Energy-Absorbing Wheel Tethers for Racecars

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ABSTRACT

Wheel tethers are frequently used on racecars to prevent detached wheels from flying freely away from the car and injuring spectators. Extremely stiff tethers may cause the wheel assembly to be either yanked back toward the car, putting the driver in danger or to be snapped free at an uncontrolled trajectory, exposing spectators, other drivers, and workers to danger.

Conceptual design of energy absorbing wheel tether systems was performed using the finite element program LS-DYNA. Two major approaches to energy absorption were explored, both of which involved metal bending. For absorbing energy through sheet metal bending, parametric studies showed that a minimum of 4 through-the-thickness integration points were required to capture good elasto-plastic behavior of shell elements. Additionally, for absorbing energy through solid tube bending, it was found that a circular cross-section in elasto-plastic bending must be modeled with a minimum of 12 solid elements in the cross-section.

The developed tether design was able to absorb a total of 10 kJ of kinetic energy from the wheel assembly. This amount of energy is equivalent to reducing the trajectory height and distance of a 68-kg wheel assembly 7.5 m (24.6 ft) and 30 m (98.4 ft), respectively, for an assembly detaching at an angle of 45-degrees.

INTRODUCTION

In 1999, the Indy Race League (IRL) began requiring its teams to use tether systems to retain wheels in an effort to reduce injuries caused by wheels that come loose during a crash. Both Indy, Formula One, and CART also began requiring their teams to use tether systems in 1999. Much of the effort was precipitated by actual injuries and deaths, particularly with spectators, at the races.

Two potential dangers exist with wheel tethers. First, the restraints can yank wheels back toward the car, putting the driver in greater danger. Secondly, tethers that snap free can accelerate the already high speeds at which many wheels fly away from vehicles during crashes (bull-whip effect). A successful design would allow the detachment of the wheel, as to not yank the wheel back toward the car but remove enough energy from the car so that the flying wheel is no longer a danger to spectators or drivers.

This paper documents the use of the finite element analysis program LS-DYNA to investigate possible improvements in tether designs. Several methods for reducing the energy from a flying wheel without a rigid connection that would yank the wheel back toward the car are examined. This system, called the Energy Absorbing Tether System, reduces the velocity of flying wheels while also reducing the possibility of impacting the car with the detached wheel.

INITIAL DESIGN CONCEPT

An initial design was developed using round steel rod around a series of steel rollers. As shown in Figure 1, the rod would be pulled between a series of four round steel rollers, bending the rod as it was pulled and thereby absorbing energy.

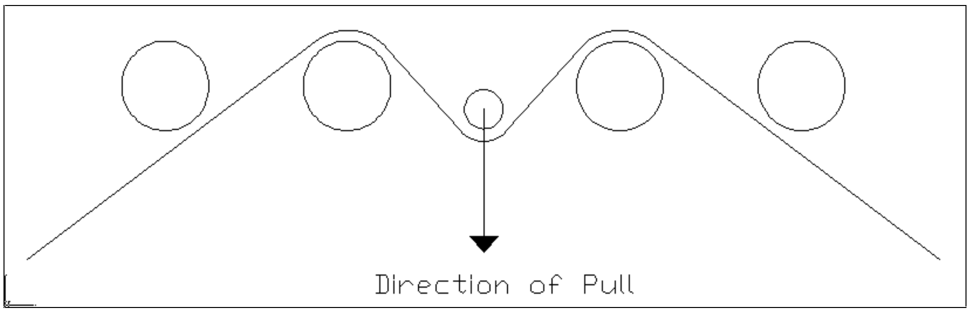

Figure 1. Initial Concept of Tether System

There are many methods of absorbing energy, including cutting, tearing, bending, and crushing. However, the bending of metal was chosen because it allows energy to be absorbed without the creation of metal fragments of any type. This factor increases the safety of the design by minimizing the possibility of metal fragments being introduced into the racetrack environment.

FINITE ELEMENT SIMULATION

The initial finite element model consisted of a 12.7-mm steel rod wrapped between 50-mm rollers. This significant size and weight dictated that a smaller design be used. The second design consisted of 25.4-mm roller bars and a 12.7-mm bar round steel rod.

The roller bars were modeled as rigid shell elements, since they were designed not to deform during the pull and the fact that they are several times larger in diameter than the round steel rod. The deformable steel rod was modeled with solid elements and LS-DYNA material type 24, an isotropic, piecewise linear plastic material. This process replicates a steel bar being drawn through Titanium rollers.

Contacts were modeled using automatic single surfaces. This contact type uses segment-based projects to account for shell thicknesses, but no contact problems were encountered.

The bar was modeled using fully integrated and selectively reduced solid elements. Loading occurred at 5 m/s. As shown in Figure 2, the rod was modeled in half-space to save computing time.

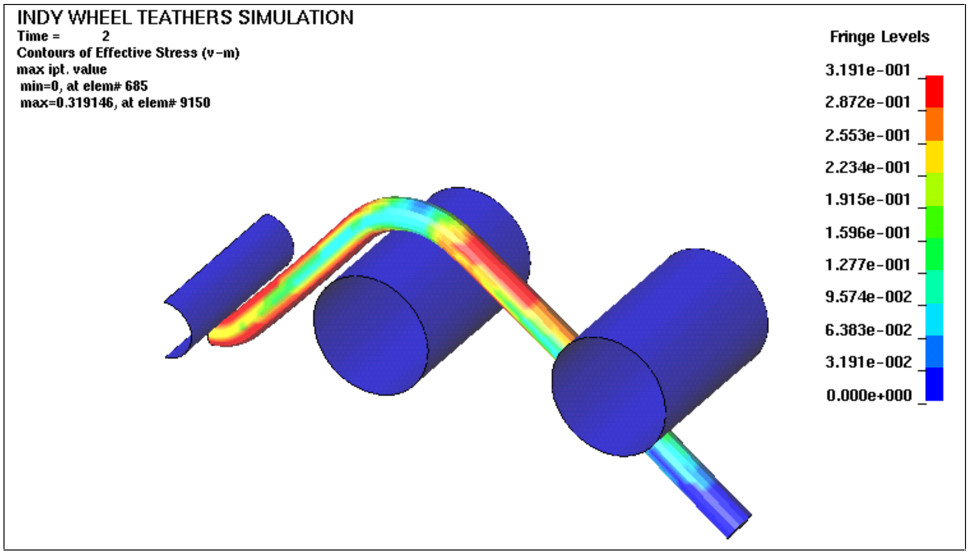

Figure 2. Round Rod between Rollers

The most important characteristic of the wheel tether is its force-deflection behavior. Significant jumps in the force-deflection curve can cause the failure of the system due to high accelerations. Additionally, the area underneath the force-deflection curve represents the energy absorbed by the system. As shown in Figure 3, the energy absorbed by the initial system was approximately 2000 N-m.

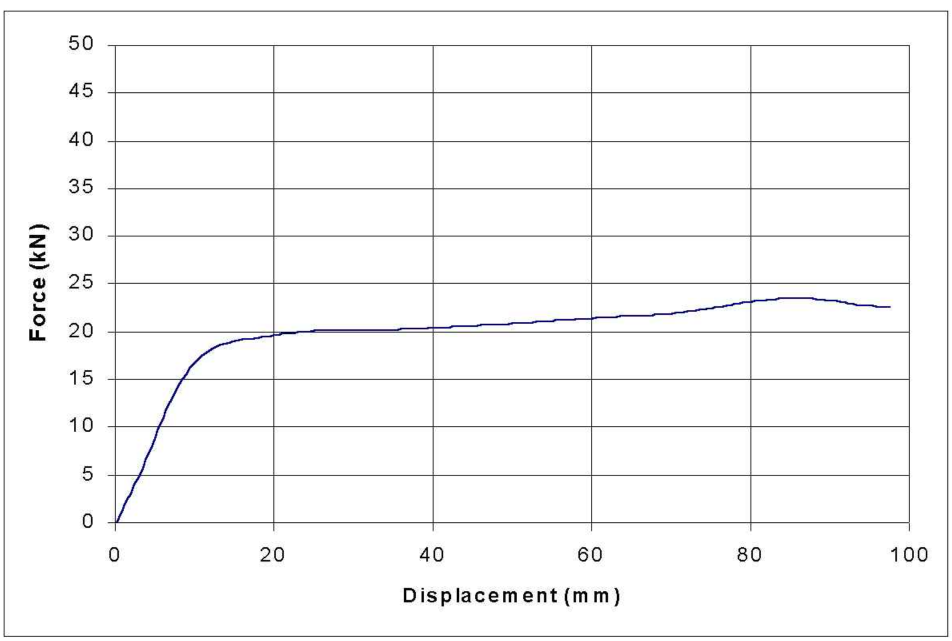

Figure 3. Force-Deflection Relationship

Required Element Density Parametric Study

An examination of the relationship between the number of elements in the cross-section compared to the accuracy of the force-deflection relationship was performed. While increasing the number of elements in the cross-section is beneficial for increasing the accuracy of a finite element model, it does, however, significantly increase modeling time.

Element cross-sections of 5, 8, 9, 12, and 48 were examined to determine the best element density to be used. Densities of 5, 8, and 9 yielded rough transitions in the force-deflection curves and difficulties with contacts due to the limited number of nodes used for the contact algorithms.

Element densities of 12 and 48 were selected for comparison. 48 elements in the cross-section took 31,475 seconds to run, the 12-element model took only 4,609 seconds, a factor of 6.8 times faster on a SGI Origin 2000 machine. The element cross-sections are shown in Figure 4.

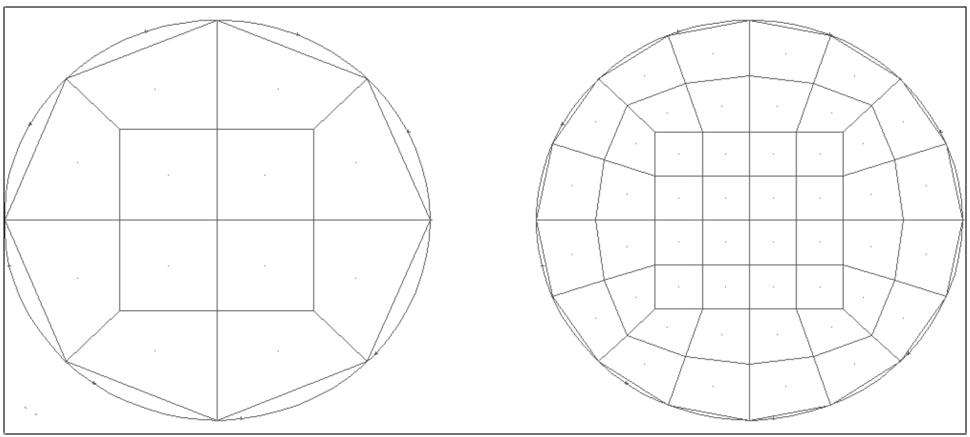

Figure 4. Element Cross-Sectional Density

The model with 48 elements in the cross-section created a smooth, uniform curve that will be assumed to be close to the exact theoretical solution; the 12 elements in the cross-section model appeared to have nearly the same energy and force-deflection characteristics.

Increasing the elements in the cross-section increases the accuracy of the finite element model in bending. As a beam undergoes bending, the cross-section transitions from tensile stresses on the outside of the bend to compressive stresses on the inside of the bend. At least three elements or integration points are required to capture this reaction.

The number of elements in the cross-section becomes more critical when representing plastic strains. The cross-section, becoming increasingly plastic, has to transition through various amounts of plasticity in the cross-section. The more elements in the cross-section, the more accurately this plastic deformation is captured. Additionally, fewer elements in the cross-section account for a stiffer force-deflection response. The force-deflection relationship for both 12 and 48 elements in the cross-section is shown in Figure 5.

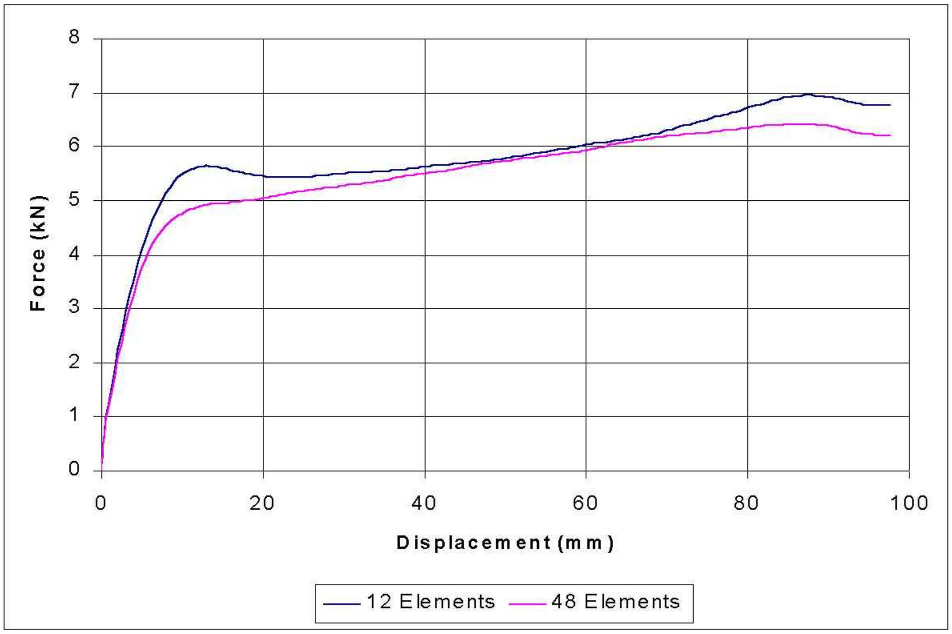

Figure 5. Comparison between 12 and 48 Elements in the Cross-Section

Modified Round Stock Design and Simulation

While any piece of equipment is always expensive and burdensome if it does not perform the required task, minimizing the weight of the tether system is of paramount importance. The initial design was large and heavy, and a smaller, lighter design was desired. The diameters of the rollers that retained the tether were reduced by half to 1 inch, reducing the weight of the rollers by a factor of 4.

Because of the decreased size, an additional length of round stock was added and bent around the rollers, as shown in Figure 6. This allowed for additional energy to be drawn from the system during bending while not increasing the size of the round stock or the rollers.

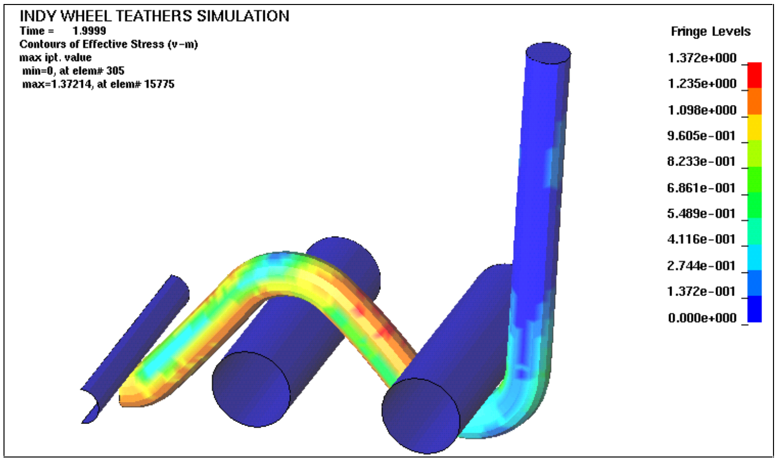

Figure 6. Lengthened Round Section Design

The energy-absorbing characteristics of the new smaller design were much less, however, as shown in Figure 7. Significant stress increases due to swinging the outer portion of the round rod outward caused the failure of the system, requiring a larger spacing between the rollers to reduce the stresses and allow proper performance of the tether system.

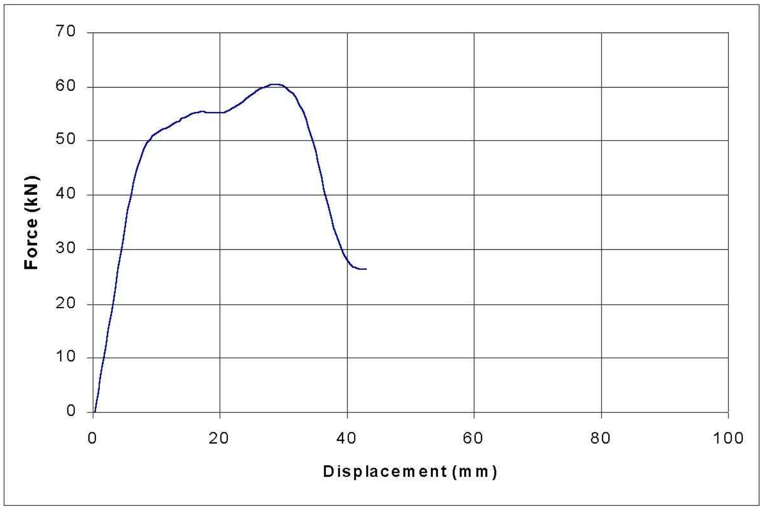

Figure 7. Force-Deflection Relationship

Additionally, the second design sweeps out as the tether is pulled, expanding the system to an unacceptable size, as shown in Figure 8. Since the wheel tether system must fit into the current IRL cars, size considerations are also a critical factor. Because of theses reasons, a system using round stock of this configuration was abandoned.

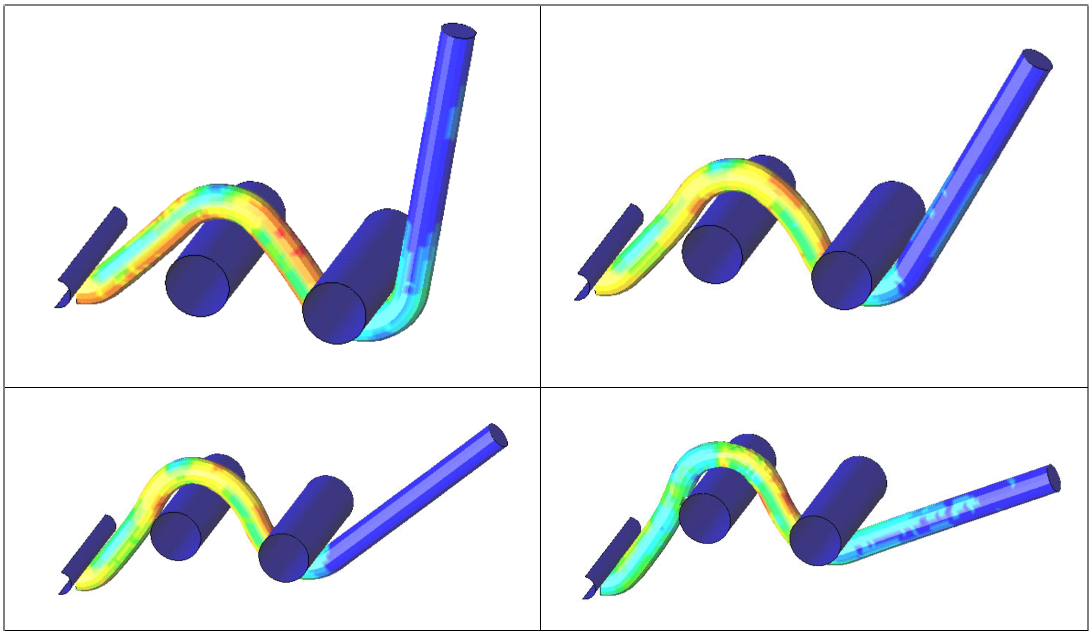

Figure 8. Expansion of the Tether System During Impact

SHEET STOCK DESIGN AND SIMULATION

Since more energy needed to be absorbed in a smaller space, flat sheet stock was used to replace the round stock. This allowed for a lengthening of the tether system, and therefore an increase in its energy-absorbing abilities, without creating excessive size or stress concentrations that would be created in increasing the round stock diameter.

Shell elements were used to model the flat stock. The Belytschko-Tsay element formulation, with 5 integration points through the thickness, was used to capture the bending of the sheet stock. The first flat stock design is shown in Figure 9.

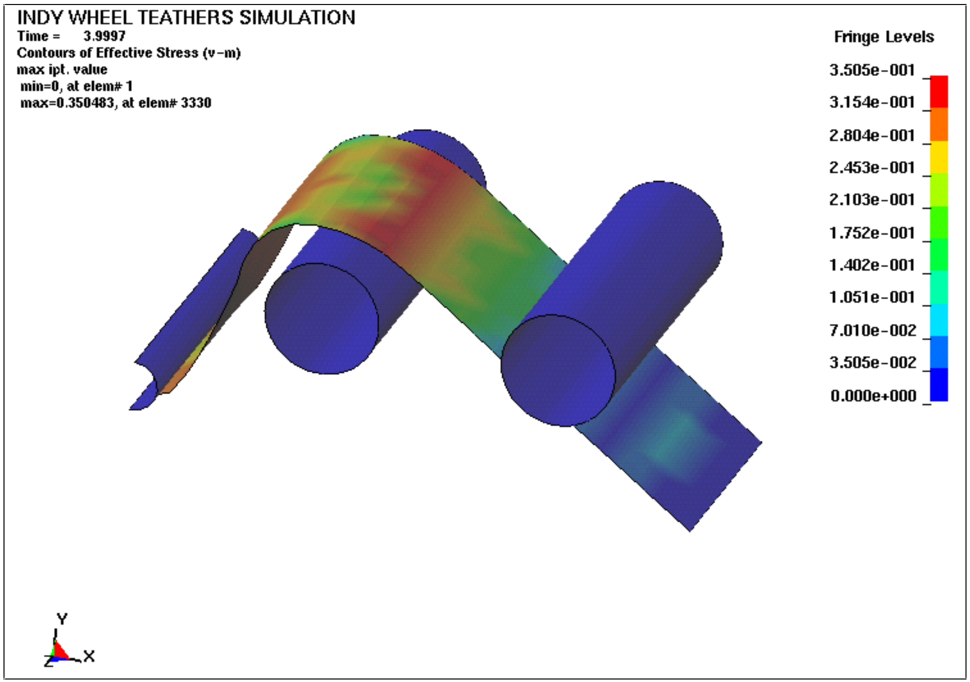

Figure 9. Sheet Steel Section

Once again, however, even the increased width of sheet steel wasn't able to absorb sufficient energy in the limited lateral space. The energy absorbed by the flat sheet stock was only slightly more than 700 N-m. The force-deflection relationship is shown in Figure 10.

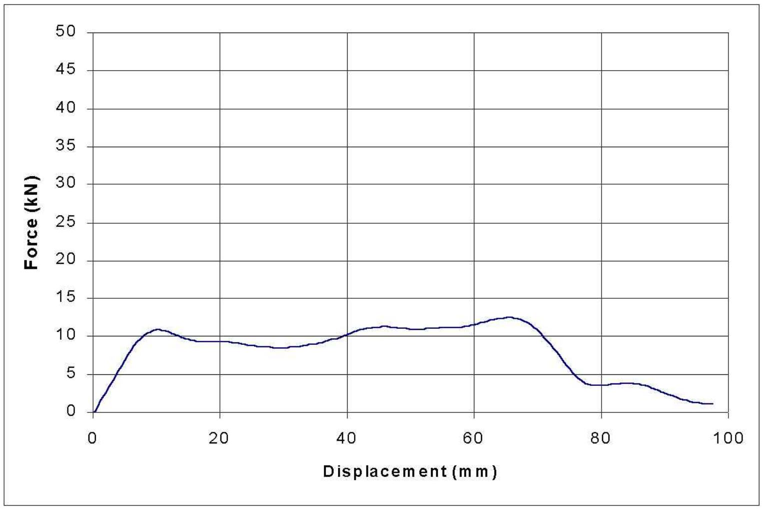

Figure 10. Force-Deflection Relationship

Integration Point Parametric Study

The number of through-the-thickness integration points can drastically affect the accuracy of a finite element model. Integration points are used to determine the resultant stresses and bending moments that are used in the simulation. Insufficient integration can lead not only to unrealistic results but also to mathematical instability.

A parametric study was performed to determine the optimum number of through-the-thickness integration points required to accurately simulate the flat sheet stock under plastic bending. The number of through-the-thickness integration points was varied in single step increments from 1 to 6. The results of this variation are shown in Figure 11.

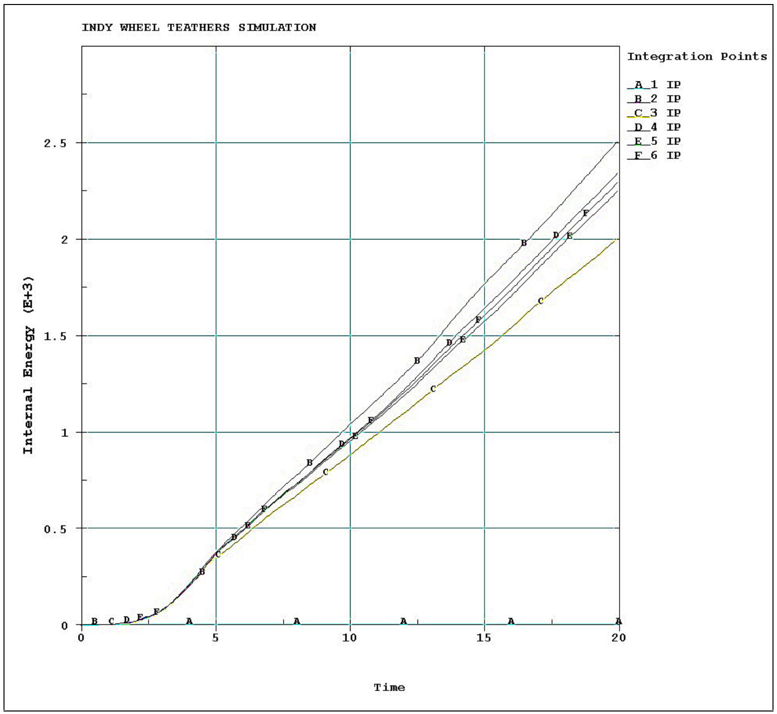

Figure 11. Effects of Through-the-Thickness Integration Points

Results of the parametric study indicate that at least 4, and preferably 6, through-the-thickness integration points are required to adequately capture elasto-plastic behavior in this application. The increasing number of through-the-thickness integration points appears to be convergent. Increasing the number of integration points beyond 6 would not be recommended because of the significant computational costs with relatively small accuracy gains. A better option would be increasing mesh density or using fully-integrated shell elements along with 6 integration points through the thickness rather than increasing the number of through-the-thickness integration points. For this project, 5 through-the-thickness integration points were used. This gave the required accuracy while still maintaining computational efficiency.

Final Wheel Tether Assembly Design

Since the wrapping of the sheet stock around the end rollers would increase the space required, a linear design was adopted. Linearity was required to increase the amount of steel available for bending. Essentially, any method of wrapping the steel around so that it would expand during impact either takes up too much space or created stress concentrations that precipitated the failure of the design. With a linear design, the steel can be bent directly in line with the pulling of the tether cable. This design is shown in Figure 12.

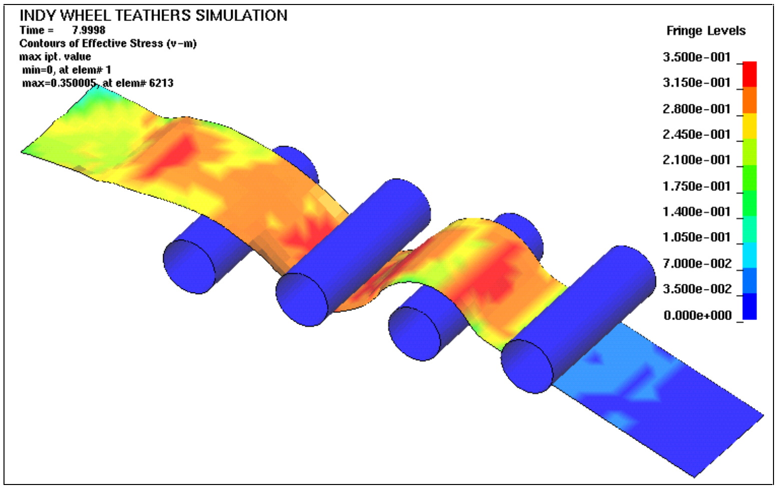

Figure 12. Sheet Steel Pullout

This design performed well, but was not able to sustain angled pulls. Guides on either side were required to guide the tether system. The guides allow for pulling at angles without increasing or decreasing the bending performed by the first roller. The guides also allow for the possibility of using the tether system on both wheels – requiring only one energy-absorbing device and thereby decreasing the weight required for the total system. The revised system with guides is shown in Figure 13.

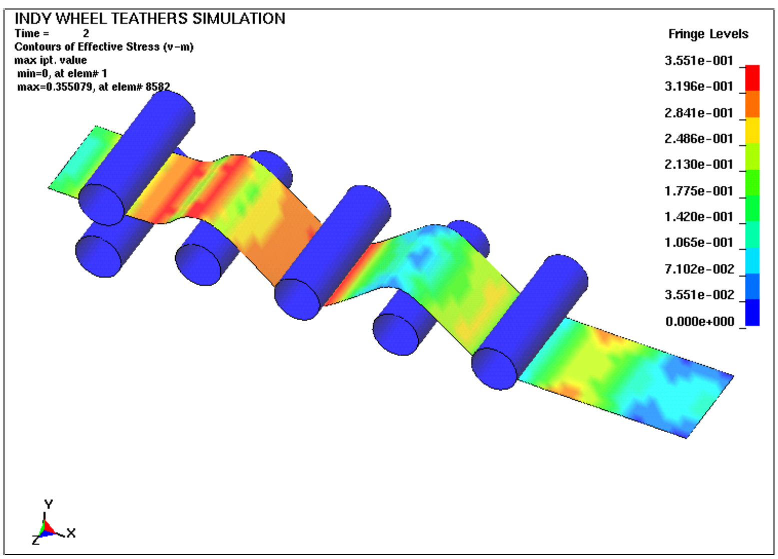

Figure 13. Tether System with Guides

The final design had good energy-absorbing qualities, absorbing 2000 N-m of energy in 100-mm of deflection. Its force-deflection relationship was also very sooth, gradually transitioning to approximately 25 kN and continuing at that level for the length of the tether. The force-deflection relationship is shown in Figure 14.

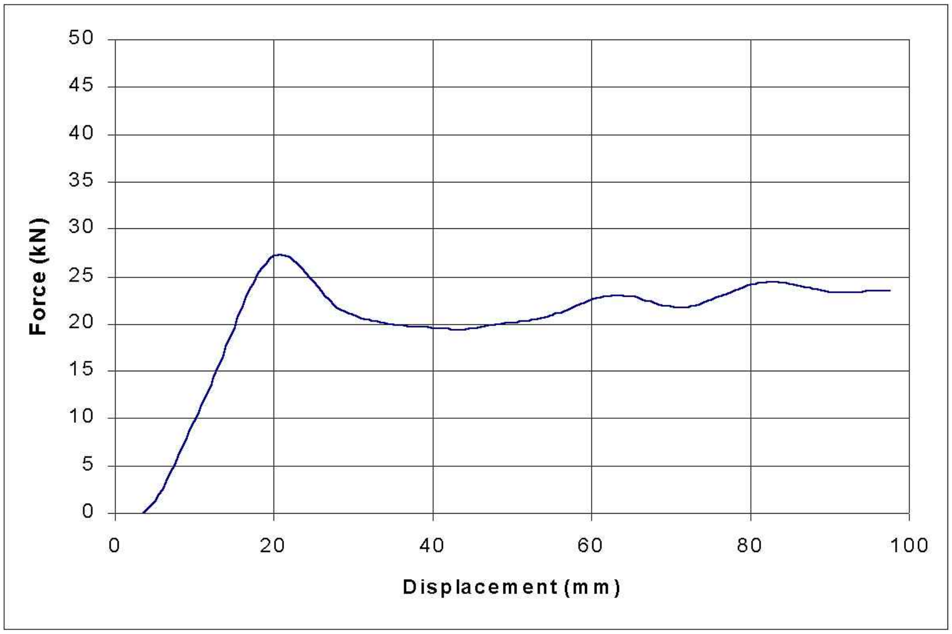

Figure 14. Force-Deflection Relationship

AN EXAMPLE IMPLEMENTATION

Testing of the final design was achieved by attaching the wheel tether assembly to a finite element of the wheel assembly. A cable element was used to attach the two entities using nodal constraints to fix the nodes on the end of the wheel tether assembly. This was done to minimize the possibility of having concentrated loads that may cause the model to become unstable. The completed finite element model is shown in Figure 15.

The wheel, tire, and tire belt were given an initial velocity perpendicular to the longitudinal axis of the car. In order to accurately simulate the event, a rotational velocity was also given to the tire and wheel assembly of 0.08 radians per millisecond. The deformed system is shown in Figure 16. Energy absorbed by the tether totaled 10,000 N-m.

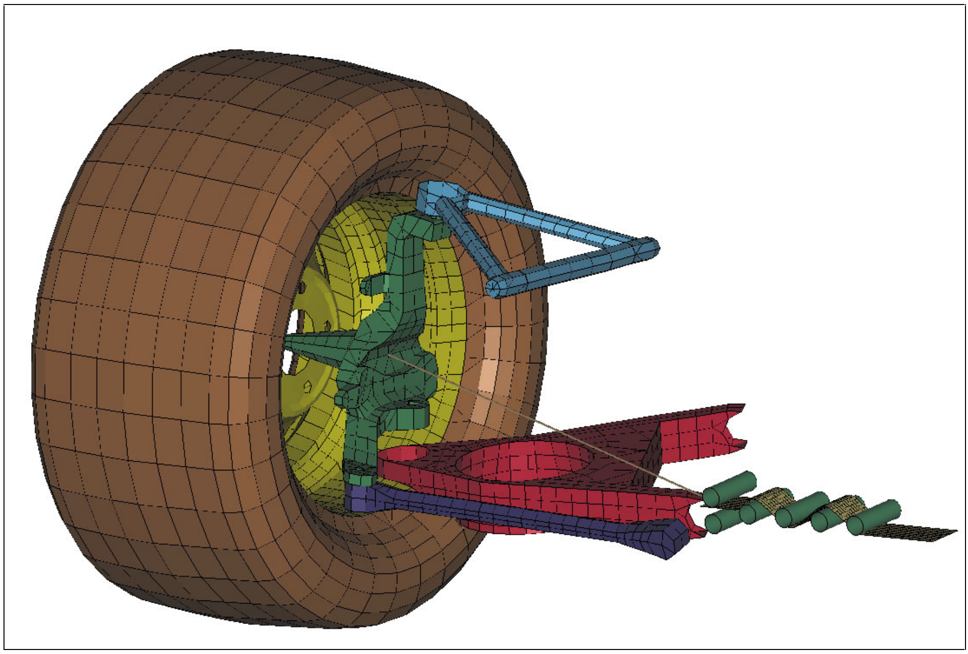

Figure 15. Final Design as Attached to Wheel Assembly

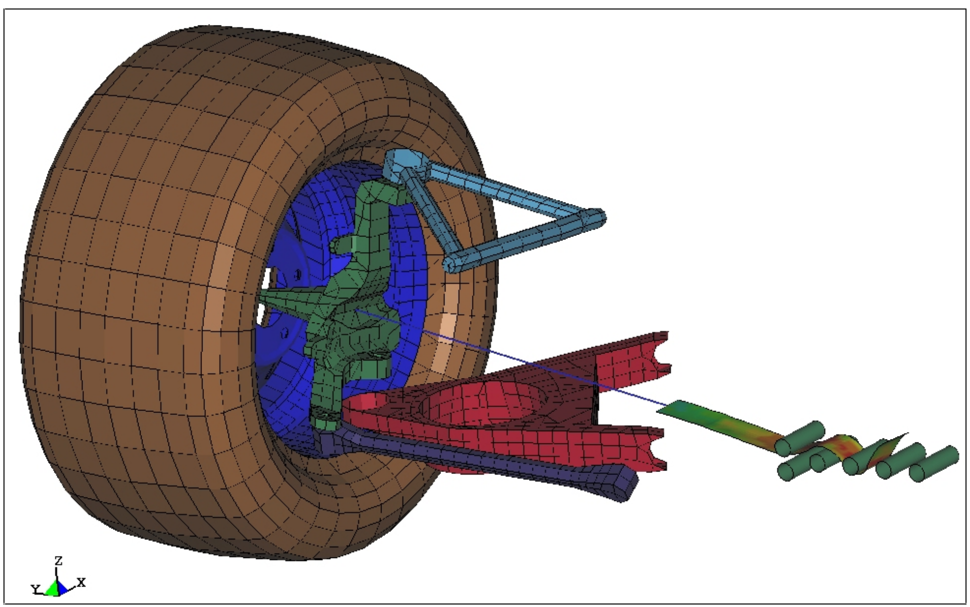

Figure 16. Assembly during Deformation

CONCLUSIONS

New concepts for energy-absorbing wheel tethers for racecars showed promise in simulation. The developed tether design was able to absorb a total of 10 kJ of kinetic energy from the wheel assembly. This amount of energy is equivalent to reducing the trajectory height and distance of a 68-kg wheel assembly 7.5 m (24.6 ft) and 30 m (98.4 ft), respectively, for an assembly detaching at an angle of 45-degrees.

It is important to recognize that the designs presented herein are just concepts and would need a detailed design and testing program before any such systems could be implemented.

ACKNOWLEDGMENTS

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