PDC electrical cable modeling using TRUSS elements

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1 Abstract

This study aims to present a proposal for finite element modeling for electrical cables of a PDC to improve the response of the virtual analysis during design phase, establishing a good interation of electrical cables during crash tests. The objective of this study is to present types of elements and contact pairs that are capable of predicting the response of electrical cables.

In current vehicles, the use of PDC units is an increasingly larger reality. In attempts for improvements they tend to occupy a larger space, which create an additional challenge to the vehicle architecture project in positioning it.

The positioning should be done in order to avoid cable ruptures and anchoring of the PDCs as much as possible. As the cables are energized there is always a risk of short circuit, for this reason, vehicle safety must be ensured by avoiding or minimizing the interaction between cables and components of the engine compartment.

In this way, a better definition of the form that the cables interact among themselves and between engine elements, led us to present contact formulations that can improve the understanding of the phenomenon.

In addition, when electrical cables interact with other components, they suffer tensile stress and must not be able to withstand compressive loads, for this, different formulations are presented as the type of finite element to be used, as in the case of TRUSS elements instead of BEAM which are able to withstand moments and compressive loads.

In order to guarantee and validate the modeling in the vehicle, a simplified model test was also carried out to assess the condition of the cable, as well as the physical tensile test.

KEYWORDS: PDC electrical cables, Truss elements, Crash tests.

2 Introduction

When preparing models to analyze crash tests, several components must be considered to ensure vehicle safety. Currently, in order to achieve a certain degree of excellence in the classification of safe vehicles, it is necessary to model not just the body, but also suspension elements, engine, transmission, fuel system and electronic components as wiring harnesses (to avoid and predict short circuits that could happen).

Component modeling takes into account the appropriate definition for the various types of elements, whether shells, solids and one-dimensional elements. Another key part is the definition of the material model that best represents the condition of the mechanical component established by the geometric property of the finite element type, associated with the state of stress that it may suffer due to loading, thus choosing a material model that allows calculating the elasticity, plasticity or even the damage is necessary.

In addition to modeling an isolated component, (thinking about the crash test universe where there are many iterations between the different components), the dynamics and modeling of the contact between the parts needs additional care.

In this context, cable modeling is no different and one must take into account this entire process described between the appropriate definition of the type of finite element to be associated, the material model capable of calculating the stress state as well as a contact formulation that allows a better approximation of the numerical modeling of the physical reality of the crash event.

The modeling strategy for entire vehicles is something already settled and for some specific condition where the model usually considered does not attend, improving is needed. Therefore what is presented in this study is a part of development in the model for cables to better predict the kinematics of cables and components surrounding it. The specific cables that are treated here is from PDC (Precision and Drive Control) cables, which had two (02) different challenges: the layout of the cable and the anchorage.

Note that electrical cables are generally made up of an intertwined core of copper wires with a polymeric coating, so a numerical model capable of considering such materials in their cross section must be sought.

3 Crash test models for cables

In modeling elements with a geometric condition where one-dimensional modeling can be used as a cable, some practices can be applied such as:

1. Model using 1D elements connected to their anchors by rigid type elements. As for the material model, if there is no concern about cable failure, elastic-type formulations for material are enough; However, the iteration of this type of modeling lacks a more robust strategy to capture the contact, the interaction between parts, thus it ends up being ineffective.

2. Use type 1 modeling but with the addition of shell elements around, these with the ability to evaluate the iteration between components, improvement in the formulation of the contact pair;

3. Cable model with 1D elements connected by rigid elements in the fixtures surrounded by solid elements to represent, in addition to the copper core, the polymeric coating.

However, to model cables and with kinematics contemplating the rigidity of the element that is trying to represent, we have some options. In this particular study it was work to develop a different way.

It should be noted that the modeling of cables seeks for types of elements where it should not be able to resist bending moments or compressive loads. Considering that, in the case of a cable, the stiffness to the load of compression must be zero (or minimum depending on the mechanical property of the material that composes it). In Figure 1 shows different models assuming the cable.

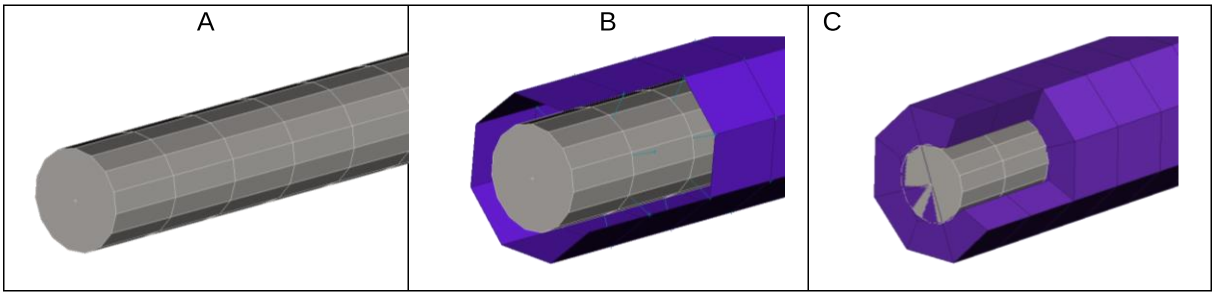


Fig.1: Different strategies for modeling a cable, 1A (only 1D), 1B (1D+shell),1C (1D+Solid).

According to [1,2,5,6,7], it used beam element-discrete beam /cable (ELFORM=6) and *MAT_CABLE_DISCRETE_BEAM (*MAT_071) this condition was performed to model safety barriers.

For the case of cables/wires of the vehicular electronic system, we regularly use one-dimensional BEAM element associated with SHELL elements predicting the polymer portion, but when evaluating the kinematics of cable movement interacting with elements of the motor span, it is clear that the influence of the high rigidity of the cable arising from the formulation of the beam element (that does not generate satisfactory and correlatable values).

Thus, specifically for this type of electronic cable, the modeling capable of reducing the effect of bending moments and the compressive portion that the model carried was revised. This was only possible with the use of TYPE TRUSS or Element Discrete. For Truss elements that have degrees of Freedom as described as pin-jointed truss element are shown in Figure 2. This element has three degrees of freedom at each node and carries an axial force [2].

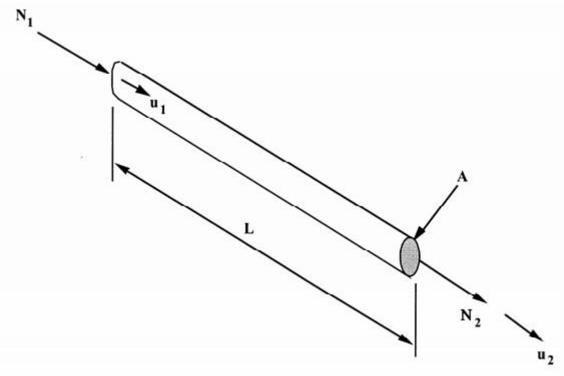


Fig.2: Truss element in LS-Dyna Theory Manual [1].

3.1 Numerical Simulations

To assess the difference between the models, we initially tried to carry out compression and traction tests on the cable with the best established practice. For the compression model, it used the principle that in order to be a cable and function as such, the result of a compressive loading should be null or as little as possible.

In this way, a model were established containing a TRUSS element for the copper core and associated with it, a SHELL element that defines the polymeric coating of the electrical cable, anchored at one end and loaded at the other. With the result, the best form was sought, towards presenting zero bending moment and compressive load zero too.

In Table 1 is presented the formulation of Beam elements.

Beam Model

Part	Technical Data	Description
BEAM elements	Diameter 6 mm Mesh size 4 mm	ELFORM= 2 Belytschko-Schwer MAT= 1 Liner material Copper Young Modulus = 100GPa Density= 8.190 kg/m³
SHELL elements	Thickness 2mm Mesh size 4 mm	ELFORM= 16 Fully integrated shell MAT= 24 MAT_PIECEWISE_LINEAR_PLASTICITY PP Young Modulus = 1,2GPa Density= 970 kg/m³

Table 1: Beam elements formulation

Truss + Shell Model

Part	Technical Data	Description
TRUSS elements	Diameter 6 mm Mesh size 4 mm	ELFORM= 3 Truss Element MAT= 1 Liner material Copper Young Modulus = 100GPa Density= 8.190 kg/m³
SHELL elements	Thickness 2mm Mesh size 4mm	ELFORM= 16 Fully integrated solid MAT= 24 MAT_PIECEWISE_LINEAR_PLASTICITY PP Young Modulus = 1,2GPa Density= 970 kg/m³

Table 2: Truss elements formulation

Truss + Solid Model

Part	Technical Data	Description
TRUSS elements	Diameter 6 mm Mesh size 4 mm	ELFORM= 3 Truss Element MAT= 3 Cowper-Symonds Copper Young Modulus = 100GPa Density= 8.190 kg/m³
HEXA elements	Outer Diameter 10mm Mesh size 4 mm	ELFORM= 2 Fully integrated solid MAT= 24 MAT_PIECEWISE_LINEAR_PLASTICITY PP Young Modulus = 1,2GPa Density= 970 kg/m³

Table 3: Truss elements formulation after physical test

In order to obtain the most faithful behavior possible from the cable and the interaction with the elements around it, several investigations were tried. To better capture the contact, we vary the friction, to capture the cable behavior, we change the type of element adopted, and to capture the failure we investigate the forms of material models available in Ls-Dyna.

Table 4 shows the types of models tested, the main ones, as well as the structural response obtained in the expected behavior column.

Loop of Investigation	Description	Expected Behavior
01- Friction 0.05	Evaluate contact between cable and other components	No
02- Friction 0.01	Evaluate contact between cable and other components	No
03- Element Type	Evaluate contact between cable and other components. Switch element type from ELFORM 16 to ELFORM 2	No
04- Traction Truss	Traction cable with 1000N	Yes
05- Traction Beam	Traction cable with 1000N	No
06- Polymer	Switch polimer material to a plastic MAT24	Yes
07- Rigid Switch	Switched RBE2 to RBE3.	Yes
08- Compression	Compression Test Beam.	No
09- Compression	Compression Test Truss.	Yes
10- RBE3 DOF123	Switched DOF of RBE3 to 123.	Yes
11- Contact	Contact with TRUSS + RBE3 DOF123 + MAT24 2mm	Yes
12- SHELL	Rupture Test: Truss + RBE3 + Shell	No
13- HEXA	Rupture Test: Truss + Hexa polymer	Yes
14- MAT 71*	MAT 71 is incompatible with TRUSS	No
15- MAT 71*	MAT 71 combined with Discrete element	No
16- MAT 71*	MAT 71 combined with Beam ELFORM 6	No

Table 4: Looping of investigations.

Adopted model is presented in Figure 3.

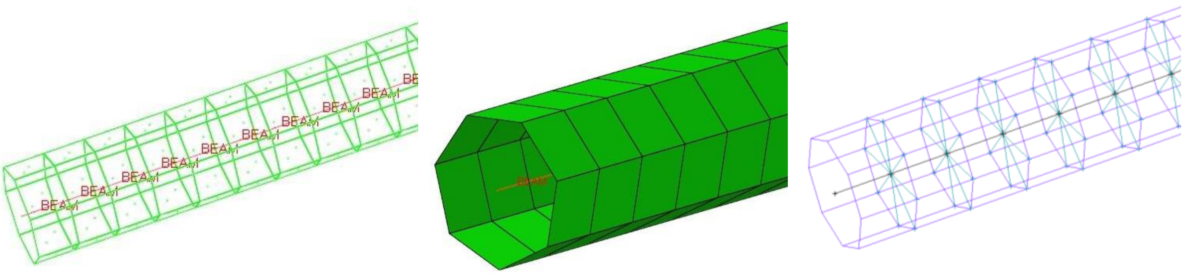


Fig.3: Modeling adopted comparison between BEAM and TRUSS.

*Note: The use of Discrete Beam together with MAT_71 for our purpose was not considered conform, because it is not possible to define the diameter of the section, and failure criteria, as for when we compare to the forces obtained in our physical test.

3.1.1 Boundary Conditions applied for Traction and Compressive test together Analytical evaluation

Considering the use of BEAM elements and TRUSS elements, two component tests were applied to evaluate the model's response. For the tensile test, 1000N was applied, and for the compression model, the prescribed displacement was applied only to ensure adequate convergence. The modeled cable considered is an electronic cable with the following dimensions:

Copper Core 4mm in diameter	Copper Material: E =100 GPa
polymer coating 2mm thick	Polymer Material E=1.18 GPa

Table 5: Material properties.

In Figure 4 there is a cross section of the cable;

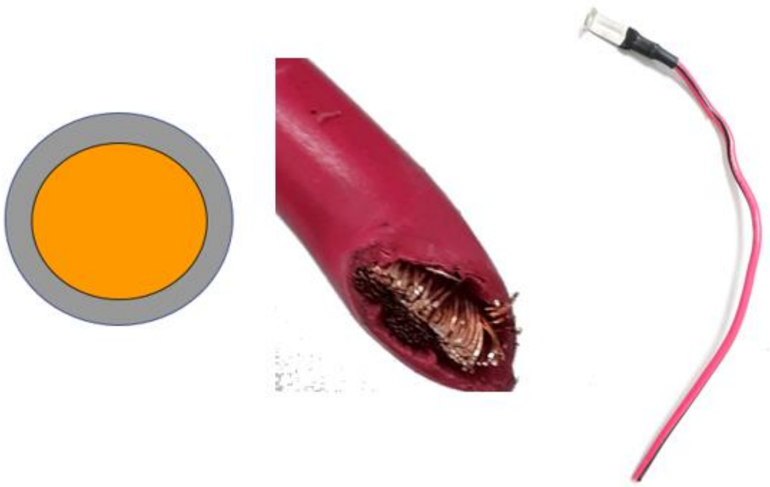


Fig.4: Transversal section of the cable.

As mentioned in Figure 4, there is the boundary condition used for the tensile test, where a length of 100mm was used.

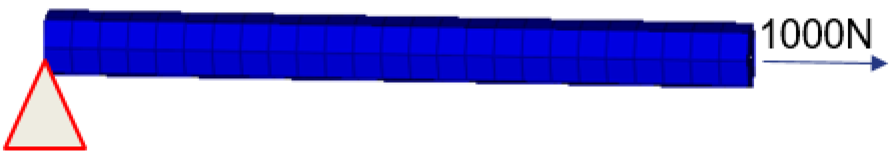


Fig.5: Transversal section of the cable.

3.1.2 Analytical evaluation

If it is considered a composite beam made up of two materials A and B and assuming for simplicity a rectangular cross-section with Young´s modulus of elasticity as E_A and E_B ($E_B > E_A$) [3], see Figure 6.

Applying a transformation to a section and making a balance of forces in the cross section capable of producing the same bending moment, it is possible to arrive at the following equation.

$$E_B A_B = n\, E_A A_A$$

n, is transformation factor;
E_B , E_A, Young's modulus of elasticity of copper and polymer respectively;
A_B, A_A, section area of cooper and polymer respectively;

Therefore, $\sigma_A = n\,\sigma_B$

And using Hooke's law - $\sigma = E\varepsilon$, together with the deformation definition $\varepsilon = \frac{\Delta L}{L_o}$;
σ , stress in the section;
ε , deformation;
ΔL, delta of length;
L_o Initial length.

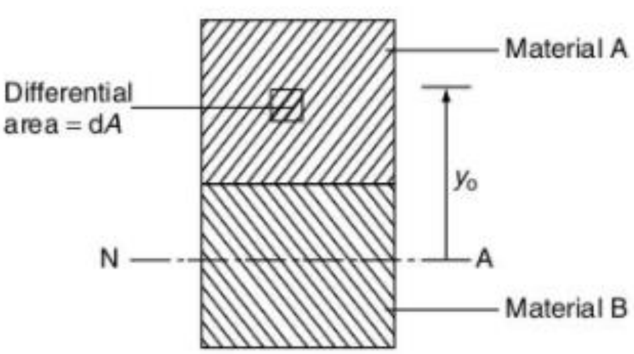


Fig.6: Cross-Section of composite beam.

In this way it is possible to calculate:

Factor n	68		**Strain Cooper**	0.080	%	Finite Element Analysis
Stress Cooper	79.6	MPa	**Strain Polymer**	0.054	%	**ΔL = 0.075mm**
Stress Polymer	63.7	MPa	**ΔL**	**0.080**	mm	**Correlation of 94%**

Table 6: Analytical calculus of final displacement

In addition to this evaluation, it will be evaluated via finite element analysis also with the proposed modeling.

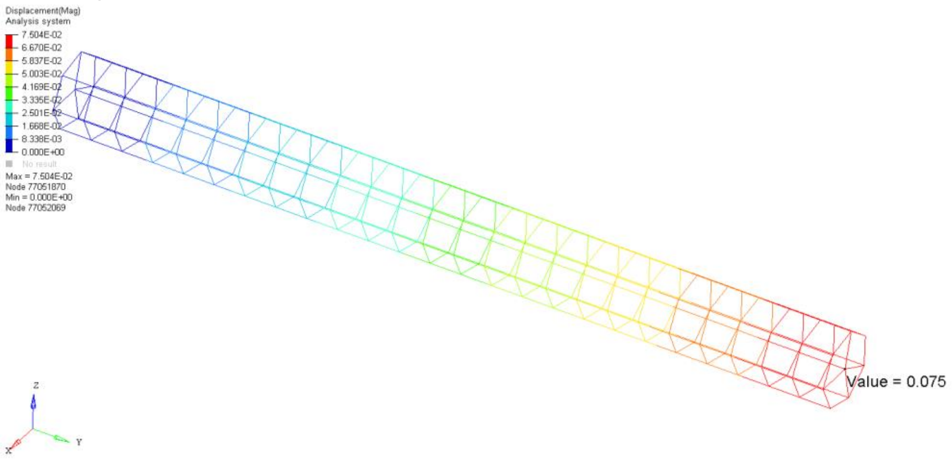


Fig.7: Displacement obtained with a simplified model.

One important note from this model is the values of the beam elements around the length that have different values of force when using Beam elements instead of Truss.

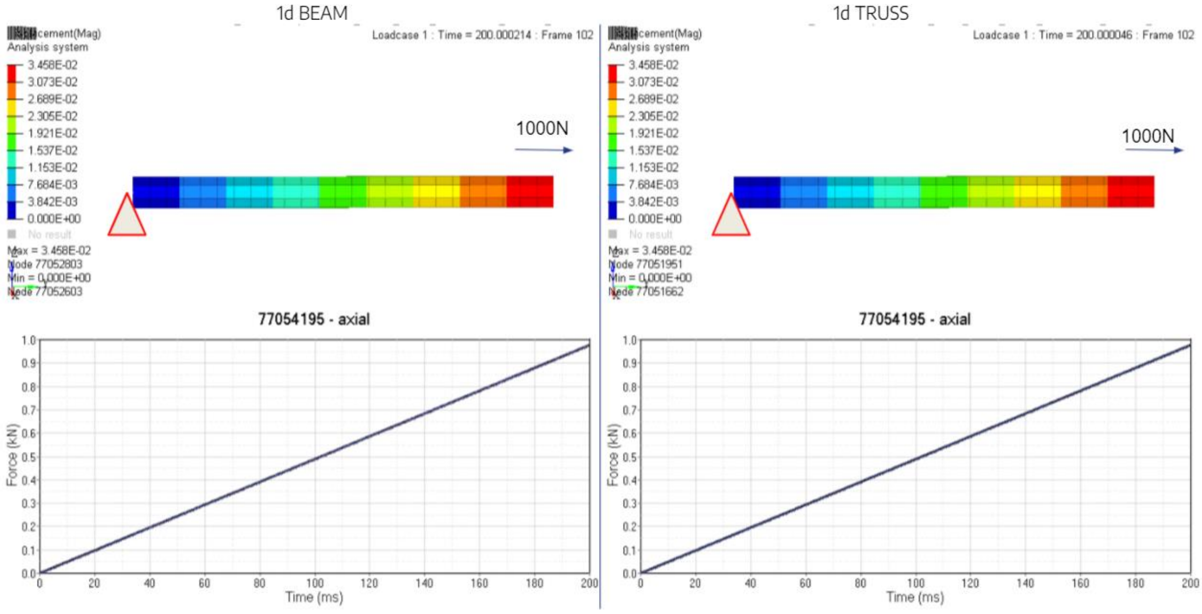


Fig.8: Variation of forces around the length of the cable.

To ensure that the virtual model also presented a good correlation regarding the behavior of the cable where bending moment load and compression load were minimized, the cable was compressed according to the two proposed models.

3.1.3 Compressive test

For a compressive test using a prescribed displacement to guarantee a good convergence, the boundary condition and the results are shown in Figures 9 and 10.

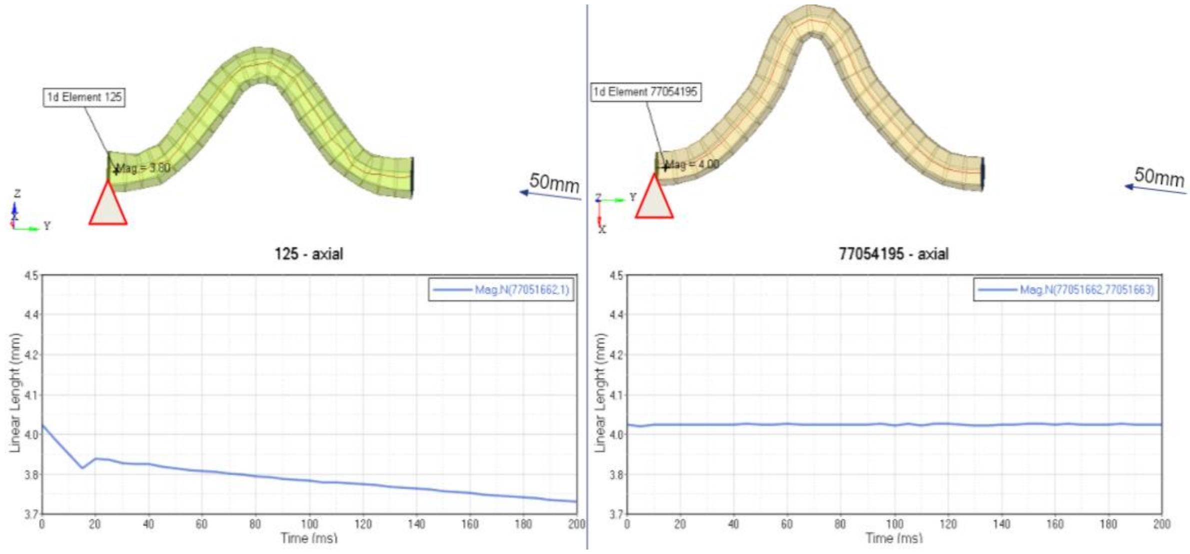


Fig.9: Differences between BEAM and TRUSS as for the displacement of elements

Additionally it was verified the influence of the moments in the element formulation. With the result, we were able to verify and validate that the TRUSS element is more effective to predict the behavior of one cable instead of the use of a beam element, because it does not have the expected capacity to absorb moments for electronic cables during the impact.

Figures 9 and 10 presents the differences of both modeling strategies.

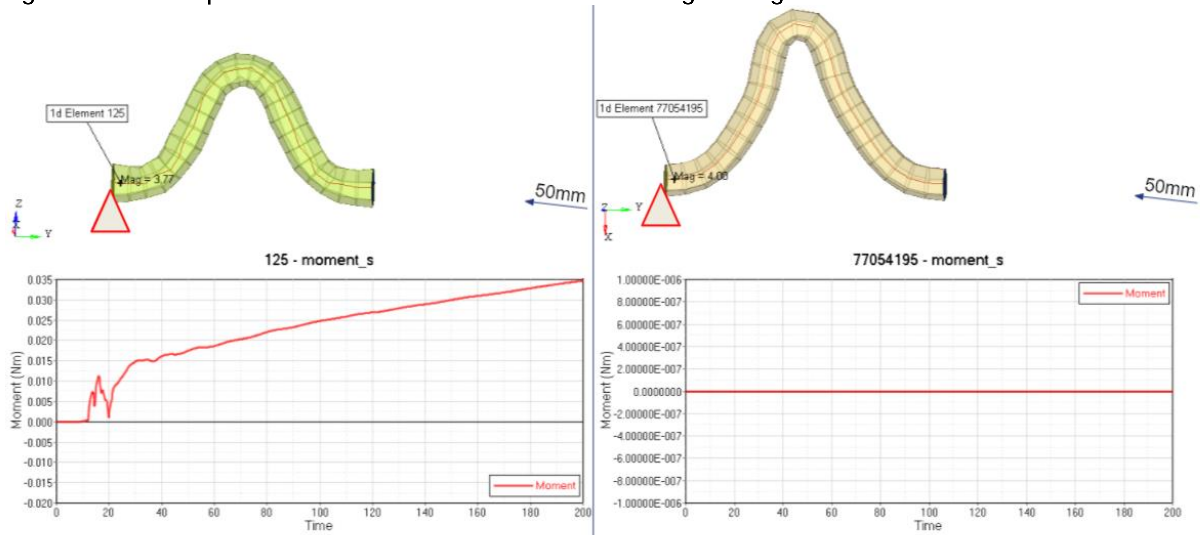
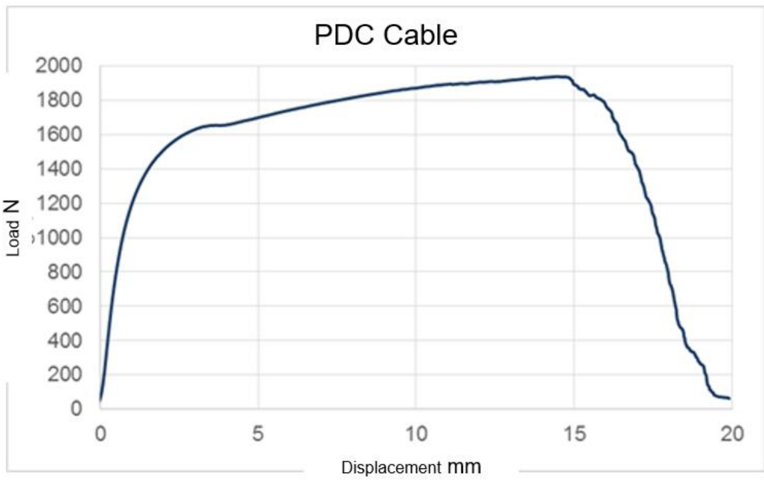


Fig.10: Differences between BEAM and TRUSS as for the bending moment of elements.

4 Physical test on an isolated component

Establishing the model that best allows to numerically represents the behavior of cables, an attempt was made to validate the breaking load of the PDC electronic cable, thus a tensile test was performed to reach the limit load value. Standard equipment for traction load was used and the test was conducted in which the response was also simulated in the virtual model.



Cable	Load Max, N	Disp., mm
PDC	1938	14,5

Fig.11: Physical test on PDC cable.

With the force and displacement data, it was possible to evaluate the stress and limit strain for the electric cable. So, mechanical properties calculated are presented as elastic modulus E= 100 GPa, Yield Stress= 23 MPa and Failure Strain= 0.17%.

In order to validate the proposed methodology, we sought to verify again if the model with TRUSS and shell elements would allow a good representation of the model.

Initial test was done in the cable simulating the traction considering the data from the physical test and assuming failure via load. Despite all the considerations, the maximum load for this methodology was 1525N and maximum elongation was 5.5mm. What is not correlated with the test. In Figure 12 is presented the evaluation conducted.

The first attempt was not considered good enough. In this way, the study was continued through a material model that was able to capture the failure with a very cost effective model as is *MAT_003, or *MAT_PLASTIC_KINEMATIC - this material allows use: Young's modulus, Yield stress, Poisson's ratio, Strain rate parameter (assumed zero) and Effective plastic strain for eroding elements. Strain rate is accounted for using the Cowper and Symonds, but here rate effects was not consider [4].

Final test to achieve validation of the observed phenomenon was possible just considering hexa-type elements with truss inside the cable (see Figure 13), adopting one-dimensional modeling associated with the material model isotropic and kinematic hardening plasticity described in table 3.

This way, besides the displacement of 14.5mm and the failure load of 1901N, was able to be captured and correlated.

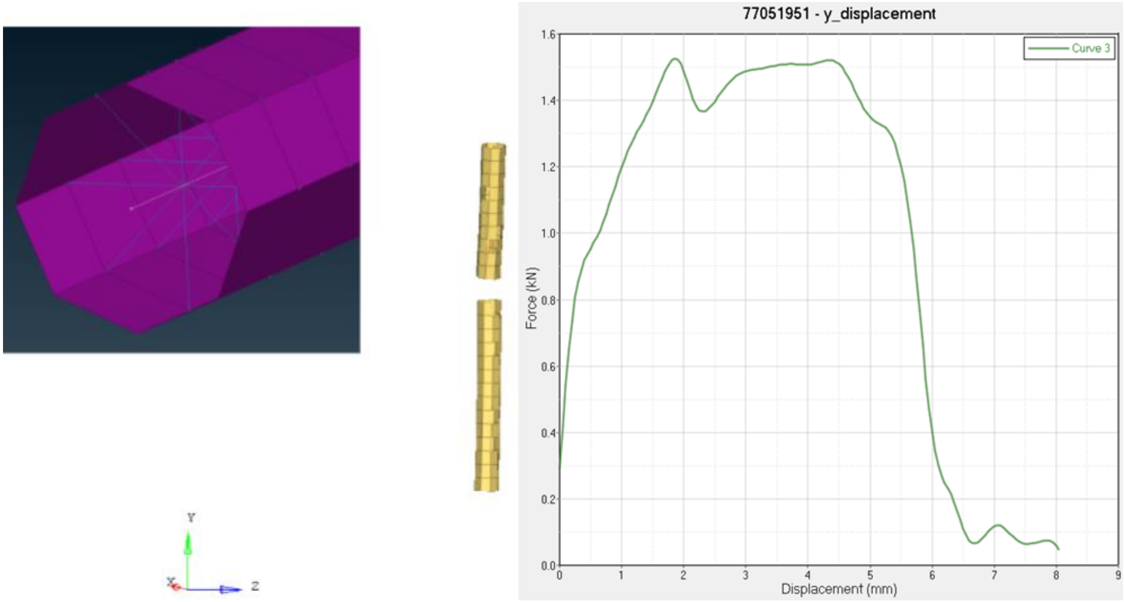


Fig.12: First Attempt of modeling.

In response to the failure mode in the physical test, the position in which the rupture occurred was just after the region where the claw was attached and not in the middle of the cable as simulated by the assumption of usage shell.

In this way, modeling using solid elements was once again able to better predict the mode of rupture found.

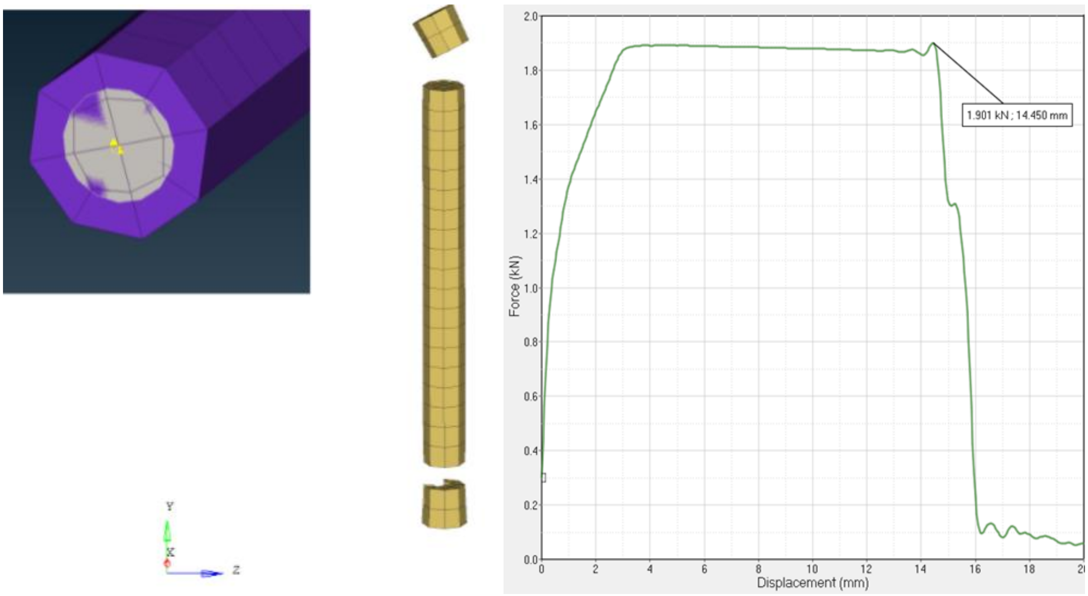


Fig.13: Final Attempt of modeling.

4.1.1 Contact formulations

During the crash test evaluation, it was noticed that the shape of the contact between the cable and the components that iterated altered the load, thus, a different modeling was added for the contact pairs in order to better capture the event kinematics.

The contact adopted for this simulation is AUTOMATIC_SINGLE_SURFACE setting the SOFT parameter to a value of 1 and dynamic and static friction are 0.2. What was noticed when adopting a rigid element connected in each 1D element up to the shell or solid element, is that if it adopted an RBE2 the deformation in the cable becomes null and the cable becomes a rigid element Figure 14A. Although if it is adopted RBE3 formulation the deformation on the surround elements occurs and the element works as a deformable component. It showed localized deformation due to the interaction between cable and components in Figure 14B.

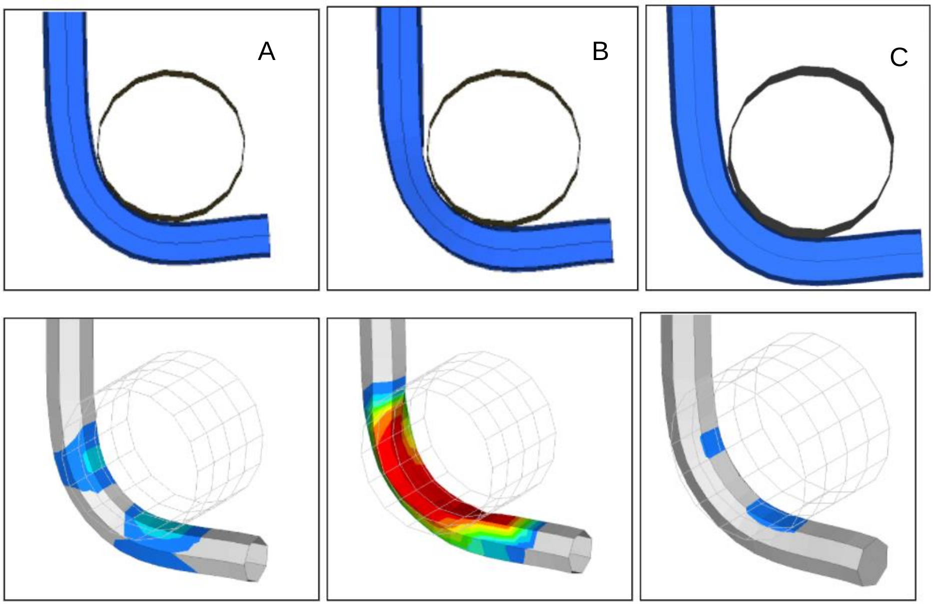
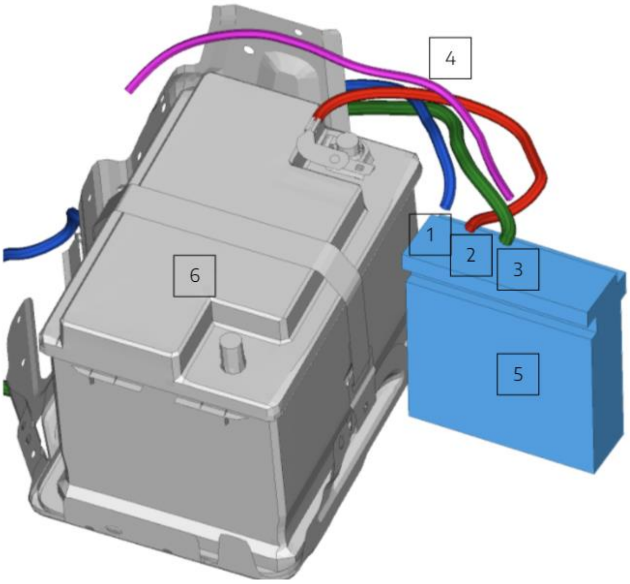


Fig.14: Contact pair with different rigids components

On the left, the model with RBE2 (CONSTRAINED NODAL RIGID BODY), keeping the area of the cable section constant. On the middle, the model with RBE3 (CONSTRAINED INTERPOLATION), deforms by modifying the cable cross-sectional area. On the right, Figure 14C the model with solid and 1d truss, presents less deformations. This behavior is related to the contacts between the elements, since the element's normal changes with the deformation.

5 Vehicle complete results

Considering the initial model, it is easy to understand the motivation to evaluate better the condition of electrical wiring. In Figure 15 is shown the installation connected in the battery and in the PDC.



ID	Component
1	PDC Cable 1
2	PDC Cable 2
3	PDC Cable 3
4	PDC Cable 4
5	Precision Drive and Control (PDC)
6	Battery

Fig.15: PDC wiring connected in battery

During a frontal crash if the battery moves in X direction, assuming that the PDC continues fixed, relative movement could occur and because of that the electric cables will suffer a tension. How much the cable is capable of supporting and where is the best position - the best layout - to place the components, is the product engineering challenge. To understand the kinematics of the event on schematic figure is presented in Figure 16.

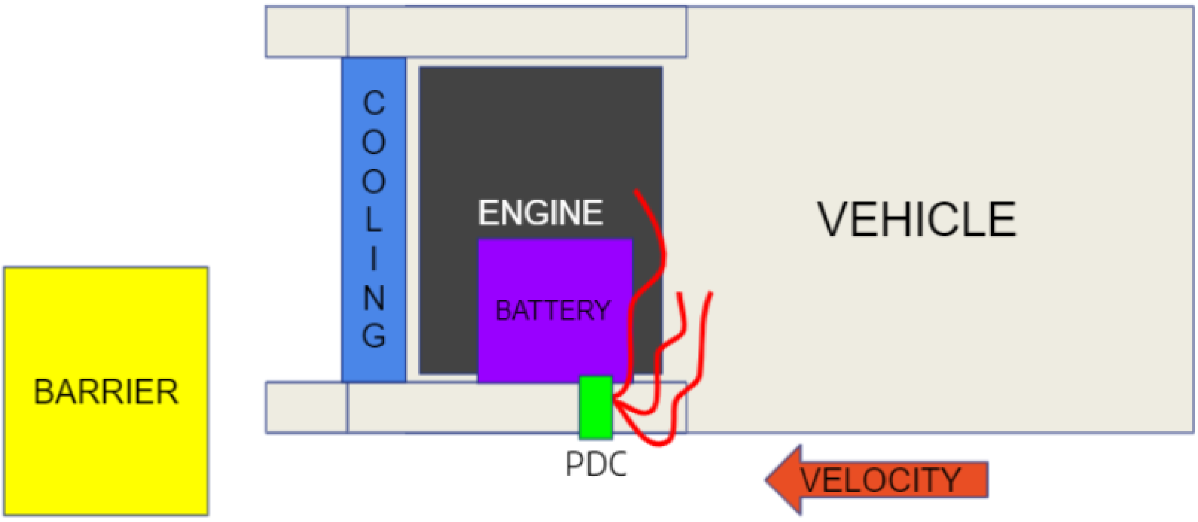


Fig.16: Crash test schematic condition for battery and PDC cables

Thus, the 3 way to model PDC cable are described, as follows:

1. The model with BEAM presented a high loads on the cables, which is not desired, more than the limit of the material;
2. The model with Truss + Shell presented a large localized deformation compared to the established layout;
3. The model with Truss + Solid was able to capture both force and contact.

In Figure 17 presents forces on the cable using Beam in formulation. It was not possible to evaluate the failure in the cable with this model and the loads occurs in the cable became overestimated.

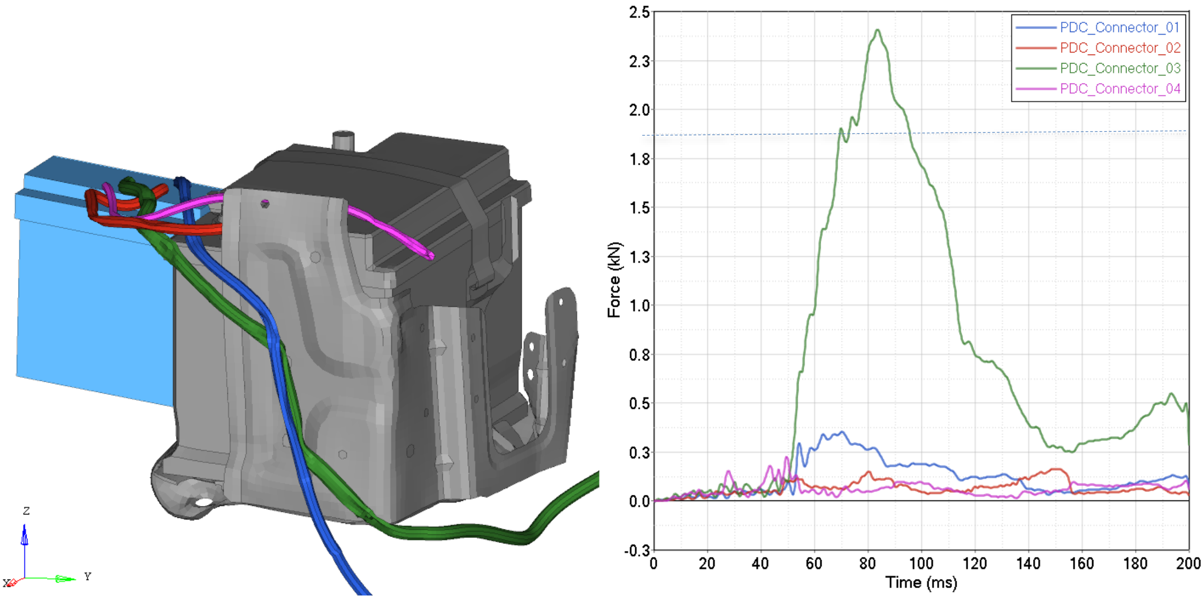


Fig.17: Forces on PDC cables (BEAM method) - Baseline layout

In Figure 18 presents forces on the cable using Truss + Shell in formulation. A good reduction occurs in the forces from the cable. Initially it was thought that the shell would meet, and after testing in the simplified model, the breakage was not good.

Therefore, we decide to verify in a complete vehicle analysis to see if the forces are reasonable. In this analysis it was detected a localized crushing in some parts of the cable, which implied changing the layout if this was found to be a problem.

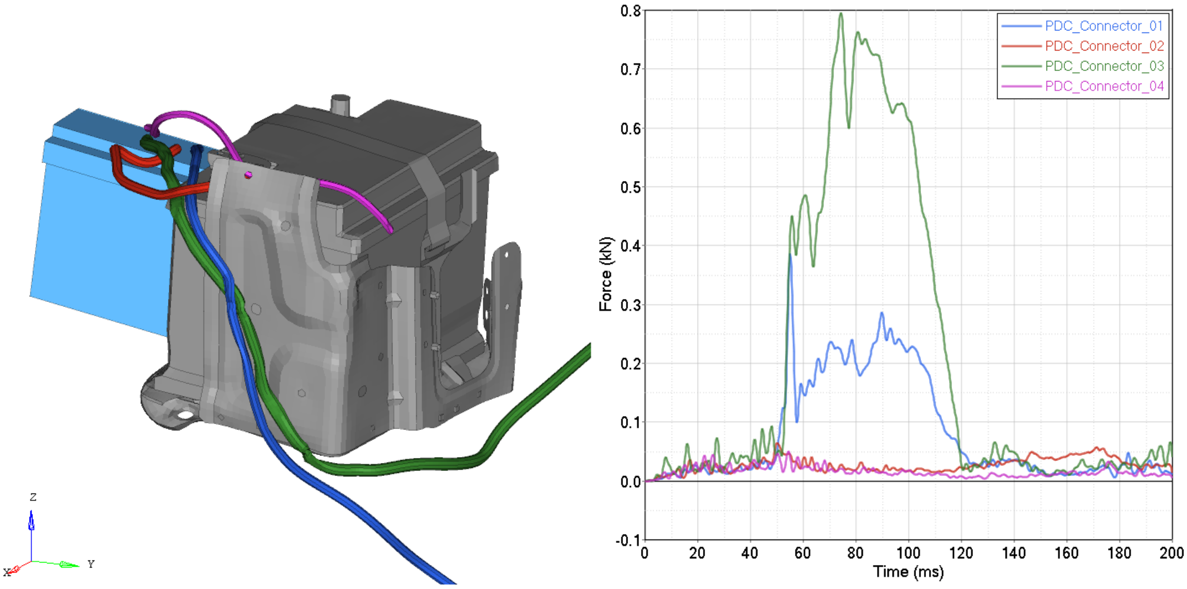


Fig.18: Forces on PDC cables (Truss + Shell method) – Baseline layout

So, assuming a new layout that was considered a solution to the initial problem that motivated this study, we saw an important change in the critical cable, which became cable 1 instead of cable 3 as we've been seeing from the beginning, see Figure 19.

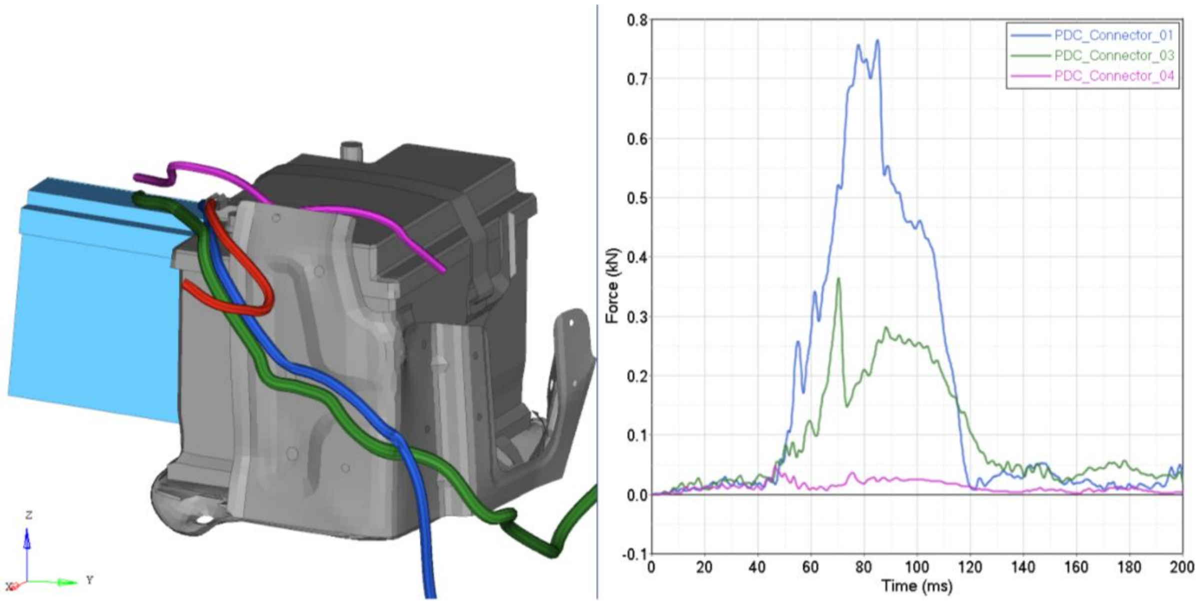


Fig.19: Forces on PDC cables (Truss + Shell method) – New layout

With these results, it were decided to do the same evaluation with the Solid +Truss formulation, what allows us to discovered that the values in the cables became near of the allowable of the anchorage. It had not been mentioned before, but if we have a cable and the forces should be continue along it, the forces on the anchorage should be the same. In Figure 20 it is possible to see that the values in the cable are less than the others formulations (from 750N to 480N).

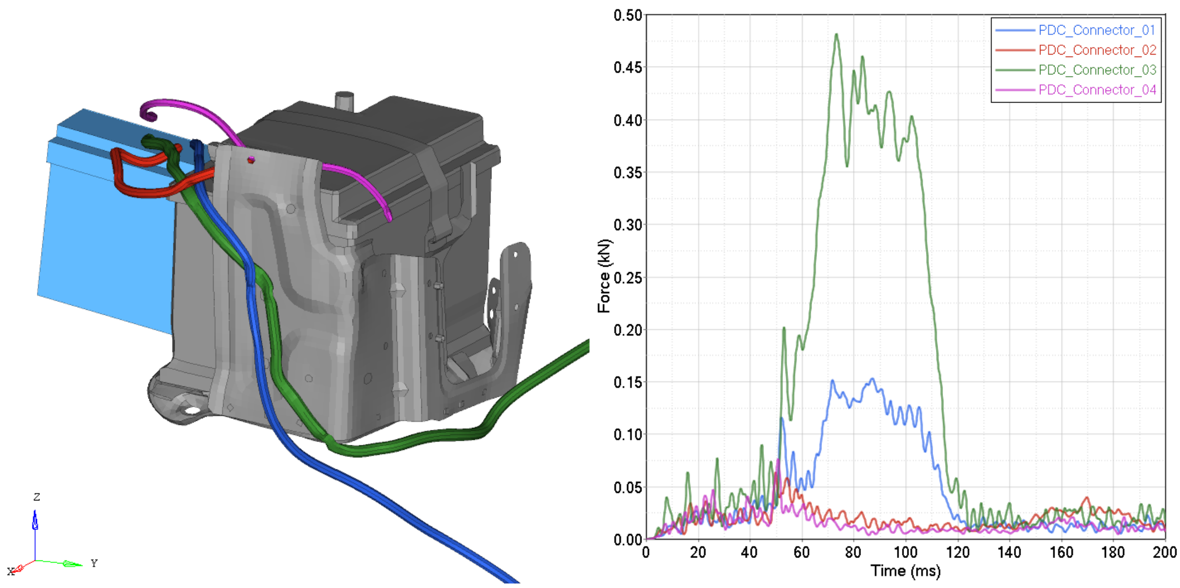


Fig.20: Forces on PDC cables (Truss + Solid method) – Baseline layout

Additionally to the new layout, using the strategy of Truss + Solid the critical change for 01, but again the values continues under the control less than 500N, and no localized crushing in the cable as it is possible to see in Figure 21.

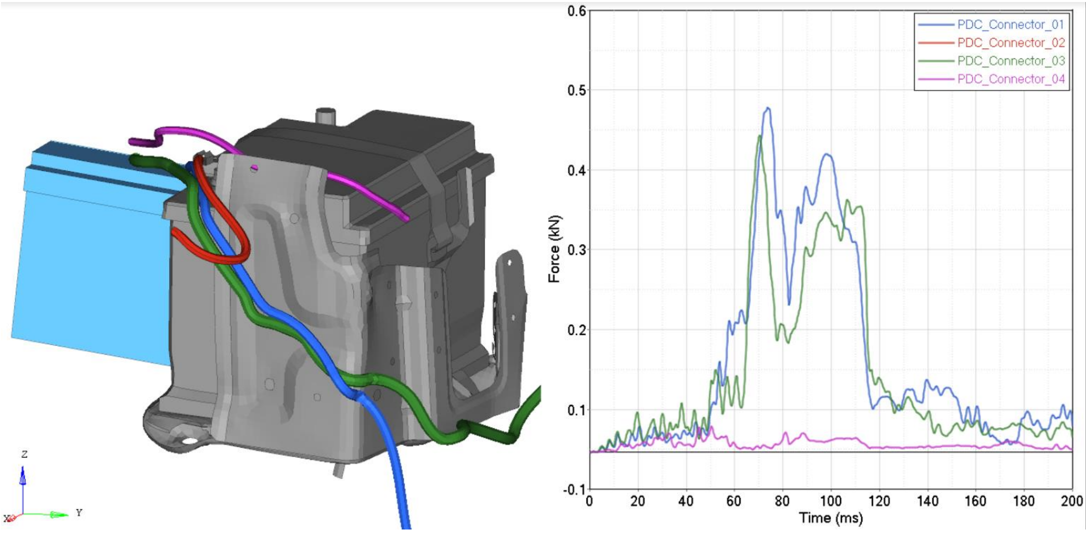


Fig.21: Forces on PDC cables (Truss + Solid method) – New layout

6 Summary

This work allowed adjust the best modeling for use of 1D TRUSS element with the characteristics of copper and solid element with polymeric properties. This method resulted in the correlation in the simplified tests – compression, traction test and in the complete vehicle test.

It can be seen that using an adequate modeling to capture the behavior of electrical / electronic cables, it is possible to evaluate the cable load, the anchorage load, as well as map the contact regions between elements that during a crash test can crush the wiring. This makes it possible to better “project” the layout of a wiring.

Something that was physically verified is the difference between the region of cable rupture in the region close to the grip of the cable and not in the central region of an element under tension as is usually seen with a dog bone type specimen, but this is a challenge for the physical test. Anyway, the ruputre obtained in the model with solid elements was considered more correlated, it is understood that this may need adjustments and improvements.

It should be noted that the use of rigid elements in the modeling connecting 1D element associated with shell or solid element can induce a fictitious rigidity and does not capture the contact well. Another test that was not fully explored was the use of the discrete element model, it was preferred to calibrate and correlate the cables in this work using truss-type elements with solid.

7 Literature

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