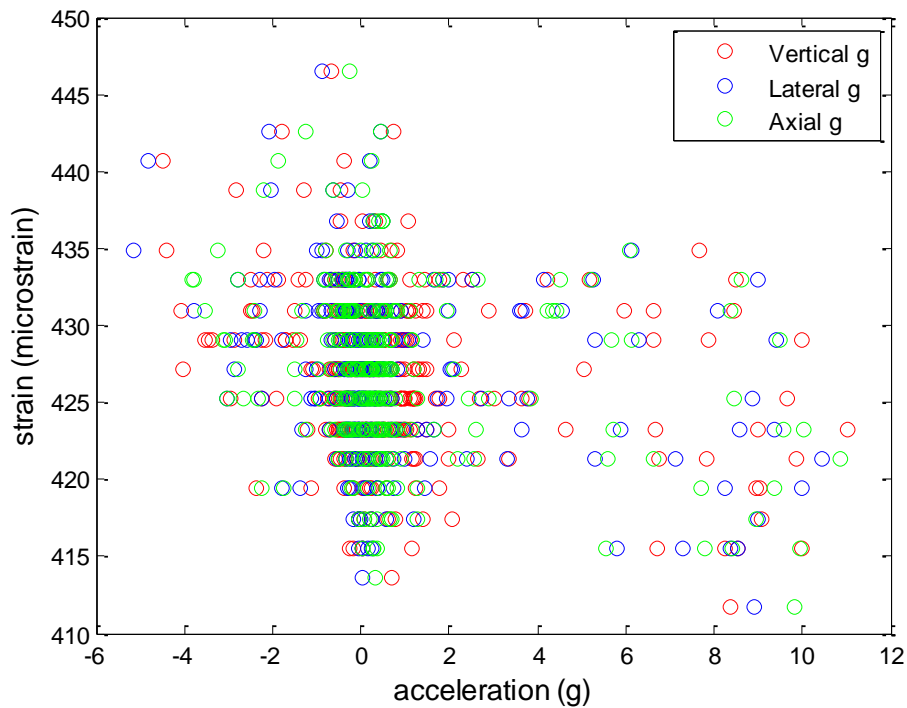
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2016 Frame Strain (LG₄) Response



2016 Frame Strain (LG₄) Response to Vertical Acceleration

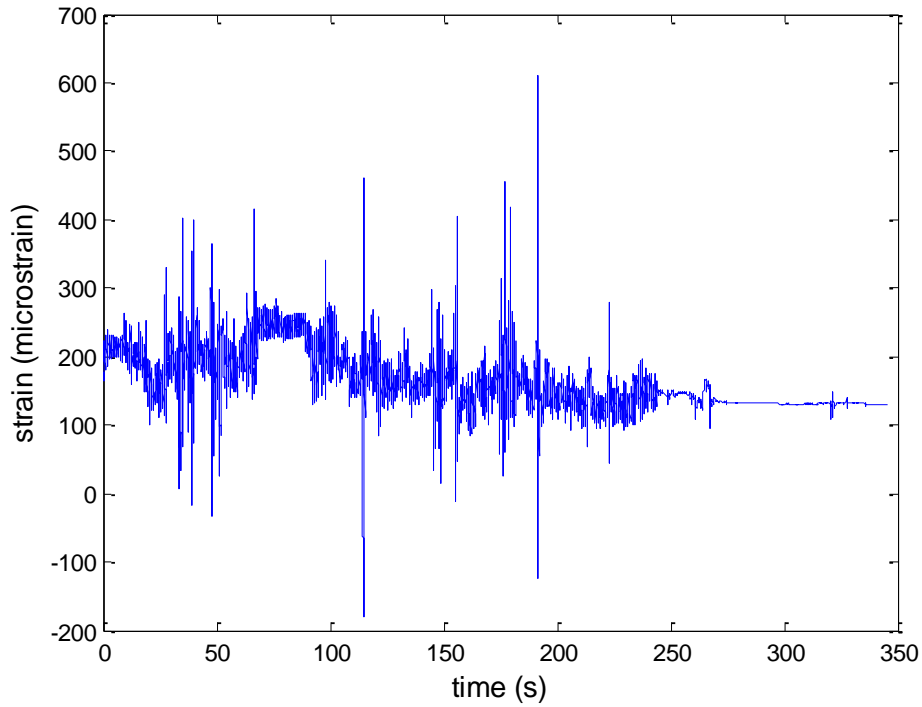


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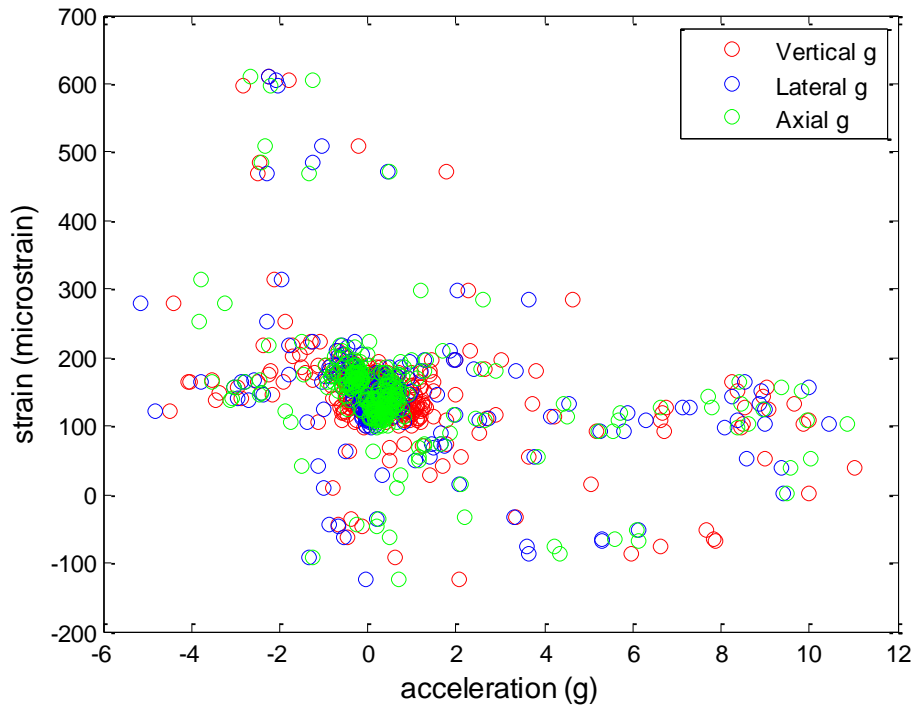
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2016 Frame Strain (LG₅) Response



2016 Frame Strain (LG₅) Response to Vertical Acceleration

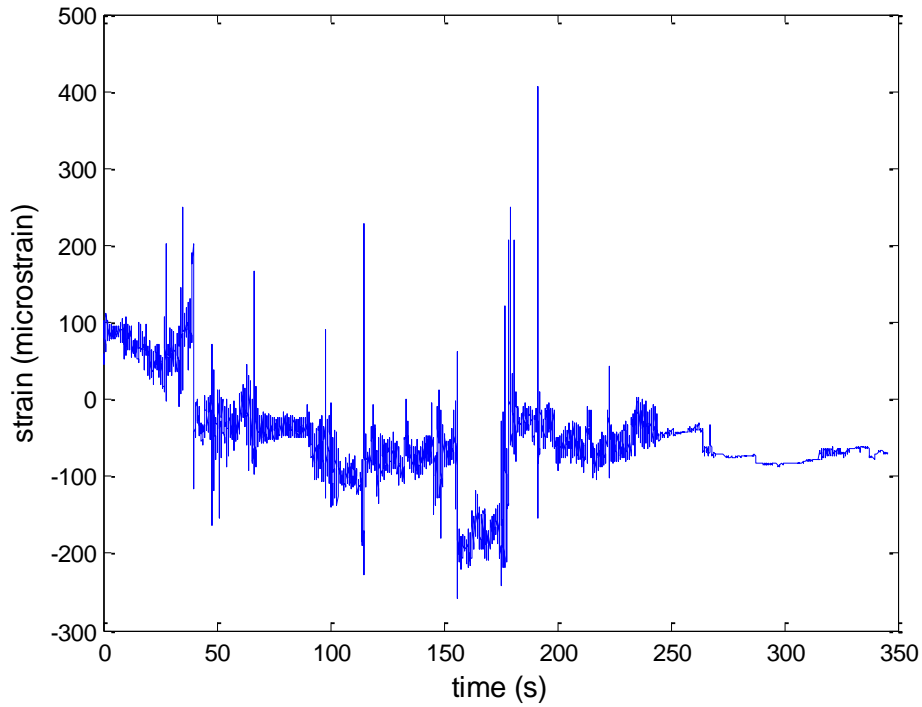


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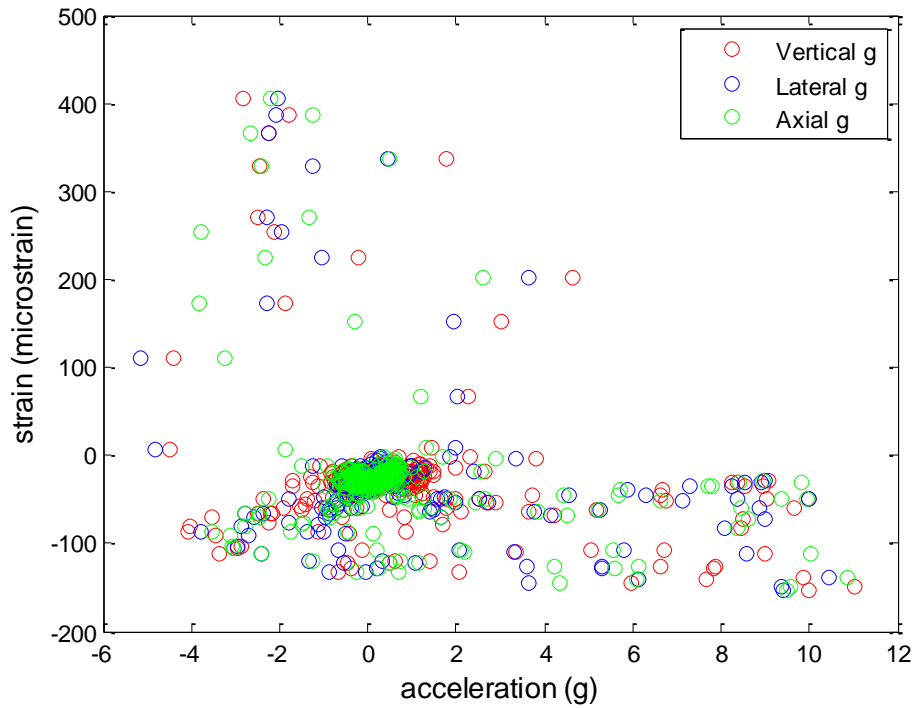
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2016 Frame Strain (LG₆) Response



2016 Frame Strain (LG₆) Response to Vertical Acceleration

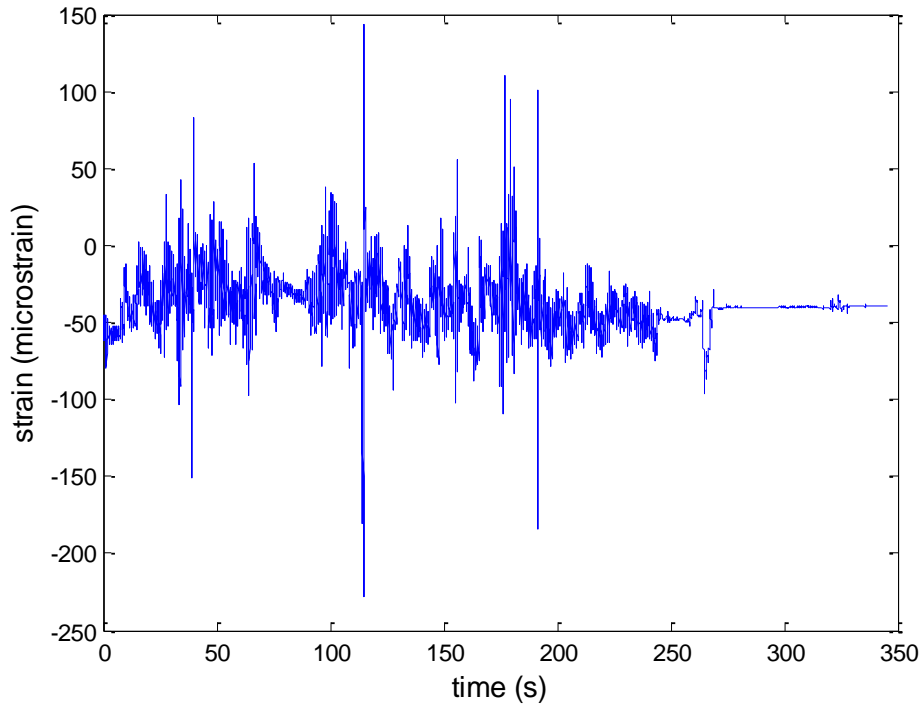


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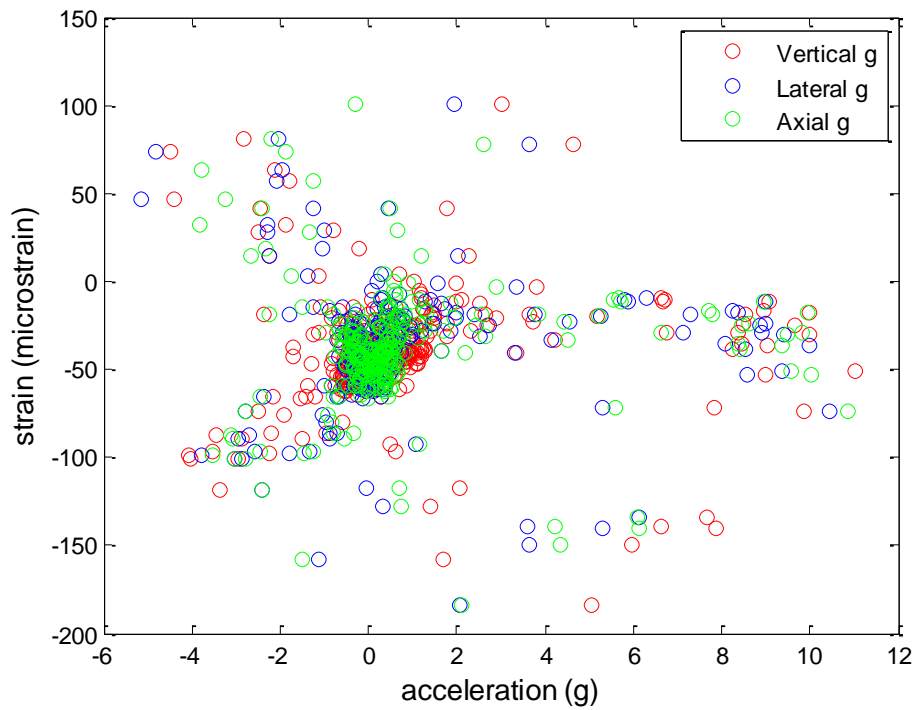
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2016 Frame Strain (RG₁) Response



2016 Frame Strain (RG₁) Response to Vertical Acceleration

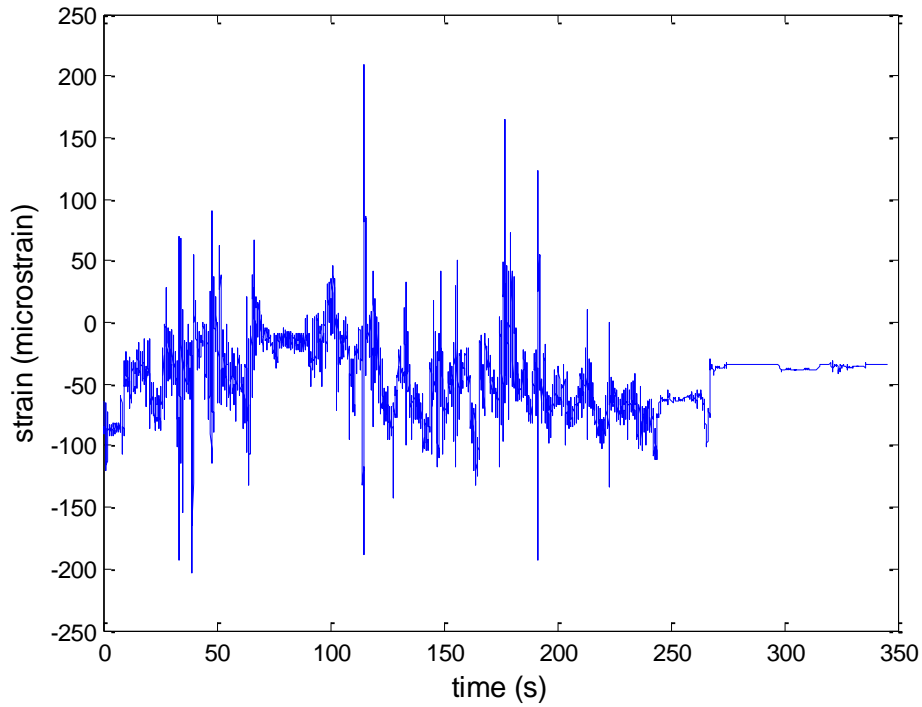


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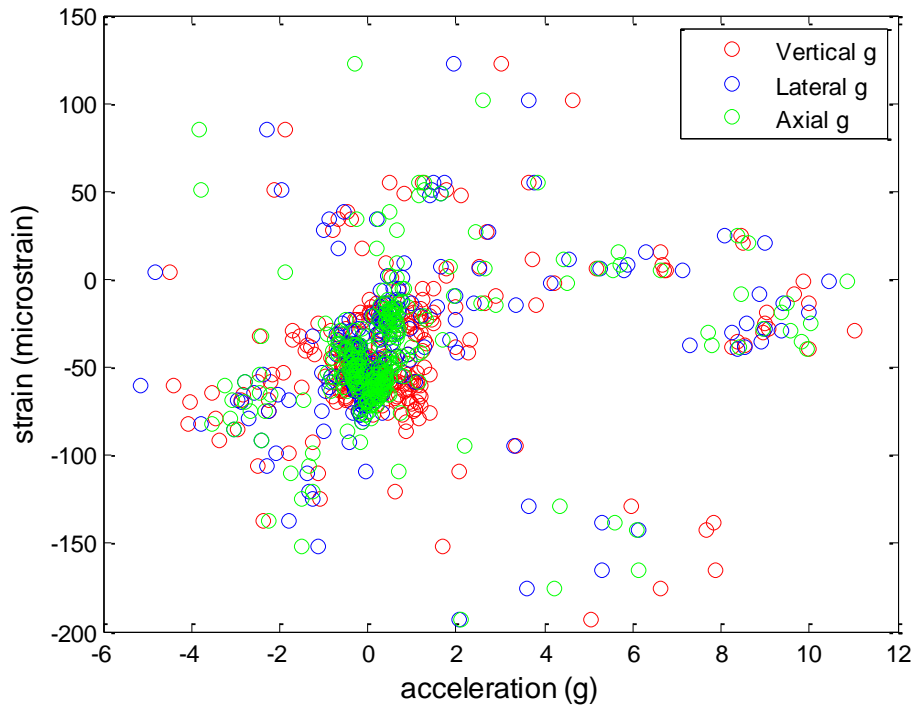
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2016 Frame Strain (RG₂) Response



2016 Frame Strain (RG₂) Response to Vertical Acceleration

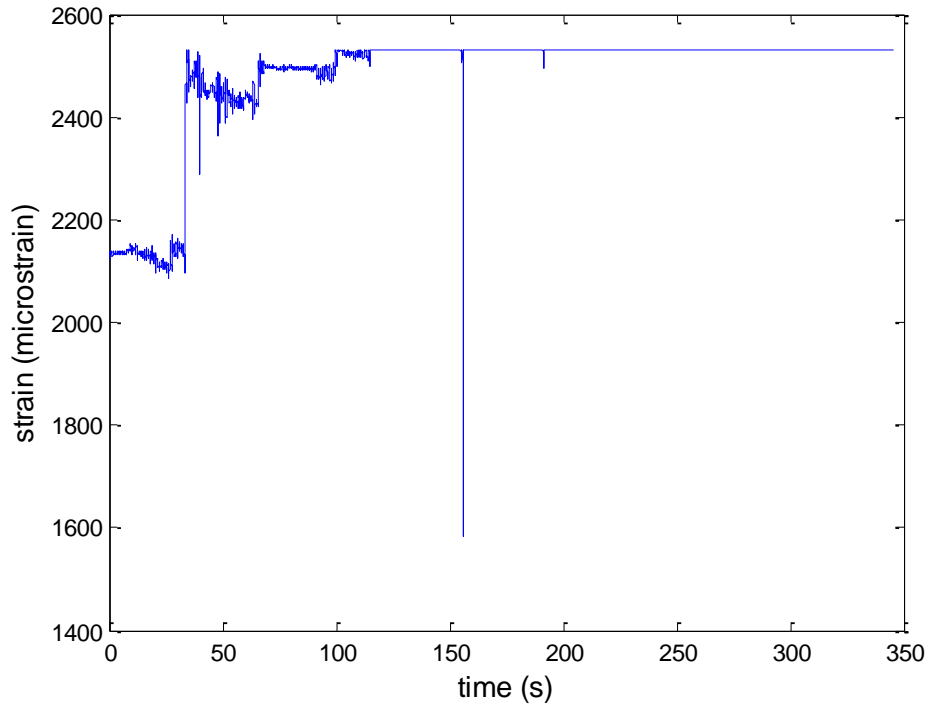


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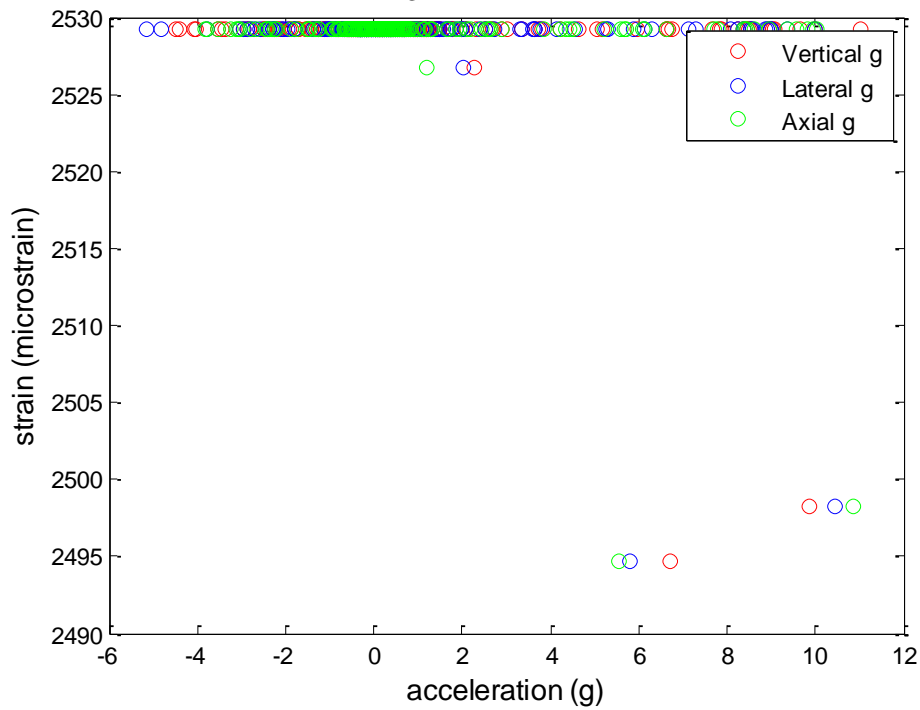
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2016 Frame Strain (RG₃) Response



2016 Frame Strain (RG₃) Response to Vertical Acceleration

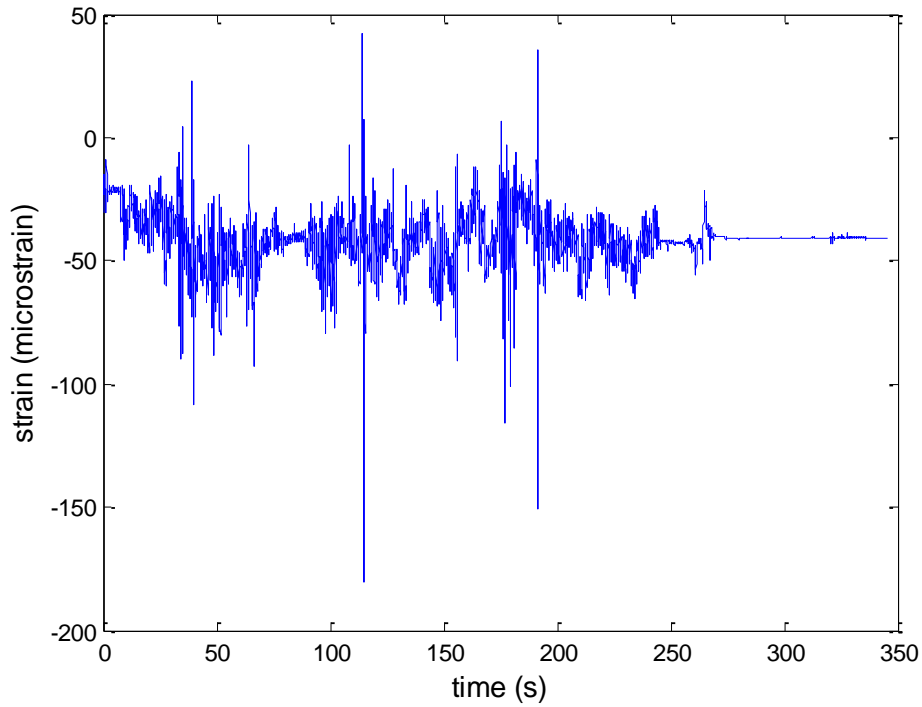


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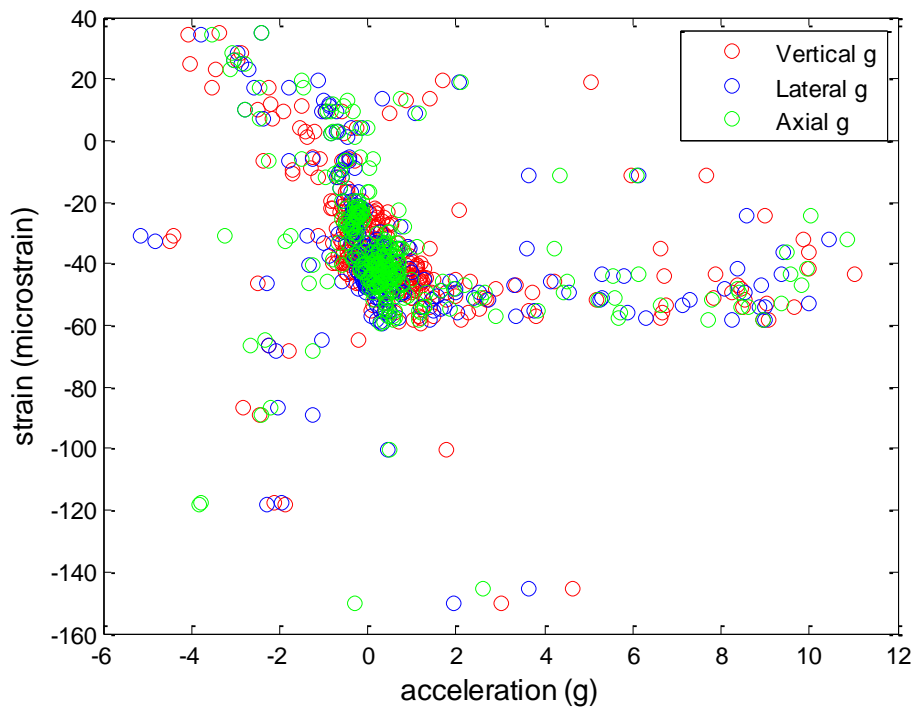
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2016 Frame Strain (RG₄) Response



2016 Frame Strain (RG₄) Response to Vertical Acceleration

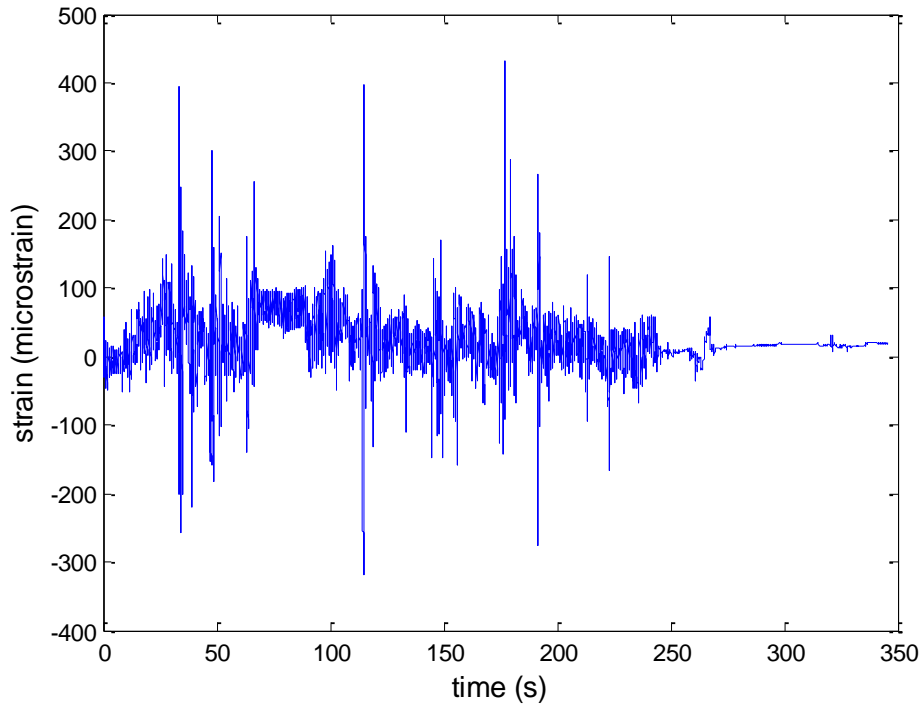


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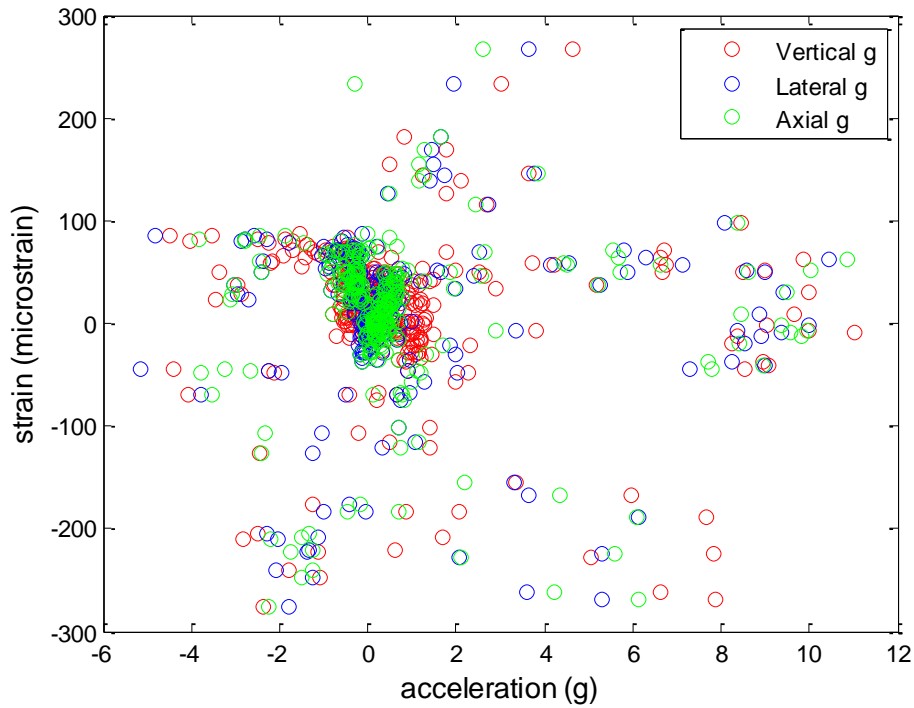
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2016 Frame Strain (RG₅) Response



2016 Frame Strain (RG₅) Response to Vertical Acceleration

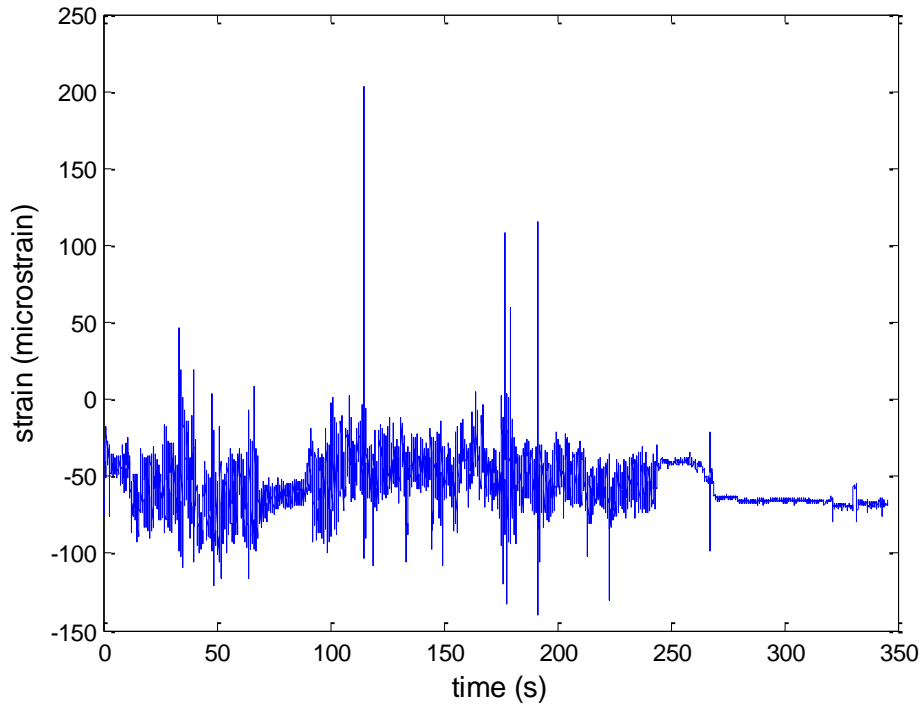


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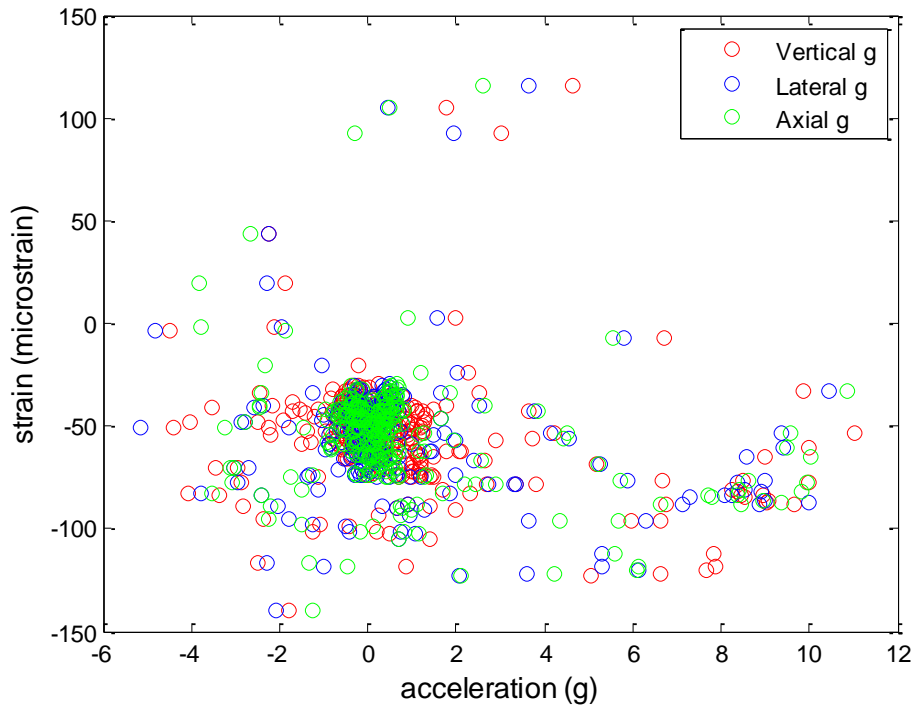
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2016 Frame Strain (RG₆) Response



2016 Frame Strain (RG₆) Response to Vertical Acceleration



APPENDIX B – Data Recording Equipment



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APPENDIX C – Budget & Strain Gauge Count

Frame Gaging Count				
		1 Car		
		Minimum	Moderate	Maximum
2 Cars	None	9	24	36
	Minimum	18	33	45
	Moderate	33	48	60
	Maximum	45	60	72

Frame Gaging Budget				
		Car 1		
		Minimum	Moderate	Maximum
Car 2	None	\$ 119.98	\$ 299.95	\$ 479.92
	Minimum	\$ 239.96	\$ 419.93	\$ 539.91
	Moderate	\$ 419.93	\$ 599.90	\$ 719.88
	Maximum	\$ 539.91	\$ 719.88	\$ 899.85