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US Army Research Laboratory

Innovative Solutions for Modeling a Rate-Activated Tether Using LS-DYNA

by Dmitriy Krayterman and Daniel Malone

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Innovative Solutions for Modeling a Rate-Activated Tether Using LS-DYNA

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14. ABSTRACT

As part of the Head Health Challenge Program, a protection concept using a rate-activated tether containing shear-thickening fluid (STF) is studied. The tether is intended to reduce the impact force experienced by a person wearing a helmet and subjected to blunt force due to a head strike against a hard surface. The tether assembly containing the STF, and designed to have a loading rate sensitivity, is modeled in LS-DYNA, a commercial explicit finite element code developed by Livermore Software Technology Corporation. Two innovative methods to model the tether are described in detail. The first method demonstrates the innovative use of MAT_PLASTICITY_POLYMER and the second method demonstrates the use of the keywords DEFINE_CURVE_FUNCTION and DEFINE_FUNCTION. This report provides inexperienced users with finite element modeling information on how to model complex systems using much less complex methods than would be indicated by the physics of the system.

15. SUBJECT TERMS

protection concept, rate-activated tether, shear-thickening fluid, LS-DYNA, finite element model

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1. Introduction

A helmeted person can experience head injury due to blunt impact with hard objects. For example, a soldier, or football player, falling backward can receive a concussion due to the whipping motion of their head and subsequent impact as the helmet strikes the ground. The Head Health Challenge Program is investigating ways to minimize the impact force due to the head striking a hard surface. Minimizing the redesign effort of existing helmets and maintaining freedom of motion are limiting criteria affecting the potential solution space. One proposed method of reducing the blunt force is to slow the helmet and the head using a rate-activated tether attached to the helmet and torso. The tether does not impede head motion at movement rates that are below those rates expected in an impact but will stiffen substantially during an impact event, slowing the helmet and head thus reducing the impact force. Rate-activated tethers are being evaluated for many other energy-attenuating applications, including helmet suspension systems.[1]

The tether design looks simple in that it is a polymer tube containing shear-thickening fluid (STF) and two long plastic ribbons (Fig. 1). STFs exhibit non-Newtonian fluid dynamics where the particles flow freely at low extension rates but bind within the fluid at higher extension rates. When integrated into a tether, the STF increases the force to extend the ribbons past one another when elongated at high rates due to particle interaction. The tubing will dilate, or bulge out, in the region of highest shear as the particles bind in the fluid. Modeling this device using finite element (FE) methods that capture the interaction would require complex methods such as Arbitrary Lagrangian Eulerian (ALE) or Smooth Particle Hydrodynamics (SPH). Fortunately, this level of modeling sophistication is not required to effectively simulate the tether in a drop experiment using a Hybrid III Anthropomorphic Test Device. Modeling the tether using ALE or SPH would only complicate and slow the drop simulation.

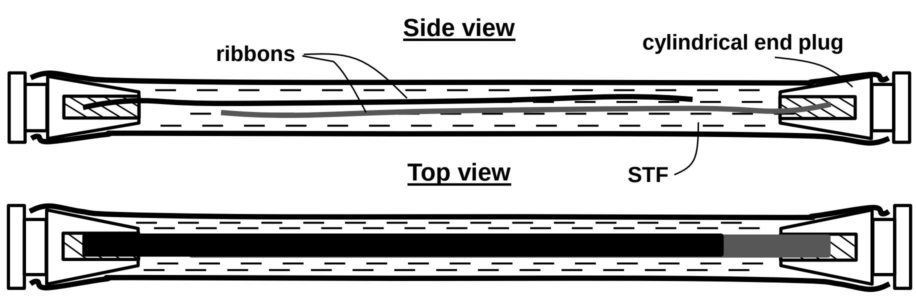

Fig. 1 Shear-thickening fluid tether

This report will describe two methods that effectively model the tether with Livermore Software Technology Corporation (LSTC) LS-DYNA FE analysis software. The methods are simple yet effective and innovative. The first method uses a conventional simplified modeling approach by simulating the polymer tube containing STF with solid elements and a material model (*MAT_PLASTICITY_POLYMER) capable of simulating rate-dependent polymer tension. The second method demonstrates the use of the analytical approach using such LS-DYNA keywords as *DEFINE_CURVE_FUNCTION and *DEFINE_FUNCTION to model simple 1-D elements that use a table of loading rate-dependent curves. By incorporating the simplified tether model into the FE model of the complete drop experiment, substantial savings in modeling, simulation, and debugging time could be achieved while still maintaining desired accuracy of the simulation.

To simplify this report, only the tether model is discussed and the model is only exercised in one direction, the z-direction. This restriction in no way indicates that the techniques described herein are limited by these assumptions.

2. Tether Design and Test Data

The tether design was presented in US Army Research Laboratory (ARL) technical reports by Torelli and Wetzel[2] and Wetzel et al.[3] with tether components and construction as shown in Fig. 1. In general, the tether construction can vary between designs in terms of tubing material, ribbon material, STF formulation, and other variables. The model correlation reported here is specific to the following tether construction: silicone Shore A50 tubing with dimensions 0.5-inch ID, 1/16-inch wall thickness, 12 inches long; STF composed of precipitated calcium carbonate (PCC) in water; PCC at approximately 75% mass fraction and 48% volume fraction; and ribbons constructed of nylon with a thickness of 0.05 inch.

At the time of model development, this rate-activated tether design was optimal for the intended application. The tether design and STF formulation have evolved toward higher performance extensional response since then. Nevertheless, the modeling methodology presented herein should apply for all rate-activated tether designs, provided that detailed load versus extensional characterization is available at various rates to serve as the basis for the model.

The tether was tested at six different velocities. Figure 2 shows the force versus deflection experimental data. There is a clear sharp increase in stiffness as the loading rate increases, demonstrating the tether's ability to allow free range of movement at low rates and high resistance at high rates. One notable feature of the tethers is that the STF will dilate within the tubing, forming a bulge that is clearly visible during high-loading-rate experiments as seen in Fig. 3.

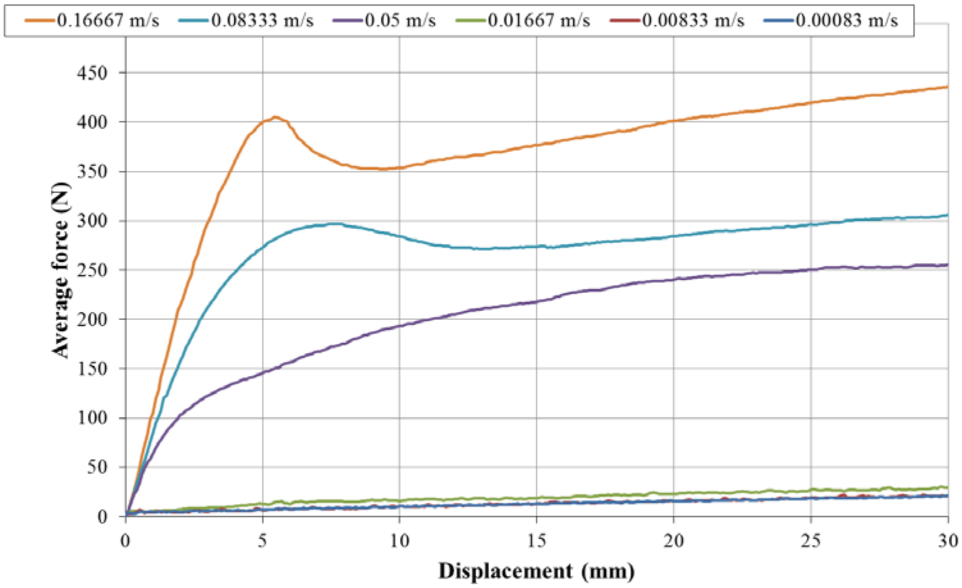

Fig. 2 Experimental data for tether

Fig. 3 Complex behavior exhibited by the tether in a high-rate tension experiment

The substantial change in area due to this dilation has a significant effect on the modeling of the tether as will be seen in the next two sections.

The methods presented in this report are the result of the investigation of this complex behavior from two different perspectives striving to find a simple and effective modeling approach. The objective of this report is to describe these

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methods, validate the models by comparing analytical and experimental results, and to introduce the FE analysis community to the innovative modeling techniques developed as a result of this effort.

3. Method One: Using Brick Elements and MAT_PLASTICITY_POLYMER

3.1 Tether FE Model

The tether body was assumed a cylinder 275 mm (10.8 inches) long and 12.7 mm (0.5 inches) in diameter. The clamps were assumed to be 15 mm long each to add up to approximately 300 mm (12 inches) total tether length. The tether body (tubing, ribbons, and STF) was modeled with solid hexahedral (brick) LS-DYNA element form1 (constant stress) elements and the clamps were modeled with 1mm steel shell elements. To simulate a tension experiment, one clamp (bottom) was fully constrained and the other end was modeled as a rigid body and assigned prescribed motion (displacement) according to the provided experimental data (Fig. 2). The hourglass control (*HOURGLASS) type 3 with coefficient of 0.12 as well as part damping (*DAMPING_PART_STIFFNESS) with coefficient of 0.07 were assigned to the tether solid component to improve simulation stability and reduce high-frequency noise in force response for all rates. The tether FE model is shown in Fig. 4.

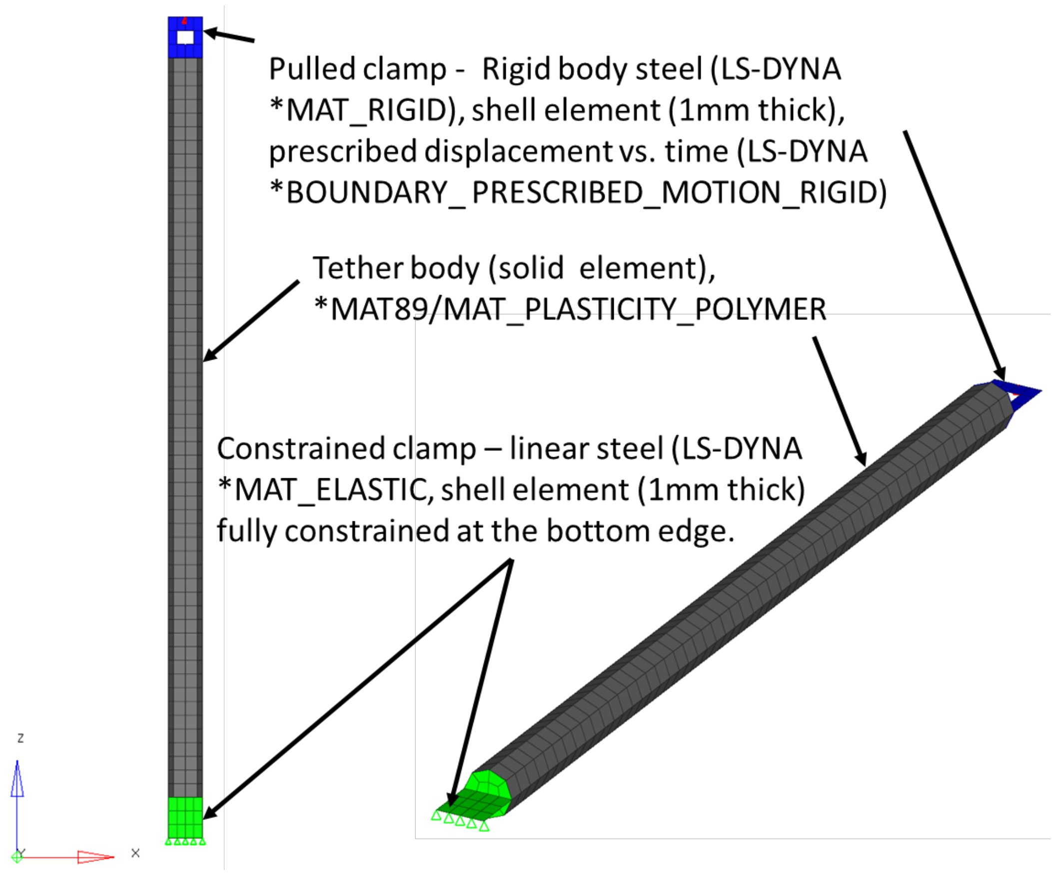

Fig. 4 Tether FE model

3.2 Tether Material Properties Selection and Verification

Several LS-DYNA material models were assessed before the final selection was made. To successfully simulate the experimentally observed nonlinear rate-dependent tether response, the selected material model had to simulate nonlinear stress–strain plasticity in tension over the entire strain (total strain) and to account for strain-rate effects. In addition, the material model had to allow strain-rate effects to be specified in table format so that for each strain rate there is a corresponding stress–strain curve derived from the experimental data. The best LS-DYNA material model, as confirmed by the LSTC technical support, that would satisfy these conditions was *MAT 89/ *MAT_PLASTICITY_POLYMER. This material model is intended for applications where the elastic and plastic sections of the response are not as clearly distinguishable as they are for metals and allows the user to specify the table ID with each strain-rate value associated to a curve ID giving the stress as a function of effective strain for that rate.[4] For strain rates between the rates listed in the table, the model interpolates the table data. The experimental data, presented as force versus displacement or force versus time (as displacement [strain] was kept constant at 30 mm), had to be converted into stress–strain curves to be used in this material model.

Initially the cross-sectional area of the tether was assumed to stay constant, so the stress would only be proportional to the applied tensile force. Although this approach showed acceptable model correlation with test results for the low strain rates (8.3 and 16.6 mm/s), it was obvious that this assumption was incorrect at higher strain rates (50, 83, and 166 mm/s) as the FE model's force response would significantly (more than 100%) differ from that of the experiment. Other attempts such as a linear variation of tube area or monotonic nonlinear changes as shown in Fig. 5 produced good results for the intermediate rates of 50 and 83 mm/s but poor results for the 166-mm/s loading rate.

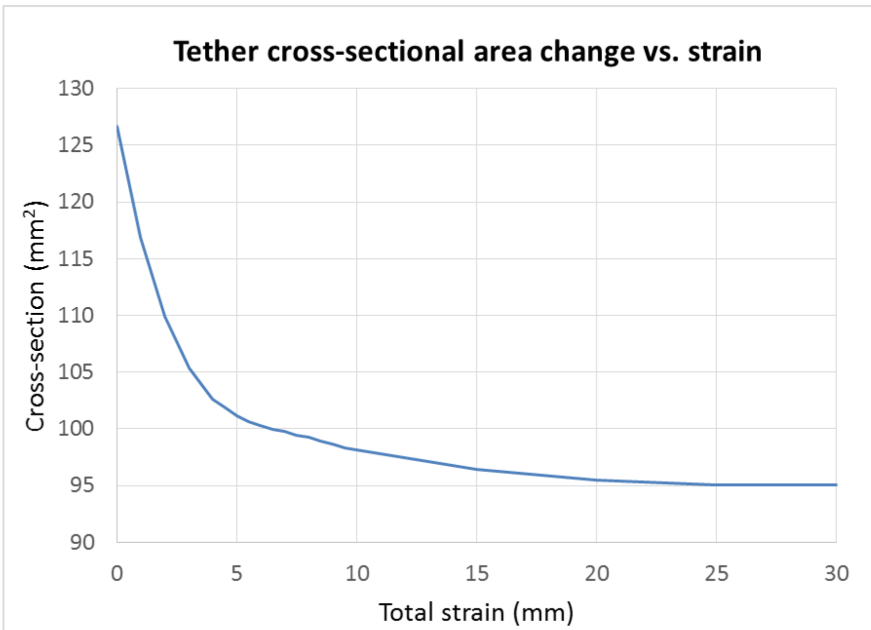

Fig. 5 Example of the nonlinear uniform tether cross-section decrease

The solution to the gross inaccuracy at the highest loading rate was to correct the stress by using the actual tube area. To convert force–displacement data into stress–strain data, the current force was divided by the current tube area calculated based on the measured tube diameter from video analysis and assuming a round cross section to obtain stress ($\sigma = F(t)/A(t)$), and the current displacement was divided by the initial tube length ($\varepsilon = \Delta L/L$). Microsoft Excel was used to make these conversions and to convert all units into to meter–kilogram–second, or the MKS system, to be later incorporated into the Hybrid III Anthropomorphic Test Device (ATD) FE model.

Because of the tube dilation at high rates, the area of the tube changes in a nonlinear non-monotonic way. These effects would have to be modeled for each of the higher tension rates separately as they are more pronounced at the highest tension rate (166 mm/s) and less pronounced as the tension rate gets lower. To include these effects, the effective cross-sectional area of the tube was assumed to be able to increase for a short time during the tension at high strain. Thus, the tube area change would be non-uniform, allowing for the increase in tube cross section to account for dilation effects. An example is shown in Fig. 6.

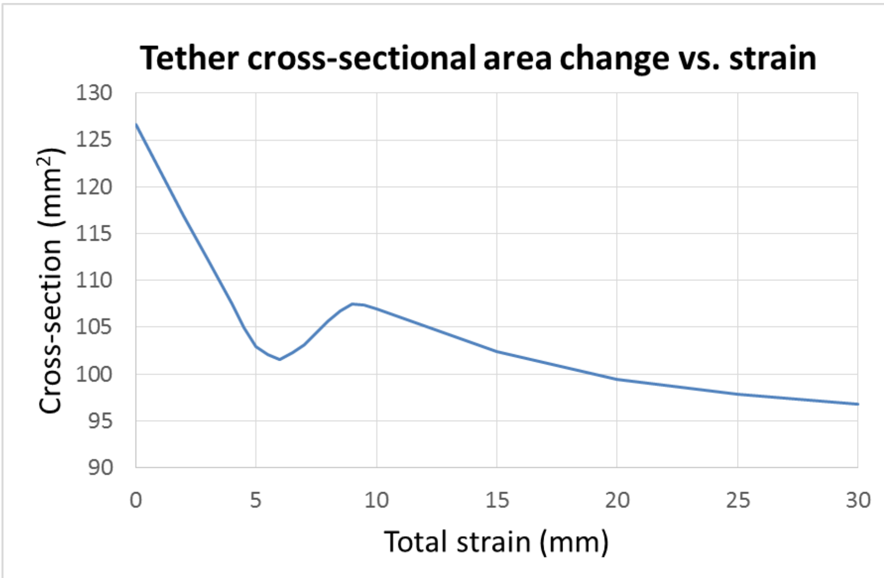

Fig. 6 Example of the nonlinear non-uniform tether cross-section decrease

3.3 Finalized Stress–Strain Input and Material Card Used in Tether FE Model

The modeling of non-uniform nonlinear tether cross-sectional area change (dilation effect) and corresponding stress–strain curve significantly improved model correlation for the highest tension rate (166 mm/s), while the uniform nonlinear tether diameter decrease seemed to work well for the lower tension rates (83 and 50 mm/s). Figures 7–9 show the finalized tube cross-sectional area change versus total strain curves and the corresponding stress–strain curves used in the *MAT 89/*MAT_PLASTICITY_POLYMER material model for all three high tension rates.

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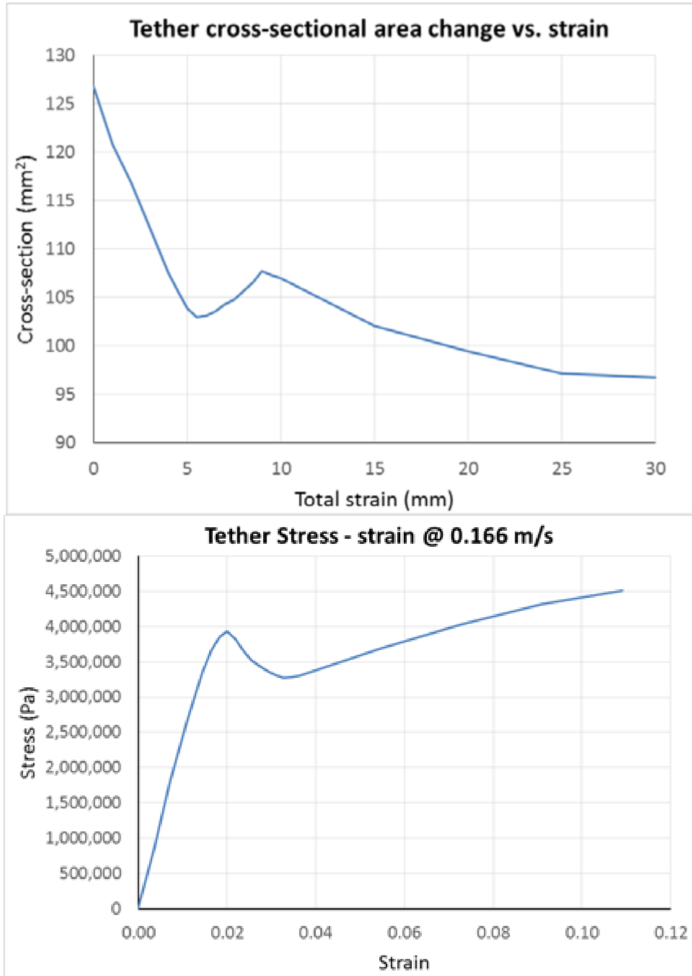

Fig. 7 Tension rate 0.166 m/s. Stress–strain material card input.

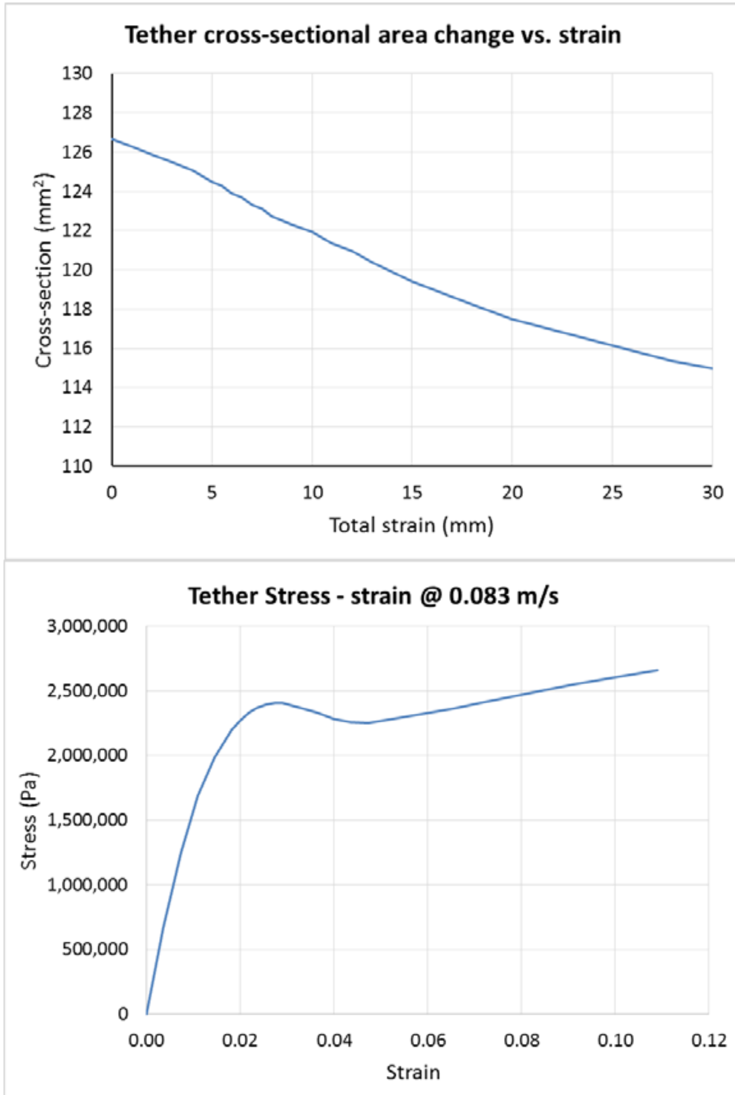

Fig. 8 Tension rate 0.083 m/s. Stress–strain material card input.

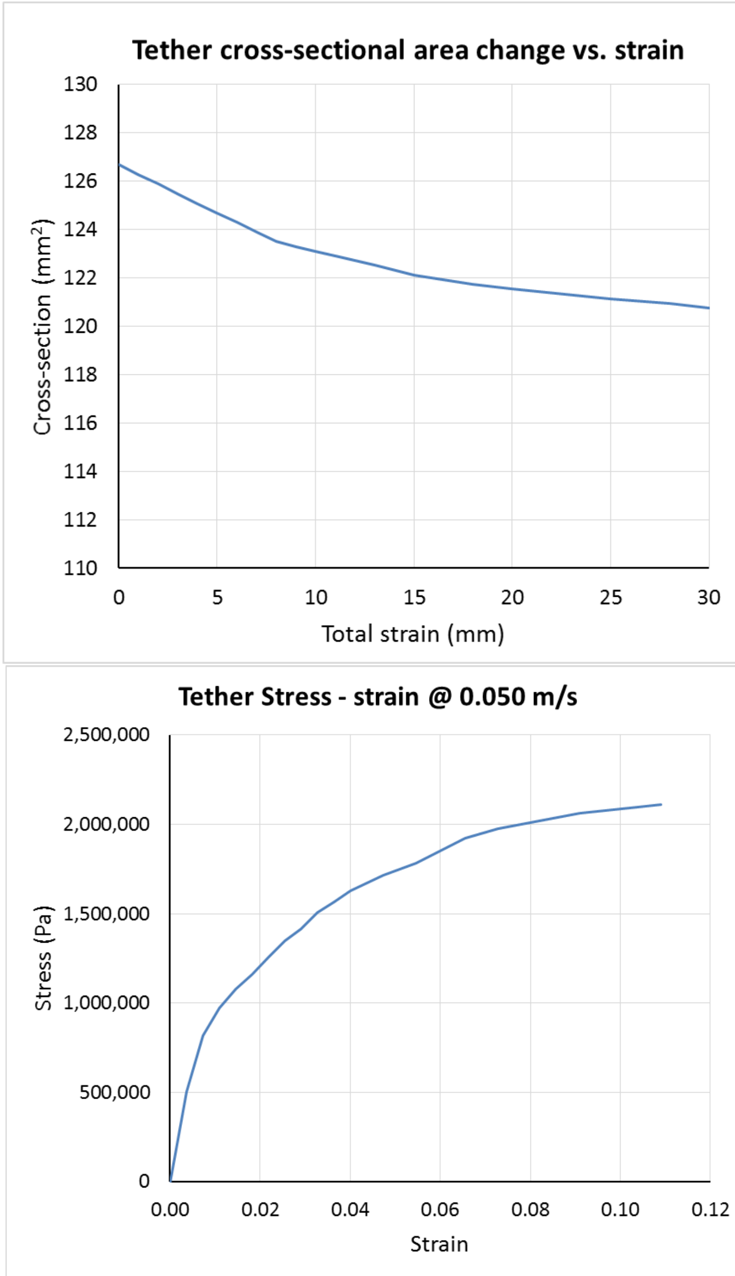

Fig. 9 Tension rate 0.050 m/s. Stress–strain material card input.

For the lowest tension rates, the tube diameter change does not seem to affect force response results, so stress–strain curves may not include this effect. The finalized stress– strain curves are shown in Fig. 10.

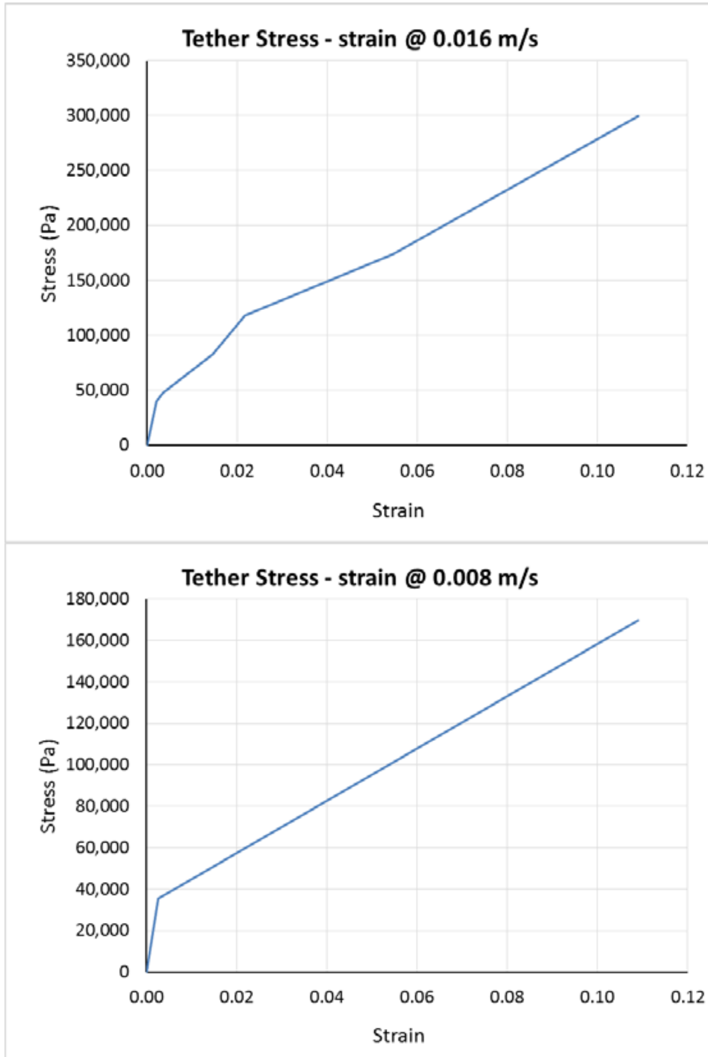

Fig. 10 Tension rates 0.016 m/s (top) and 0.008 m/s (bottom). Stress–strain material card input.

The final LS-DYNA card with material parameters common for all simulations is shown in Fig. 11.

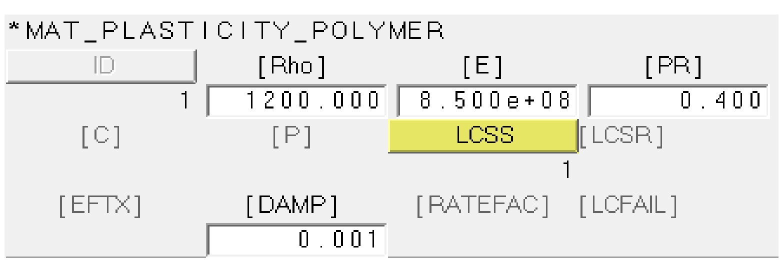

Fig. 11 LS-DYNA material type 89 card parameters used in FE model

The LCSS parameter in the material card points to a table ID (1) that lists all strain rates in the left column and corresponding stress–strain curve IDs in the right column (Fig. 12). The strain rate is calculated by dividing the tension rate by the initial tether length. For example, 0.166-m/s tension rate divided by the initial length of 0.275 m equals strain rate of 0.6.

```
*DEFINE_TABLE
         1
                    0.03          2
                    0.06          3
                    0.18          4
                     0.3          5
                     0.6          6
```

Fig. 12 Strain rate vs. stress–strain curve ID table used in tether material model

3.4 Simulation Results

The model correlation to experimental results for low 8.3- and 16.6-mm/s tension rates is shown in Fig. 13.

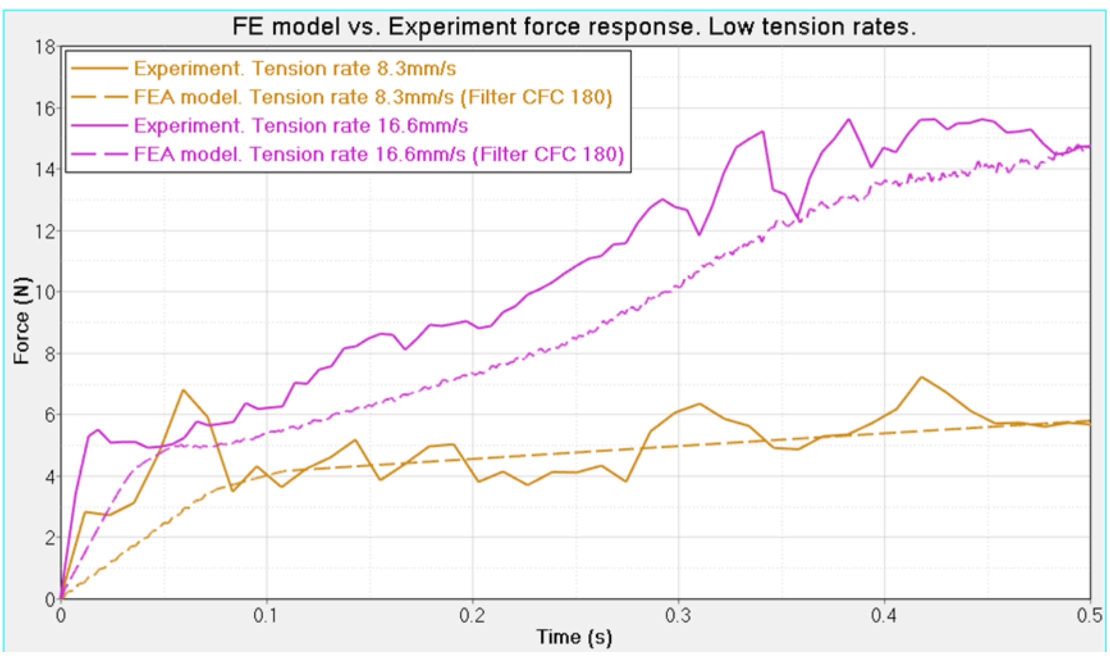

Fig. 13 Model correlation to experimental results for low tension rates

The model correlation to experimental results for high 50-, 83-, and 166-mm/s tension rates is shown in Fig. 14.

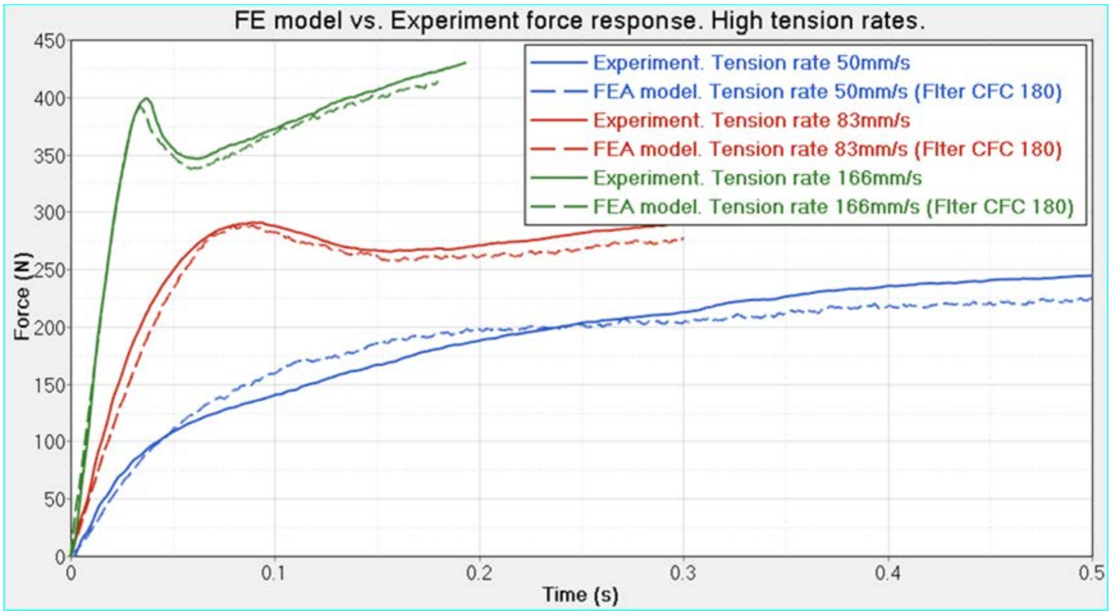

Fig. 14 Model correlation to experimental results for high tension rates

The finalized model correlated reasonably well with experimental results for all tension rates in terms of response curve peaks and shapes. Additional tension rates of 120 and 35 mm/s at which no experimental data existed, were modeled to verify how well the model interpolates between the experimental data. The model shows very reasonable response for these tension rates with curve trends and peaks as expected (Fig. 15), proving that the model is valid for the entire range of tension rates between 8.3 and 166 mm/s.

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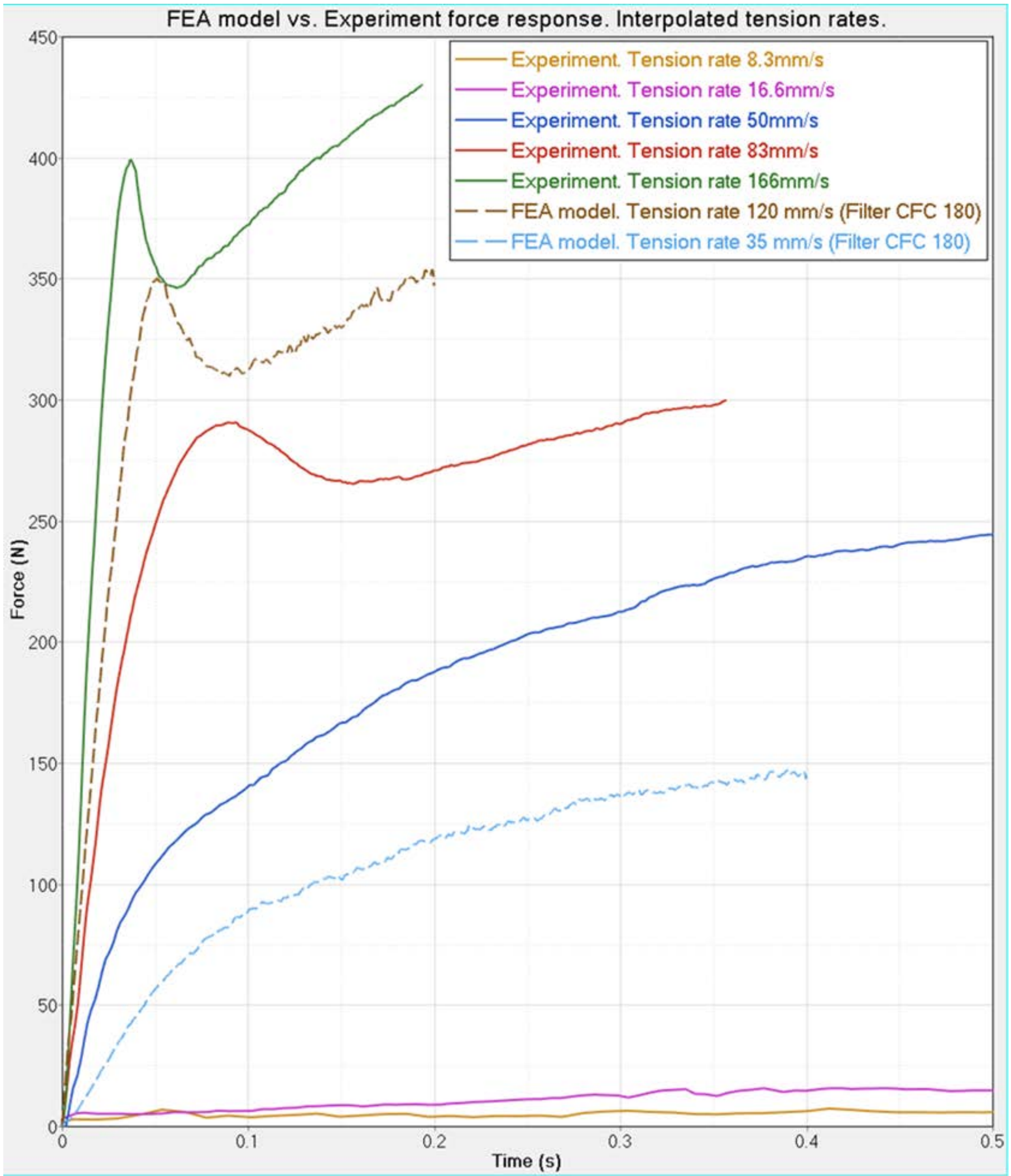

Fig. 15 Model correlation to experimental results for interpolated tension rates

4. Method Two: Using Functions in LS-DYNA

4.1 Details of Method

The motivation for this method is found in the simplicity of using a 1-D element such as a discrete spring since such elements use force versus deflection data just like the load curves shown in Fig. 2. Unfortunately, LS-DYNA does not offer a material model that provides the rate-dependent behavior displayed by the tether.

The closest material model for a discrete element is material *MAT_SPRING_NONLINEAR _ELASTIC. This material model offers a velocity-dependent scaling factor but is inadequate for describing the changing shape of the experimental curves shown in Fig. 2. LS-DYNA offers two alternatives. The first is the capability to compile “user-defined” material models with the LS-DYNA executable. The second is the capability to add programming functions to the FE model keyword file. These functions interact in real time with the LS-DYNA executable. These commands are specific to the LS-DYNA executable and are not related to any programming language.

The first alternative is complicated by the need for a compiler to compile the LS-DYNA code with the included user material model. FE modelers that work in organizations with restrictions on the installation of software might have difficulty pursuing this option. The second alternative is always available because the commands are issued within the LS-DYNA FE model keyword file. The LS-DYNA executable will read the commands when it reads the keyword file and execute those commands during the FE simulation.

A list of the functions available within LS-DYNA can be found in the LS-DYNA User Manual under the *DEFINE_CURVE_FUNCTION keyword. This functionality allows for the real-time extraction of data such as displacements, velocities, accelerations, stresses, forces, and moments from the simulation. The extracted data can then be treated as input to calculations, including logic statements. The calculated data can then be used in real time by the simulation. For instance, the velocities of two nodes can be read at each time step, the difference between them calculated and then used to determine a force response of a system. The ability to program within a keyword file greatly expands the capability of LS-DYNA simulations and dramatically enhances the utility of LS-DYNA.

Five types of functions are used to simulate the tether response. The function types are displacement, velocity, tabulated data, polynomial, and “IF” functions. These functions will create a reaction force on a node at one end of the tether that will model the force response of the tether. Functions are used to extract the displacement and velocity of two nodes at either end of the tether in real time. These data are then used as input to a series of “IF” functions that outputs the corresponding reaction force. The FE model used to simulate the tether is shown in Fig. 16.

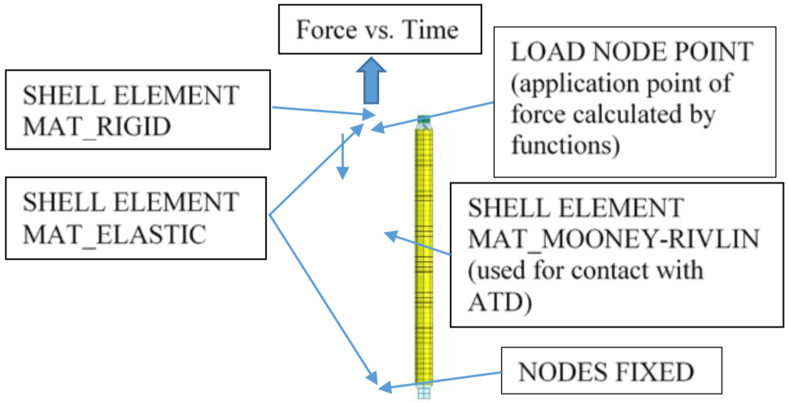

Fig. 16 Method Two tether FE model

The nodes used to measure the relative displacement (strain) of the tether and the relative velocity between the ends of the tether are shown in Fig. 17. Each node is at the center of the associated end plug.

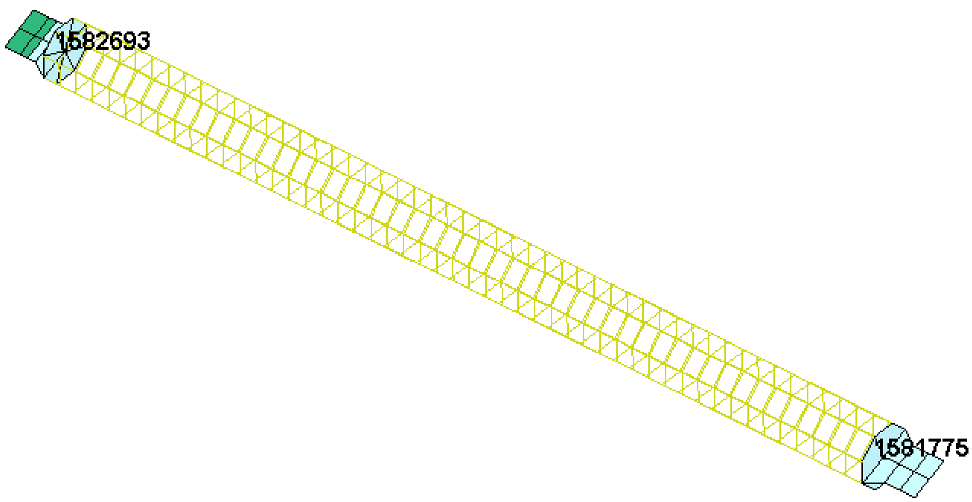

Fig. 17 Node locations for displacement and velocity measurement

The keyword program will use the nodes in Fig. 17 to calculate the elongation of the tether and the rate of strain. The commands for the relative displacement (strain) and velocity are shown in Figs. 18 and 19, respectively. Figure 18 is a screenshot from LS-PrePost, an LS-DYNA pre- and postprocessor. Figure 19 is the card as seen in the keyword file.

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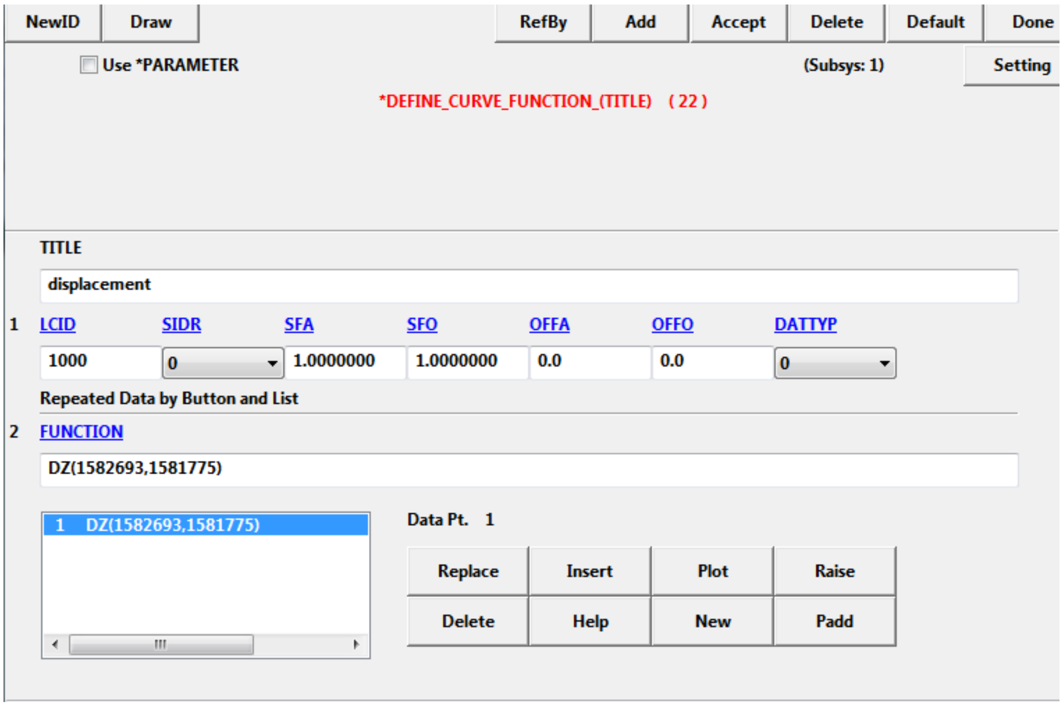

Fig. 18 Screenshot of LS-PrePost showing displacement function

```
*DEFINE_CURVE_FUNCTION_TITLE
velocity
$#   lcid    sidr    sfa    sfo   offa   offo  dattyp
     1001       0    1.0    1.0    0.0    0.0       0
$#                                              function
VZ(1582693,1581775)
```

Fig. 19 Keyword file card showing velocity function

As can be seen in Figs. 18 and 19, the keyword command is *DEFINE_CURVE_FUNCTION. The displacement function is DZ(1582693,1581775), which calculates at every time step the displacement between the two nodes. The velocity function is VZ(1582693,1581775). These functions are called by other functions by referencing the load curve number using the command "lc1000" for displacement and "lc1001" for velocity. This will become clear as the algorithm is further explained.

The algorithm to calculate the nodal force based on the loading rate-dependent force versus deflection experimental data proceeds as in Fig. 20. Each block of Fig. 20 represents an action by the analyst to create all of the needed cards within the keyword file. The following paragraphs will discuss each block and show examples of the cards so the format is clear.

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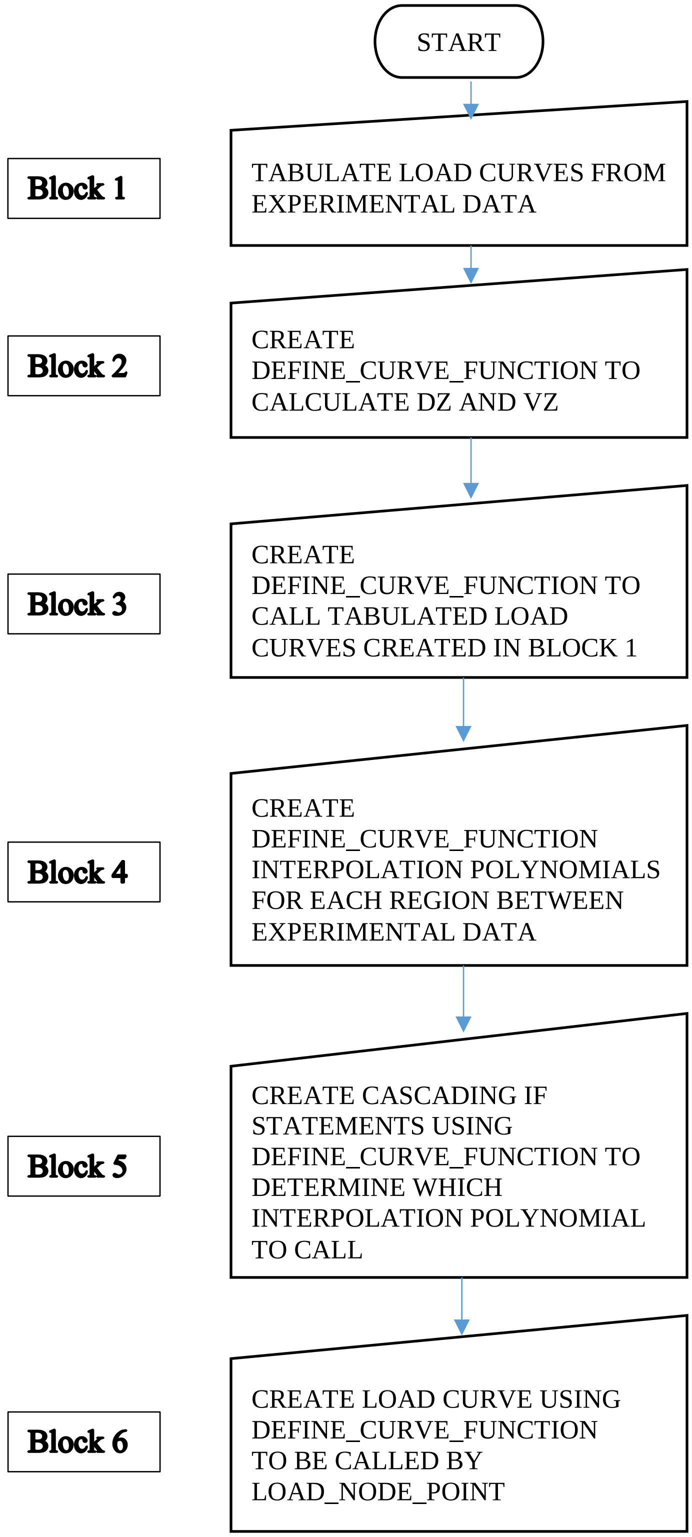

Fig. 20 Flowchart of required function cards

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Block 1 is the input from the experimental data but instead of using the *DEFINE_CURVE card (as is usually the case) the *DEFINE_FUNCTION_TABULATED card is used. An example of the card is shown in Fig. 21. This card contains an entry for the FUNCTION name. The FUNCTION name is used by other cards and equations to call data from this card. Other cards requesting data will call the FUNCTION name, which in this case is FvsD083. For example, the equation FvsD083(lc1000) calls the load curve lc1000 defined by the *DEFINE_CURVE_FUNCTION card shown in Fig. 18, extracts the displacement (Block 2) from it, and uses the displacement as the argument to read the tabulated data from the *DEFINE_FUNCTION_TABULATED card.

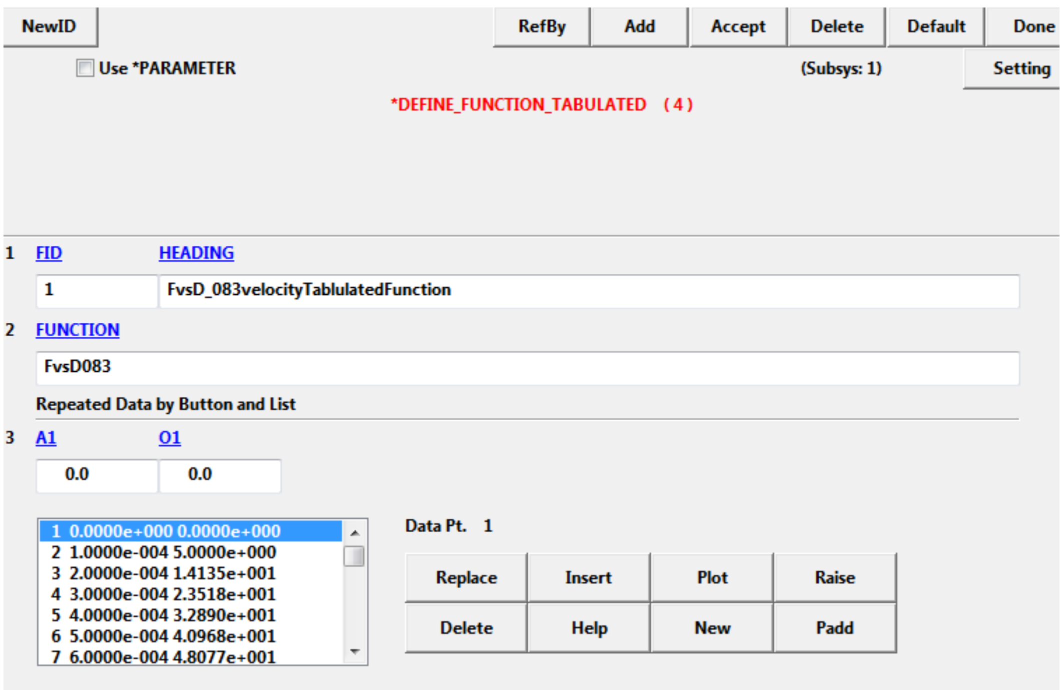

Fig. 21 Tabulated function card

Block 2 is the calculation of displacement and velocity. Figures 18 and 19 have already shown how to read nodal data and calculate properties like displacement and velocity. These cards will be called during program execution by other *DEFINE_CURVE_FUNCTION cards.

Block 3 creates load curves for each loading rate tabulated in Block 1. This block creates *DEFINE_CURVE_FUNCTION cards, each of which calls the displacement load curve (see Fig. 18 as an example for how to create a displacement load curve) and uses that load curve as the argument for the tabulated force versus deflection curve, which is called by its function name (i.e., FvdD167). Figure 22 shows the card (in keyword format) that calls the data for the force at the 0.167-m/s

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velocity. The displacement load curve, lc1000, is the argument passed to the function FvdD167 and the load curve ID in Fig. 22 is 1004. At each time step the load curve 1004 (lc1004) (Fig. 22) provides the force for the real time (current) displacement of the 0.167-m/s loading rate. Other functions can call lc1004 if the force at 0.167 m/s is required.

```
*DEFINE_CURVE_FUNCTION_TITLE
.167 Force at displacement @ 0.167 velocity
$#   lcid     sidr     sfa     sfo     offa     offo   dattyp
     1004        0     1.0     1.0      0.0      0.0        0
$#                                                   function
FvsD167(lc1000)
```

Fig. 22 Calling a tabulated function

Block 4 is the creation of polynomial functions. The polynomial function and its description are shown in Fig. 23. The interpolation function between different force versus deflection curves is assumed to be linear and will only use x, x0, a0, and a1.

POLY(x, $x0$, $a0$, …, $a30$)	Evaluates a standard polynomial at the user specified value x. The parameters x0, a0, a1, …, a30 are used to define the constants for the polynomial defined by: $P(x) = a_0 + a_1(x - x_0) + a_2(x - x_0)^2 + \cdots + a_n(x - x_0)^n$

(LS-DYNA USER Manual[4])

Fig. 23 LS-DYNA manual description of polynomial function

As an example, a polynomial interpolation will be constructed between the 0.167- and the 0.83-m/s force versus deflection curves. The force at any deflection and for velocities at or between the two velocities is as shown:

$$F = F_{0.083} + (F_{0.167} - F_{0.083}) * \left(\frac{V_z - 0.083}{0.167 - 0.083}\right) \tag{1}$$

The polynomial card in LS-DYNA would be as shown in Fig. 24. Lc1004 is the force at 0.167 m/s. Lc1003 is the force at 0.083 m/s. Lc1002 is the ratio term. Figure 25 shows how to create a card of a ratio.

```
*DEFINE_CURVE_FUNCTION_TITLE
.167 thru 0.083 Force Interpolation vs displacement
$#    lcid      sidr      sfa       sfo      offa      offo    dattyp
      1006         0      1.0       1.0       0.0       0.0         0
$#                                                          function
POLY(lc1004,lc1003,lc1003,lc1002)
```

Fig. 24 Example of polynomial function keyword card

```
*DEFINE_CURVE_FUNCTION_TITLE
.167 thru 0.083 Velocity Interpolation
$#    lcid      sidr      sfa       sfo      offa      offo    dattyp
      1002         0      1.0       1.0       0.0       0.0         0
$#                                                          function
(VZ(1582693,1581775)-0.083)/(0.167-0.083)
```

Fig. 25 Example of velocity interpolation keyword card

Block 5 is the creation of a series of cascading IF statements. These are used to determine the correct interpolation polynomial so that the force per time step can be calculated. The IF statements will determine if the current nodal velocity is above, below, or between any of the experimentally obtained loading rates. An IF statement is shown in Fig. 26 with the description.

IF(lcid1, lcid2, lcid3, lcid4)	Arithmetic if conditional where lcid# is the load curve ID for *DEFINE_CURVE or *DEFINE_CURVE_-FUNCTION. $$\mathrm{IF} = \begin{cases} \text{ordinate of lcid2} & \text{if ordinate of lcid1} < 0 \\ \text{ordinate of lcid3} & \text{if ordinate of lcid1} = 0 \\ \text{ordinate of lcid4} & \text{if ordinate of lcid1} > 0 \end{cases}$$

(LS-DYNA user manual[4])

Fig. 26 LS-DYNA manual description of IF function

The first term of the IF statement in Fig. 27 adjusts the velocity to be relative to the 0.167-m/s velocity. The second term sends the code to the second IF statement in the chain where the velocity will be compared to the next lower velocity load curve, 0.083 m/s. The last two terms both point to lc1004, which is the force versus deflection for the 0.167-m/s loading rate. Since there are no data beyond 0.167 m/s, anything above that velocity will use the 0.167-m/s force versus deflection curve.

```
*DEFINE_CURVE_FUNCTION_TITLE
Use This Curve for Load Node Card
$#    lcid     sidr      sfa      sfo     offa     offo   dattyp
      1021        0      1.0      1.0      0.0      0.0        0
$#                                                      function
IF(lc1001-0.167,lc1022,lc1004,lc1004)
```

Fig. 27 Example of IF statement keyword card

The IF statements cascade through all of the loading rates until the correct range is determined and then the associated polynomial is called to interpolate the force.

4.2 Simulation Results for Method Two

Simulations at 0.1667, 0.0833, 0.05, 0.01667, and 0.0083 m/s were run. Figures 28 and 29 show that the simulations track the experimental data, indicating that the technique reproduces the experimental results. Simulations at 0.125- and 0.064-m/s rates are in between the experimental data. The code properly linearly interpolates between the experimental loading rates. Experimental evidence would need to be provided to determine if a linear assumption is adequate for the tether rates between the tabulated data. If not, then the linear assumption can be modified using more terms in the polynomial function. Figure 29 shows the experimental results and simulations at lower velocities. The experimental results were smoothed before including in the LS-DYNA keyword file, which is why the simulation does not track the experimental results for these rates.

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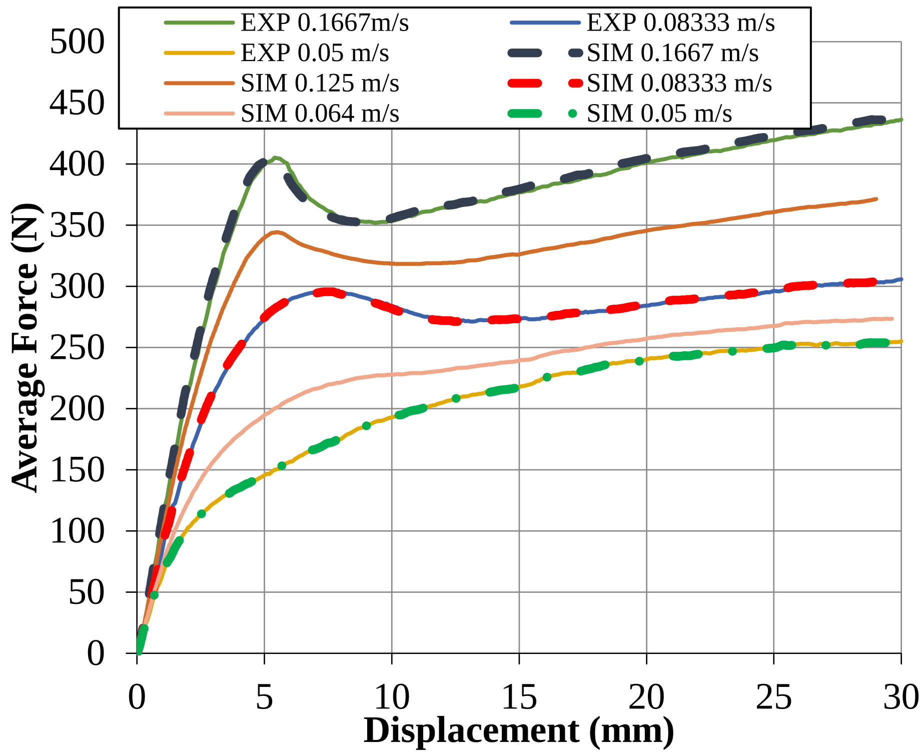

Fig. 28 Simulation and experimental data for 0.1667, 0.833, and 0.05 m/s. Also shown are linearly interpolated simulations for 0.125 and 0.064 m/s.

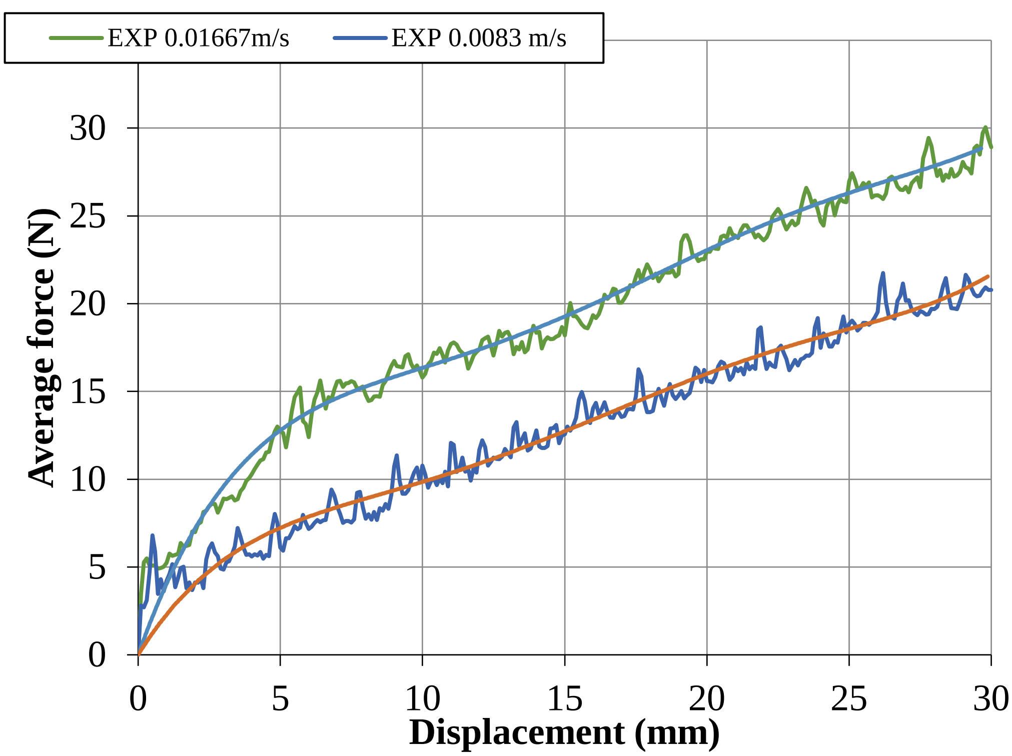

Fig. 29 Simulation and experimental data for 0.01667 and 0.0083 m/s

5. Conclusion

Two methods have been reported to model the behavior of the STF tether used in the Head Health Challenge Program. Both showed how a complex mechanical behavior could be simulated using simplified techniques rather than extreme detail modeling using ALE or SPH methods. Both simplified methods were able to simulate the tether and can be included in FE models using the ATD.

Method One showed how to effectively adapt a material model available within LS-DYNA to capture the complex high-strain-rate effects (dilation) observed in the experiments. The drawback of the method is that it still requires a small-element mesh to capture the geometry of the tether assembly, which may lower the time step of the entire model and, therefore, adversely impact compute time of the complex assembly. Furthermore Method One requires that video be recorded during high rate tension testing of the tethers so that changes in effective cross-sectional area due to dilation can be accounted for in the model.

Method Two demonstrated how another available LS–DYNA functionality, such as user-defined functions, could be used to simulate the complex high-strain-rate effects of the tether assembly. This approach does not require any additional mesh and is quick and efficient. However, component interactions such as contacts require additional steps like that shown in Fig. 16 where a shell part is added to provide ATD contact. This method also requires additional modeling skills and compiler for the LS-DYNA code to implement.

6. References

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List of Symbols, Abbreviations, and Acronyms

ALE	Arbitrary Lagrangian Eulerian
ARL	US Army Research Laboratory
ATD	Anthropomorphic Test Device
FE	finite element
ID	identification
LSTC	Livermore Software Technology Corporation
PCC	precipitated calcium carbonate
SPH	Smooth Particle Hydrodynamics
STF	shear-thickening fluid

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