Use of Abaqus/CAE and True-Load^{TM} to Determine External and Internal Loading of a Full Suspension Mountain Bicycle

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***Abstract**: Trek Bicycle Corporation has long been at the leading edge in the bicycle industry. Treks bicycles are subjected to the most rigorous testing in the industry and their frames are covered by a lifetime warranty. To maintain the highest level of safety and quality, real world loads need to be properly understood. Trek Factory Racing professional athletes are pushing that understanding; most recently attempting a front flip across a 72 foot canyon. The loads generated for such an event are certainly beyond current understanding and testing protocols.*

A process using Abaqus and the True-Load™ plug-in (Wolf Star Technologies) will be presented that effectively converts a full-suspension mountain bicycle into a load transducer. A fully instrumented Trek Aluminum Session 29er mountain bike (strain gauges, accelerometer, shock sensors, GPS, etc…) is used with high speed video to record a high load event. These data, in conjunction with the Abaqus / True-Load™ process, are used to determine the external loads on the bicycle. A comparison of laboratory testing loads to the external loads is made. The implementation of the Abaqus / True-Load™ process increases Treks knowledge of loading environments and aligns with Treks history of innovation and reliability.

***Keywords**: Abaqus CAE, True-Load™, Bicycle, External Loads, Internal Loads, Experimental Verification*

1. Introduction

Trek Bicycle Corporation has long been at the leading edge in the bicycle industry. Treks' bicycles are subjected to the most rigorous testing in the industry and their frames are covered by a lifetime warranty. To maintain the highest level of safety and quality, real world loads need to be properly understood. Trek Factory Racing professional athletes are pushing that understanding; most recently attempting a front flip across a 72 foot canyon, see *Figure 1*. The loads generated for such an event are certainly beyond current understanding and testing protocols.

The closet industry test requirements (Ref. ISO 4210-6, Annex C) to this event load the rear of the bicycle to 2800 N to ensure safety. Trek performs a similar laboratory test that goes above and beyond this test (minimum required load before failure is 5338 N (1200 lb)) and additionally tests the bicycle to failure, see *Figure 2*. We believe these tests neither load the frame to the level of professional riders nor in the same manner.

Figure 1. Trek professional mountain bike rider, Tom van Steenbergen, tries to front flip the 72-foot canyon gap at Red Bull Rampage (October 2014).

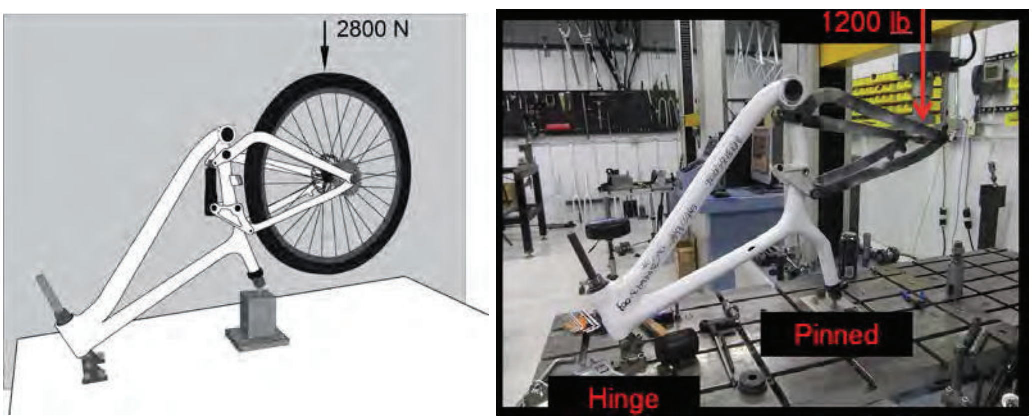

Figure 2. SS-EN ISO 4210-6 Tire clearance test and the Trek DOP test configurations.

The goal of this work is to develop a process using Abaqus/CAE and the True-Load^{TM} plug-in (Wolf Star Technologies) that can quantify the loads created in the field during extreme use cases. These data can then be compared to current laboratory tests, used to develop new laboratory tests, or modify existing ones.

2. Finite Element Model

The test platform is a production Session 29er Aluminum bicycle and is modeled in Abaqus/CAE using solid (C3D10) and shell (S8R) elements. All shell elements are constant thickness even though the tubing of the bicycle is butted. The tapered sections of these tubes have a thickness equal to the average thickness of the tubing through that region. Several portions of the bicycle are modeled as aluminum solids and are indicated by the green elements in *Figure 3* below. The rocker link is model using solid elements as well but is made from Magnesium AZ90 alloy.

Note that during the event time of interest, see discussion in Section 4, the suspension system is under a relatively constant state equal to 140 mm of front fork compression and a fully compressed rear shock. The front fork is idealized using beam (B31) elements and the rear shock using connector elements. The rear end of the bicycle is oriented such that the rear shock is in the fully compressed configuration.

Tie constraints are used to model welds, load transfer from the fork to frame, and at frame pivots. The connections of the parts, i.e. rocker link to the main frame, are modeled using connector elements. Beam, link, and hinge connectors are used throughout the finite element model (FEM) depending upon the application.

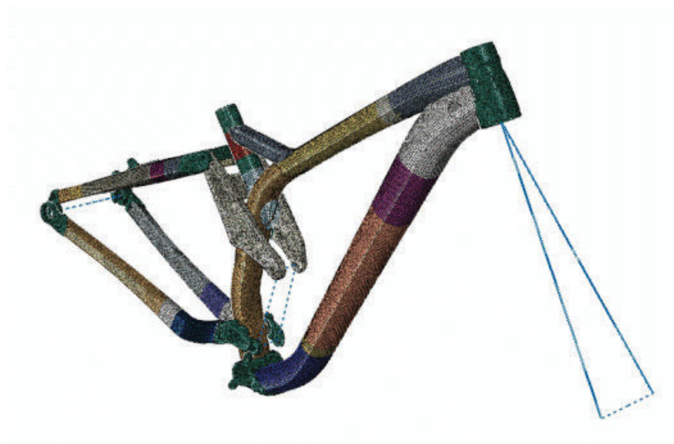

Figure 3. Aluminum Session 29er finite element model.

FEMs of the wheel and tire system have not yet been developed and, therefore, have not been included. As such, boundary conditions are applied to the center of the rear and front dropouts. At the rear all degrees of freedom (DOF) are held fixed except rotation about the axle. At the front all DOF are held fixed except rotation about the axle and movement in the FWD/AFT direction.

A set of assumed unit load cases were applied at the center of the bottom bracket (BB) and at the left hand side handle bar locations. The objective of the unit load cases are to allow the FEM to be placed in a multitude of independent strain states that True-Load^{TM} can amplify and combine in such a way as to match the strains produced in the field. The initial set of unit loads at the BB included all force directions (X, Y, and Z) and moments Mx and My. The initial set of unit loads at the handle bar (HB) included all force directions and moments Mx and Mz. The set of unit loads were subsequently reduced during the FEM refinement stage of the analysis where the model and its boundary conditions and unit loads are iterated until an acceptable level of strain correlation is reached.

2.1 True-Load^{TM}

True-Load™ is a set of Abaqus/CAE plug-ins that essentially turns any structure into its own load transducer. The Wolf Star True-Load™ construct creates a mathematical relationship between user supplied unit loads and strain gage strain measurements. As a result measured strain data can be used to back calculate real-world loading on the structure.

True-Load™ consists of three major components: Pre-Test; Post-Test and True-QSE™. Pre-Test will be used to locate strain gauges on the structure. Pre-Test will create a strain proportionality matrix that will be used to relate strain values to load cases. Post-Test uses the strain proportionality matrix defined in the Pre-Test module and measured strain data to create loading histories. Post-Test will create a True-QSE™ event that will be used to interrogate the structure. The True-QSE™ module will be used to open the event created by True-Load™ to allow the user to perform advanced post processing functions. The overall flow of using True-Load™ is illustrated in Figure 4. See the True-Load^{TM} documentation for further discussion regarding the theory used to determine optimal strain gage locations and determination of loading histories for each unit load case.

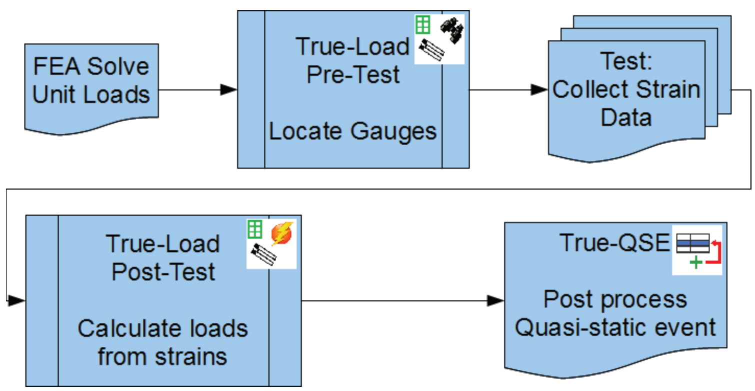

Figure 4. True-Load^{TM} process flow.

Using Pre-test to determine optimal strain gage placement requires the generation of an element set in Abaqus/CAE during the preprocessing phase. This element set is then used in Pre-Test as a set of candidate elements for gage placement. Within Pre-Test the element set and unit loads cases are selected and then the strain proportionality matrix is calculated. True-Load^{TM} provides a set of tools for rotating, orienting, and moving strain gages for both fine-tuning the quality of the strain proportionality matrix and to ease placement of the gages on the structure. Additionally, tools are available for generating dimensioned figures for specifying the strain gage placement.

3. Instrumentation and Testing

23 data channels (12 strain gages, 3 tri-axial accelerometers, 1 linear potentiometer, and 1 Hall Effect sensor) were used on board a DTS (Diversified Technical Systems, Inc.), SLICE data acquisition system (DAS), see *Figure 5*. Data was collected at 5,000 Hz each (7 million data points per minute). The use of this very small and completely on-board DAS allowed for the first time data collection during extreme mountain bike events with no hindrance on the rider what-so-

ever. Previously used DASs required the use of a backpack to carry the data collection and battery hardware and, therefore, also required a set of wires from the bicycle to a backpack which greatly restricted the riders' movement. The bottom image of *Figure 5* shows the old DAS as was used for a road vibration measurement test where the backpack and required wire harness can be seen.

Twelve strain gages (Vishay Precision Group) were placed throughout the frame according to the True-Load^{TM} Pre-Test analysis. Three tri-axial accelerometers (Dytran Instruments, Inc.) were mounted to the frame and fork (non-drive side AFT chain stay, Center of Head Tube, rear of seat tube) and were used for visualization of the frame movements during the event of interest. Additionally, a KA Sensors linear potentiometer, commonly used in the motorsports and automotive industry, was used to measure front fork travel and a small and inexpensive Hall Effect sensor (obtained from DigiKey), was incorporated into the rear linkage and calibrated to indicate the rear shock length, see *Figure 6*. Sensor cables and wiring were custom designed and installed to reduced bulk and weight. A small 2600 mAh battery was used to power the system, lasts for many hours of testing, and was mounted directly to the main frame.

Figure 5. Session 29er mountain bike showing the DTS SLICE DAS (top). Old DAS requiring backpack and wire harness (bottom).


Figure 6. Linear potentiometer (left) used for front fork displacement measurements and Hall Effect sensor (right) used for rear shock displacement measurements.

For this initial research two load cases were post-processed fully through the True-Load™ process. The first load case was a fairly large straight drop off of a wooden structure (Deer Hunter, see *Figure 7*). The second was a jump landing with substantial sideways movement of the bicycle during landing. The purposes of using these two load cases were:

1) Determine external and internal loads for a load case capable of fully compressing the rear suspension. Compare these loads to the laboratory 'equivalent' test (Drop Out Push).
2) Compare lateral forces generated in the sideways landing case (Mojo, data segment 10) to both Deer Hunter and Drop Out Push.


Figure 7. Deer Hunter straight drop landing load case (left) and Mojo "sideways" landing load case (right), Trek Trails.

4. Post Processing and Analysis

Data from one event on the Deer Hunter trail is shown in *Figure 8*. The trail used for this testing contains several turns, berms, rocks and roots etc… Data was collected from the beginning of the trail to shortly after landing the jump of concern. Data shown in *Figure 8* is for the portion of the event while the rider was airborne to just after landing the jump. Note that all data channels are “quite” while the rider is airborne, e.g. all strain data shows zero strain and the front fork, accelerometers show zero acceleration, and rear shock show zero change in length.

Upon impact, strain channels become active again and suspension begins to compress. Note the portion of the data indicated by the dashed red bars. There is a 12 msec portion of time where the suspension is again in a somewhat steady state but compressed. For this period of time the rear suspension is fully compressed and the front fork is in a steady 140 mm of compression. This is the configuration for which the FEM was generated.

Strain data for this 12 msec period of time is shown in *Figure 9* and is the strain data used within True-Load^{TM} for the strain correlation analysis. Note the sharp spike in strain shortly after the beginning of this 12 msec period of time. The rear suspension is fully compressed but not all of the energy from the impact has been absorbed. The bicycle frame itself needs to absorb this energy as strain energy. A rapid increase in strain shows up strongly in the chain stays and seats stays.

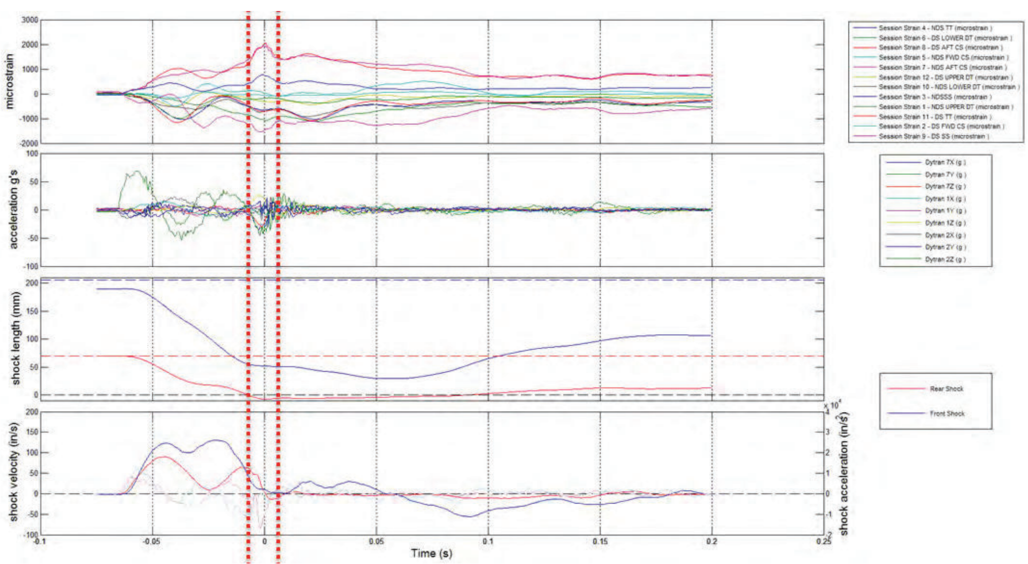

Figure 8. Sensor data from Deer Hunter landing case, data segment 23. Data starts with bicycle airborne. Note that shock velocity data are calculated data.

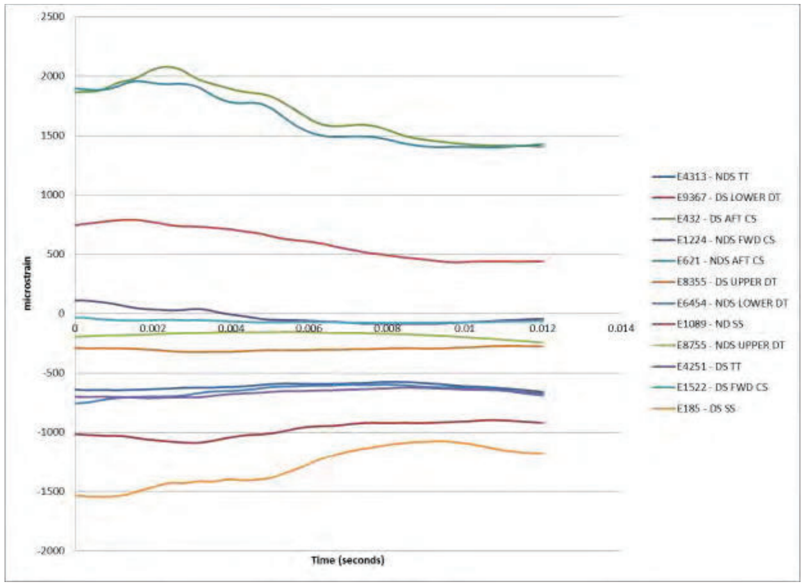

Figure 9. Strain gage data from Deer Hunter load case, 12 msec of data during impact where rear shock and front fork are in a near steady state configuration.

The strain proportionality matrix created in True-Load^{TM} Pre-Test was imported into Post-Test along with the strain gauge data discussed above. True-Load^{TM} Post-Test generated a load amplification curve for each of the unit load cases that minimize the error between the field strains and the finite element strains. An example amplification curve for the forward and downward load on the bottom bracket is shown in *Figure 10*.

The peak amplification for the X direction load on the bottom bracket occurs at time equal to 2.2 msec and corresponds to a load factor of 17.25, or a total BB-Fx load of 17,250N (3,880 lb). The BB-Fy maximum load factor occurs at time equal to 2.6 msec and corresponds to a load factor of 4.90, or a total load of 4,900N (1,100 lb). Note how the peak in the load amplification curves corresponds to the peak the in strain signature in the chain stays and seat stays shown in *Figure 9*.

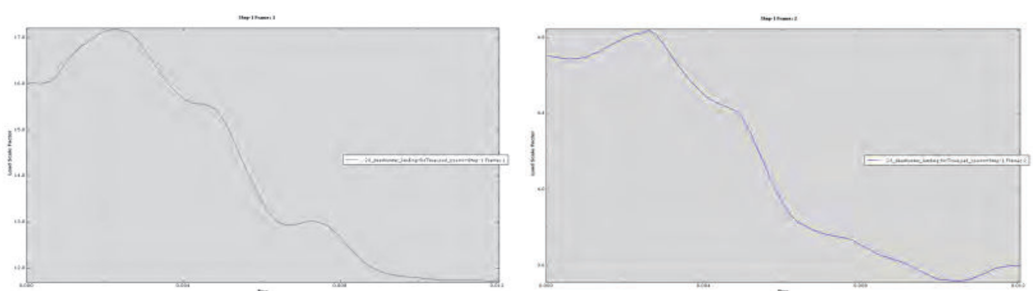

Figure 10. Load amplification curves for BB-Fx (left) and BB-Fy (right); Deer Hunter load case.

Additional post-processing tools provided by True-load™ include the strain data cross plot, and strain gauge / FEM strain vs time for each strain channel. As can be seen in *Figure 11* the load amplifications have provided a reasonably close strain state in the bicycle frame as compared to the field measured strains. Only one of nine strain gage channels used in the analysis has an error greater than 8% and in that case (gage 2 – Drive Side Forward Chain Stay) the error is conservative and off by approximately 90 $\mu\varepsilon$.

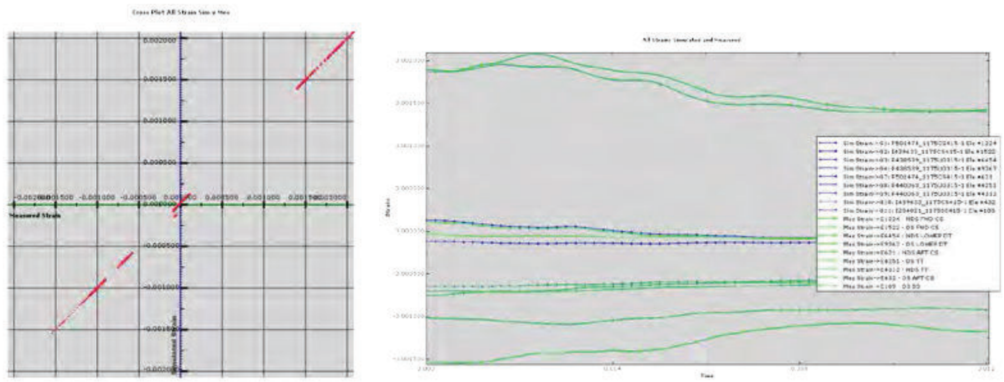

Figure 11. Strain data cross plot (left) and history plot (right) for all strain gages; Deer Hunter load case.

True-Load™ QSE generates an output database in which all loading histories are combined and is useful to visualize the loaded bicycle and its deflected shape. Additionally, reaction forces can easily be extracted from the QSE ODB. Reaction forces at the center of the rear drop out are compared to forces applied during the DOP test case in *Table 1*. The reaction forces shown are for the maximum loading condition during each event.

Note that the loads generated in the field cases both far exceed the DOP lab case. Also note the Z (lateral) load for both field cases is non-zero but is not large. Additionally, the Mojo field case, which was assumed would generate a much larger Z load than the Deer Hunter load case, only generates about 330 N lateral force.

Table 1. Field Cases versus Drop Out Push rear end loads.

Load Case	Y Load (N)	Z Load (N)
DOP Lab Case	5338	0
Deer Hunter Field Case	8663	-129
Mojo Field Case	6386	-331

An additional step in the analysis process is necessary to enable the extraction of internal loads. For ease of processing, the load amplification factors at a single point in time are extracted and used as inputs to a single time step static finite element model. This model is created to enable the request for nodal forces due to elemental stresses (NFORC) which are needed to extract loads within the Free Body Diagram (FBD) cut feature within Abaqus/CAE. *Table 2* shows the load distribution through the seat stays and chain stays as extracted from Abaqus /CAE using the FBD cut tool.

Table 2. Load distribution through Seat Stays and Chain Stays.

Load Case		**Seat Stay Loads**			**Chain Stay Loads**		
		Fx	**Fy**	**Fz**	**Fx**	**Fy**	**Fz**
DOP	Drive Side	-2997	-1316	410	2975	-1328	-441
	Non-drive Side	-3036	-1333	-379	3058	-1361	411
Deer Hunter	Drive Side	-1962	-865	317	8245	-3645	-1113
	Non-drive Side	-1956	-851	-196	7516	-3302	1120
Mojo	Drive Side	-1425	-615	141	5499	-2413	-909
	Non-drive Side	-1592	-707	-254	6016	-2651	692

As can be seen by scrutinizing the load distributions, the DOP case has a significantly larger proportion of the rear end load passing through the seat stays. It appears that the fixity provided at the seat collar and top of the head tube during the DOP lab case contribute to drawing load through the seat stays. Also note that the chain stays are much more highly loaded in the field cases than they are in the DOP lab case. This is also seen by looking at strain plot comparisons for Deer Hunter load case versus DOP lab case, see *Figure 12*.

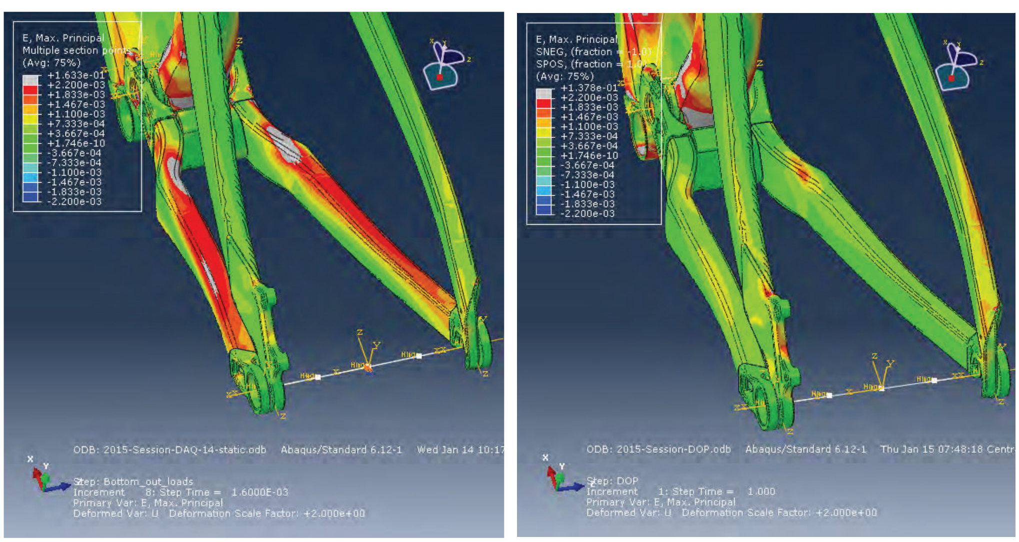

Figure 12. Principal strain distribution in the chain stays for the Deer Hunter (left) and DOP (right) load cases.

5. Conclusions / Summary / Future Work

A full suspension mountain bike was successfully instrumented with strain gages, accelerometers, and suspension travel sensors and data was collected for post processing within Abaqus/CAE and True-Load^{TM}. With the use of True-Load^{TM} we were able to generate load amplification curves and subsequently compile a quasi-static event that allows for the extraction of external loads and internal loads. These loads were compared to a laboratory case (DOP) and it is found that loads generated in the field far exceed those currently being tested. Additionally, it is found that as a result of the boundary conditions in the lab the strain state of the seat stays and chain stays is different in the laboratory than it is in the field.

The FEM accurately idealized the bicycle frame with shell and solid elements but the fork was inadequately idealized with beam elements. Additionally, wheels were not modeled and assumptions were made regarding boundary conditions at the center of the rear and front drop outs. Further refinement of the FEM to include these details may result in even better strain correlation.

It was seen that lateral loading of the rear end of the bicycle during field testing was small. Additional field load cases will be tested in future testing that should generate larger lateral loading, i.e. over-rotated 360 degree rotated jump. Also, additional testing is planned with a professional athlete with plans to perform even larger stunts to measure the amount of load increase for these even more extreme events.

We are also investigating the use of multi-body dynamics software to allow scaling of load cases in the box. This removes the need to field test for every case where loads are needed to be determined.

6. References

1. Cycles – Safety requirements for bicycles – Part 6: Frame and fork test methods, ISO 4210-6:2014, Swedish Standards Institute, Stockholm, Sweden.
2. User Manual / Documentation for True-Load^{TM}, Wolf Star Technologies, Milwaukee, WI.