COBEM-2017-2015

WEIGHT REDUCTION OF THE PICKUP CARGO BED BY REPLACING METAL PANELS WITH POLYMER COMPOSITE MATERIALS

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Abstract. Seeking to take advantage of the benefits of composite materials, some automakers applied composites to the cargo beds of their pickups, replacing traditional metallic structures. Applied to this region of the vehicle, the composites allow the reduction of parts by integration of functions and, due to the large size of the cargo beds, promote high potential weight reduction. After a benchmarking procedure, it was observed that only the complete replacement of metal panels generated efficient weight reduction. Keeping this in view, in this work, the feasibility of complete replacement of metal panels with panels of composite materials is analyzed through benchmarking procedure, modeling and finite element analysis.

Keywords: composites, cargo bed, weight reduction, pickup truck.

1. INTRODUCTION

Before 1970 the polymers were not considered as engineering materials. Today, plastics can be applied to structural applications, in part, thanks to the development of polymeric composites, allowing the weight of the vehicles remain roughly the same despite the addition of components in recent years (Sehanobish 2009).

The materials industry, including the sectors of polymers, is focusing on innovating its products to meet the new emission requirements. In Brazil, the guidelines regarding the emissions are given by the *Programa de Incentivo à Inovação Tecnológica e Adensamento da Cadeia Produtiva de Veículos Automotores (Inovar-Auto)* (Inovar-Auto s.d.).

In general, the advantages offered by composites are: reduction of parts due to integration of functionality in fewer parts; weight reduction and adaptation to customers' needs in relation to safety and comfort; easy production; changing a piece implies little change in production tools; noise reduction and possibility of manufacturing the parts with high finish, eliminating costs in the final stages of assembling (Biron, Thermosets and Composites: Material Selection, Applications, Manufacturing, and Cost Analysis 2004).

Seeking to take advantage of the benefits of composite materials, some automakers applied composites to the cargo beds of their pickups, replacing traditional metallic structures. Applied to this region of the vehicle, the composites allow the reduction of parts by integration of functions and, due to the large size of the bed cargos, promote high potential weight reduction. Chevrolet Silverado was the first to have a polyurethane bed reinforced with glass fiber (Strumberger, Gospocic e Bartulic 2005). Following this same concept, were released later, Toyota Tacoma, Honda Ridgeline and Ford Explorer Sport Trac.

In this work, the feasibility of replacing metal panels with panels of composite materials with structural functions in pickups of the Fiat Chrysler Group is analyzed in terms of resistance and required stiffness.

2. EXPERIMENTAL AND COMPUTATIONAL PROCEDURE

The methodology could be detailed as:

Phase 1
- Development of a coefficient of correlation. In this case, the proposed coefficient makes a correlation between the cargo bed capacity in litters and the total weight of the cargo bed internal components. By using such coefficient, we can compare pickups of different sizes e capacities;
- Carry out a comparative study between different vehicles.

Phase 2
- Analysis of the available materials and choice of the one which gives the highest weigh-saving. This stage is accomplished analyzing the relation resistance/density of the materials and choosing the material with the highest value. A tensile test is performed in order to determine experimentally the mechanical properties that will feed the virtual tests. The materials considered allows the processing by injection moulding.
- Design a new cargo bed with the material selected. This phase can be described by four steps:
1. Current vehicle FEM global analysis;
2. In each part of the vehicle load box, substitute the properties of the selected material to verify the effect of the application of the material in specific regions of the vehicle. This is done by substituting one part at a time and simulating the hole vehicle structure when that is subjected to torsional, flexional and localized loads.
3. New geometry will be designed to substitute the parts tested in the previous step with composite parts that can be moulded by injection. This step is made with the purpose of approximate the study to a situation where the parts could really be constructed, but further studies about the connections with the other parts of the vehicle and about the parameters of the injection moulding process must be carried out.
4. Insert the new parts in the structure and perform the FEM analysis to verify the behaviour of the hole vehicle when equipped with the parts with the selected materials.
5. If the parts don't meet the requirements of stiffness, use step 2 to reinforce the geometry in the regions which show to be more sensitive to material change.
6. Analysis of the weight reduction achieved.

3. RESULTS AND DISCUSSION

3.1 Benchmarking Procedure

The benchmarking procedure was performed using the database A2mac1. Unfortunately, the full data needed to perform this stage of the work is not available and the mass of the parts where estimated based on the dimensions of the vehicle structures and the materials which they are made of. The volume is generally informed by the OEM. The comparison is summarized in Table 1:

Table 1 - benchmarking of current pickup models.

Vehicle	Mass of the components of the cargo bed (kg)	Volume of the cargo bed (liters)	Volume/Mass (Liters/Kg)
A	36,07	820	22,73
B	26,99	580	21,49
C	54,6	1248	22,86
D	34,904	1169	33,49
E	100,49	1504	14,97

The research, presented in terms of the mass of the cargo bed components, cargo bed volume and the ratio between these two features, shows that vehicle C is that with higher volume capacity by mass unity of material of the bed components, while the E offers the worst performance. With similar ratios between volume and mass, vehicles C, A and B almost have the same performance. This may be explained by the fact that the C still present lateral metal panels under the composite panels, which makes the weight reduction less effective.

The pickup D has a cargo bed completely made of composite materials, which gives the best efficiency in terms of capacity by unit mass of the cargo bed parts, followed by C, that also has a composite cargo bed. This implies that the use of composite materials in the cargo bed structure can improve its efficiency, as can be seen in other studies. The pickup Chevrolet Silverado, saved 23kg of mass implementing a HD-SRIM composite cargo bed (Hope e Vietor 2014). Ford also saved 21kg and reduced from 45 to 1 the number of parts by applying a SMC cargo bed (Koeten 1993).

Based on the data shown in Table 1 and the studies and the already existing works, the structure of the pickup A is studied with the purpose of substitute some steel parts by composite materials, reducing weight and the number of components.

3.2 Materials Research

The choice of the material most suitable to the application in the pickup A cargo bed was chosen between those present in the materials database of FCA Group and those which the properties were provided by the suppliers. Table 2 summarizes the properties of interest of the materials considered. The materials were also restricted to those that could processed by injection molding, that is the most used process, what could imply in better prices and logistics. It is also a process that allows high volume of production (Beaumont 2016).

In Table 2, the materials considered are shown. One of these materials is the Polyamide 66. Known as Nylon 66, this material is classified as an engineering material due its high tensile strength, stiffness and heat resistance. It's commonly processed as fibers (Peacock e Calhoun 2006). In the automotive industry, the material can be found applied to gears of steering systems (Advanced Materials & Processes, 2004).

Another material considered is Polypropylene. It has high resistance and high melt point compared to other low-cost polymers (Callister Jr. e Rethwish 2014). It can be found in bumpers, spoilers, external trims and battery box (Biron, Thermoplastics and Thermoplastics Composites 2013).

Table 2. Materials available to be used in the cargo bed structure

MATERIAL	Commercial name	Tensile Strength – 23°C (MPa)	Density (Kg/m³)	Specific Tensile Strength (Tensile Strength/Density)
PA 66	CELSTRAN PA 66 40 Natural	215	1450	0,148275862
PA 66	CELSTRAN PA66 GF 30 BLACK	160	1360	0,117647059
PA 66	CELSTRAN PA 66 GF50-02	180	1570	0,114649682
PA 66+PTFE+FV	LNP Lubricomp RFL36S BK1A842BRLM	155	1500	0,103333333
PP	PP 150.80 HC	104	1140	0,09122807
PP	Xmod GD301HPB/P001	104	1140	0,09122807
PA 6	Durethan BKV 50 H2.0	140	1570	0,089171975
PC+ABS	Bayblend® T88 GF-10	95	1220	0,077868852
PP	PP 120.60	77	1110	0,069369369
PP	PP 130.50	66	1120	0,058928571

The materials are compared to each other in terms of the specific tensile strength. The highest values of this property imply that the material can resist to determined loads adding less mass, which is desirable to the purposes of this work. So, the material with the highest specific tensile strength was chosen, which is the CELSTRAN PA 66 40 Natural, a polyamide 66 reinforced with 40% of glass fiber.

Tensile tests were carried out with 5 test specimens of CELSTRAN PA 66 40 Natural to confirm its mechanical properties. The tests were conducted following the guidelines given by standard ISO 527. The results are depicted in Figure 1:
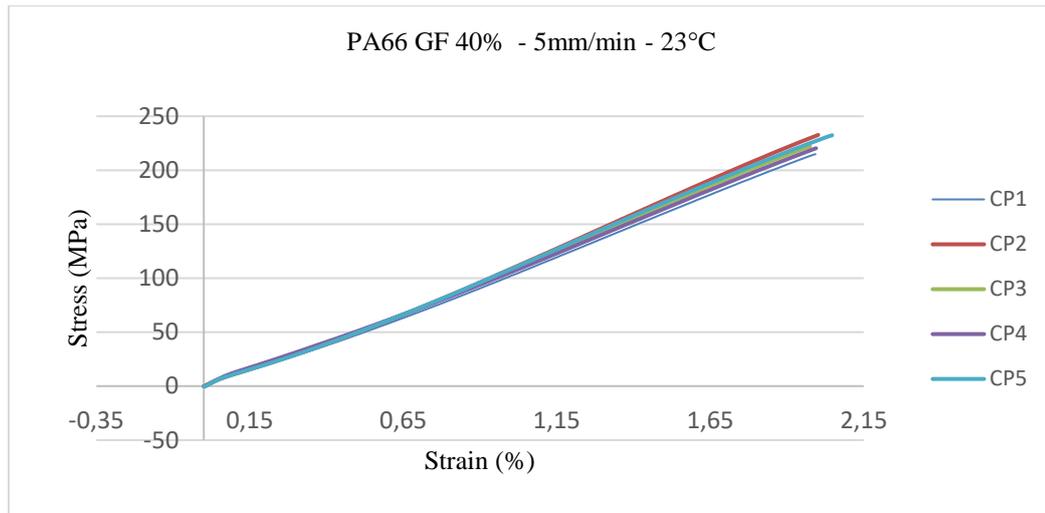
Figure 1: Stress x strain tensile test of PA66 40% GF

These results allow to determine the properties shown in Table 3:

Table 3. Properties of PA66 40% GF obtained from tensile test

Property	Spec.1	Spec. 2	Spec. 3	Spec. 4	Spec. 5	Average
Young Modulus (GPa)	11,59	12,71	12,18	11,75	12,37	12,12
Tensile Strength (MPa)	214,89	232,67	222,12	220,35	232,43	224,49

Figure 1 shows that the test specimens follow a fragile behavior, with negligible plastic deformation before break. Considering this fact, it is reasonable to assume that the material follows a straight line with constant Young Modulus. This allows saving a lot of computer efforts performing just a linear analysis.

3.3 Analysis of the current vehicle frame

The current frame of the pickup A cargo bed is depicted in Figure 2 and Figure 3.
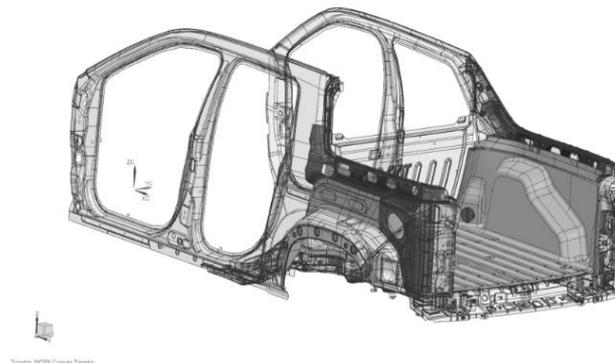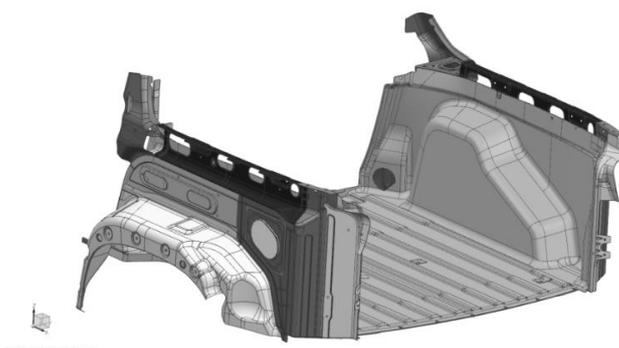

Figure 2. Current frame with steel parts

Figure 3. Current steel parts isolated visualization

It is composed by 24 parts, 23 parts made of steel and 1 part made of PP (plastic bedliner), with a total mass of 46,9kg. With this configuration, the whole vehicle is virtually submitted to a torsional and a flexional test. It is also submitted to a localized application of loads. These tests have the purpose of verify the stiffness of the hole vehicle when submitted to these kinds of load. The virtual tests were carried out using the preprocessor Hypermesh (Altair Engineering Inc. 2014) and Abaqus solver (Dassault Systèmes 2012). The test consists in substitute the material of each part at a time with reinforced Nylon 66 and analyze the behavior of the vehicle in terms of its torsional, bending and stiffness. All the parts to be substituted are depicted in Figure 4 and described in Table 4. Just parts numbers 3 to 23 will be tested with polyamide 66 because just these parts have structural function.
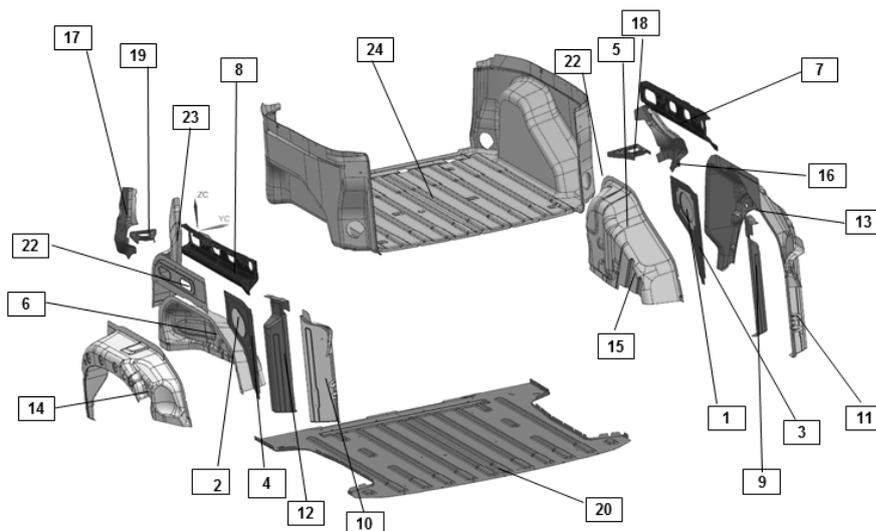

Figure 4. Parts to be virtually tested with PA66 40% GF

Table 4. Name and mass of steel parts that will be replaced with PA66 40% GF

	Part	Mass (Kg)		Part	Mass (Kg)
1	Riparo Acqua Dx	0,07	**13**	Passaruota Esterno Dx	2,45
2	Riparo Acqua Sx	0,07	**14**	Passaruota Esterno Ex	2,13
3	Ossatura Vano Carico Dx	0,47	**15**	Rinforzo	0,92
4	Ossatura Vano Carico Sx	0,47	**16**	Riforzo esterno angolare Dx	0,92
5	Passaruota posteriore Dx	3,74	**17**	Riforzo esterno angolare Sx	0,92
6	Passaruota posteriore Sx	3,06	**18**	Diaframa rinforzo Dx	0,23

7	Longherina in Cintura Dx	1,8	19	Diaframa rinforzo Sx	0,23
8	Longherina in Cintura Sx	1,8	20	Pavimento	11,83
9	Riporto Scatolamento Mont. Post. Dx	1,06	21	Riporto esterno passuota Sx	0,57
10	Riporto Scatolamento Mont. Post. Sx	1,06	22	Esterno angolare in cintura Dx	1,23
11	Scatolamento Mont Post Dx	1,35	23	Esterno angolare in cintura Sx	1,23
12	Scatolamento Mont Post Sx	1,35	24	Cassone	9,17
				Total	48,2

The bending and stiffness virtual tests, the localized load test and the used mesh parameters follow the guidelines of FCA's internal standards.

3.4 Torsional Stiffness Virtual Test

The torsional stiffness test is a widely recognized metric used to assess the structural performance of the vehicle. Each automotive company developed its procedures to make this assessment and there is no industry standard.

The test consists in applying a torsion moment equivalent to $Mx = 2000Nm$ in the virtual structure shown in Figure 5:
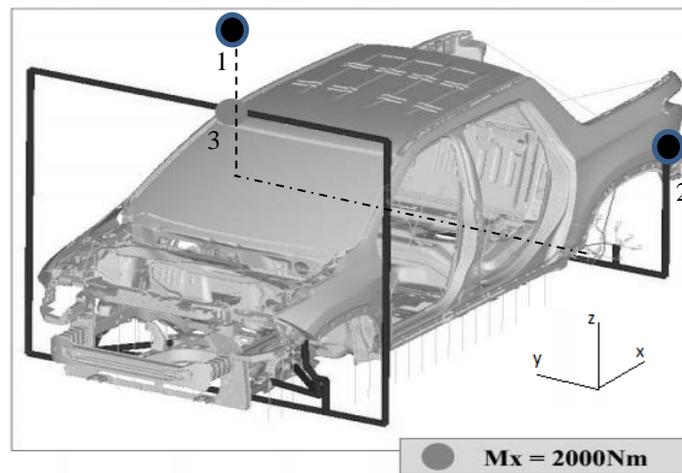
Figure 5. Constraints in torsional stiffness test model

Points 1 and 2 have no degrees of freedom in translation or rotation. Point 3 can just rotate around x direction. The torsional stiffness is measured by Eq. 1:

$$K_T = \frac{T}{\theta} = \frac{T}{\left(\text{atan}\left(\frac{z_1 - z_2}{b}\right) - \text{atan}\left(\frac{z_3 - z_4}{d}\right)\right)\frac{180}{\pi}} \qquad (1)$$

Where,

T – applied torque;
z_{1-4} - displacement in vertical direction of the points shown in Figure 6;
b – distance between points 1 and 2;
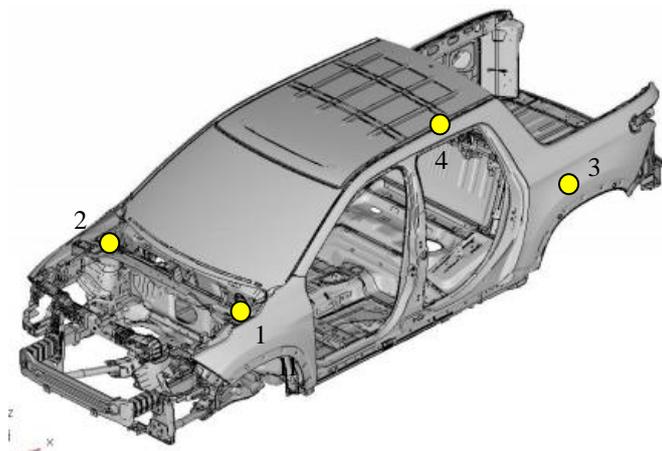d – distance between points 3 and 4;

Figure 6. Points of measurement of vertical displacement

The parts shown in Figure 4 are traditionally made by steel and are, one at a time, substituted with PA66 40%GF and the test is performed, so that the effect on the stiffness of each part can be assessed. The parts are simulated with a thickness of 3mm, a value considered optimum for long fiber reinforced polymers because avoid the differential shrinkage of the polymer, that occurs with thick plastic materials, and the breakage of the fibers, that usually occurs with thin injected plastic parts (Hope e Vietor 2014).

The effect of each part in the global stiffness is shown in Figure 7:
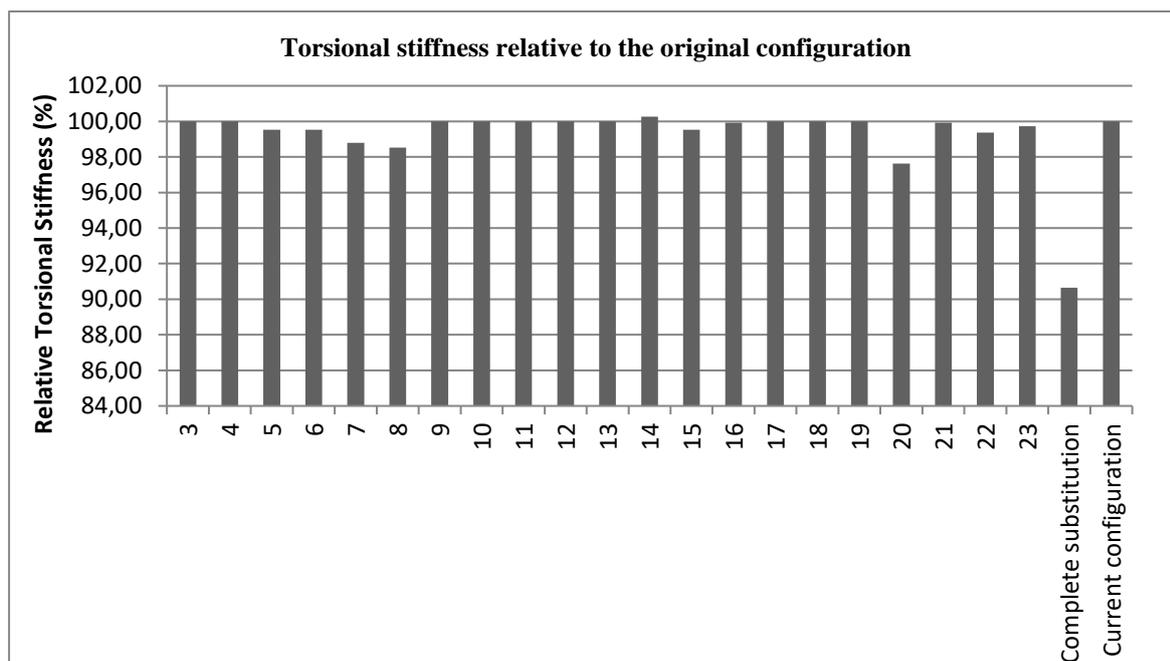
Figure 7. Decrease in torsional stiffness for each part material substitution

As can be seen in Figure 7, some parts can individually make the torsional stiffness drop up to 2,27% relative to the original steel configuration. In this case, the regions where the parts 5, 6, 7, 8, 10, 15, 22 and 23 should be reinforced with ribs in the final design to compensate the drop in torsional stiffness with ribs.

3.5 Bending Stiffness Test

Like the torsional stiffness test, also the flexural stiffness test is a widely recognized metric used to assess the structural performance of the vehicle and is not covered by any industry standard, being developed separately inside each company.

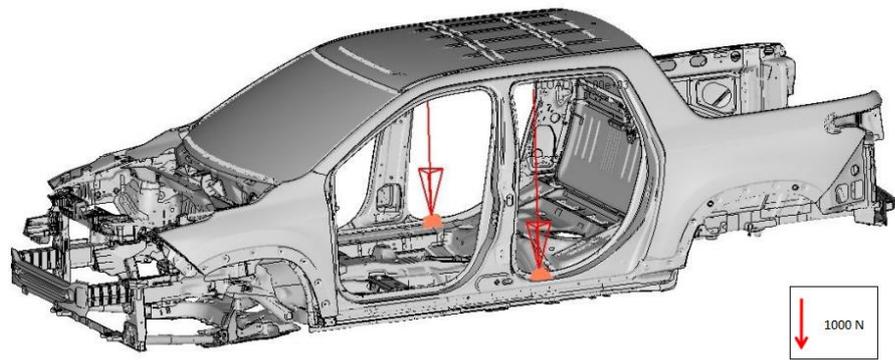The test consists in applying a force of 1000N in the locations in Figure 8.

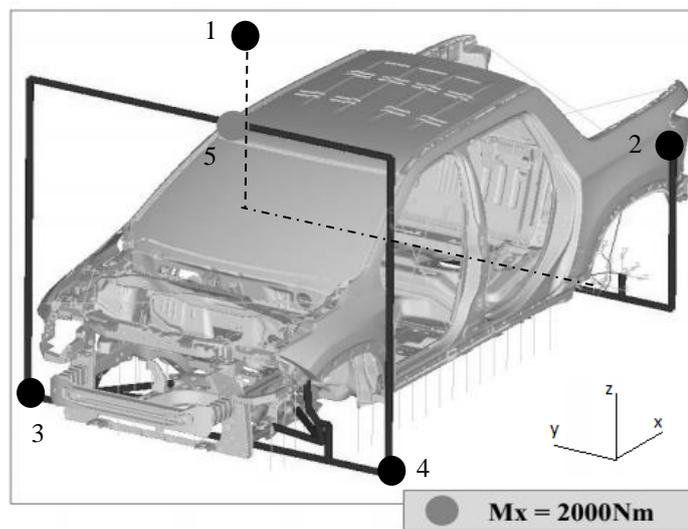Figure 8. Application of forces in bending stiffness virtual test

Figure 9. Constraints in the bending stiffness test model

In Figure 9, points 1 to 4 have no degrees of freedom in translation but can rotate around x and z axis. Point 5 can just rotate around x direction. The bending stiffness is calculated by Eq. 2:

$$K_B = \frac{F}{z} = \frac{F}{\left(\frac{z_1 - z_2}{2}\right) - \left(\frac{z_3 + z_4 + z_5 + z_6}{4}\right)}$$

(2)

Where,

F – applied force;
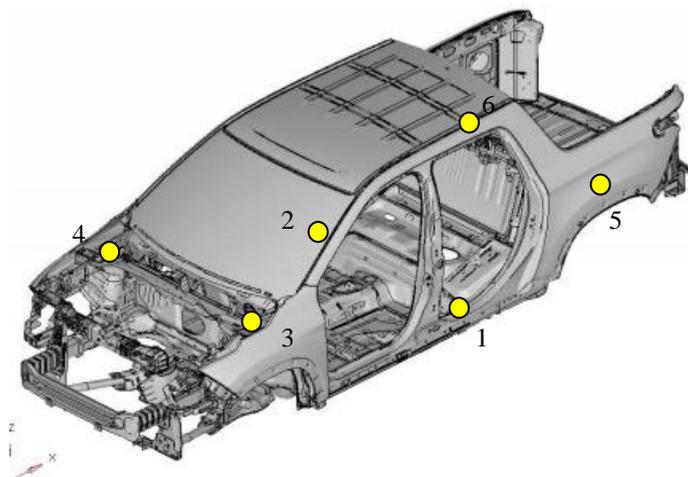z_{1-6} - displacement in vertical direction of the points shown in Figure 10;

Figure 10. Measure points of vertical displacement

As in the torsional stiffness test, the steel parts were substituted with PA66 40% GF and the effect of each one on the global bending stiffness is summarized in Figure 11. The drop in bending stiffness caused by the substitution of all parts intended to be replaced is less intense in the flexional test than in the torsional test. Also, the parts that play a major role in the drop of bending stiffness are the same that cause the reduction in torsional stiffness. This means that a reinforcement in these regions could improve the performance of stiffness in both cases.
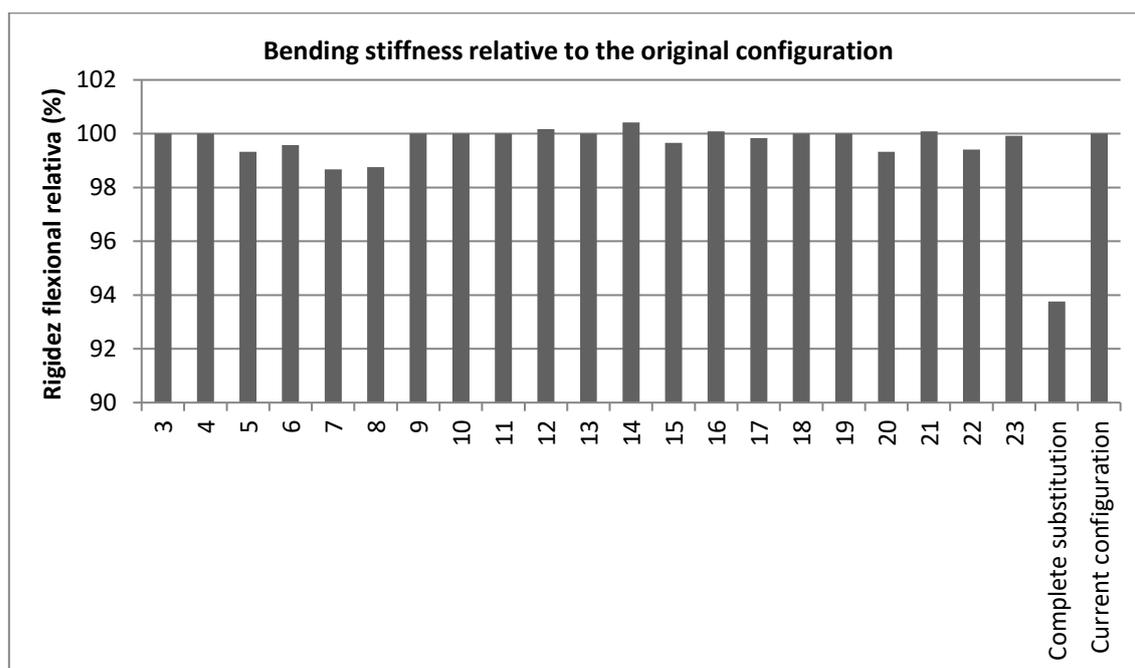

Figure 11. Decrease in bending stiffness for each part material substitution

3.6 Local Stiffness

This test aims to verify the local stiffness of critical parts of the pick-up bed liner that usually are loaded with luggage and/or goods. In this test, a force equivalent to 2500 N is applied on the locations of the bed liner show in Figure 12 by a rigid disc with diameter of 250 mm.
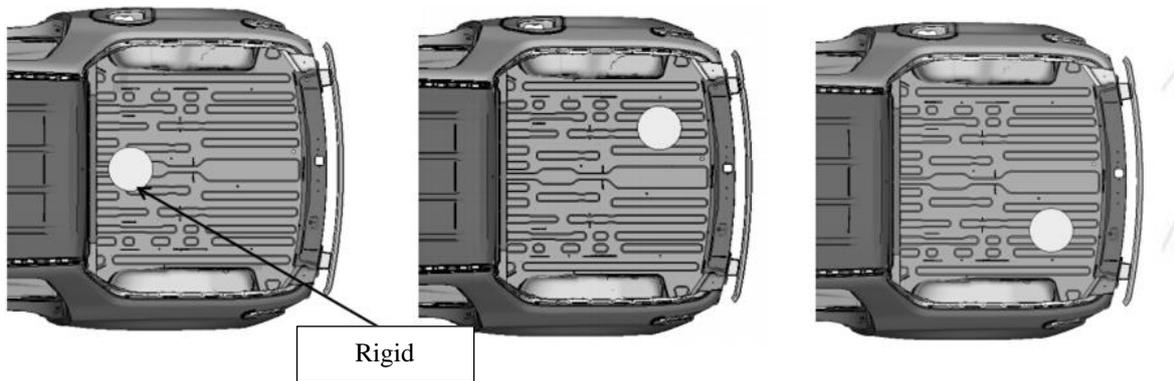
Figure 12. Points of application of local force

In the test of local stiffness, the replace of the metallic bed liner with a PA6640% GF had a positive result in all the cases shown in Figure 12. The stiffness was measured by determining the maximum displacement of the bed liner. In all the cases, the displacement when using the reinforced Nylon was less than in the case where metallic bed liner was used, as summarized in Table 5. In other words, the bed liner must be reinforced in order to improve the vehicle's torsional and bending stiffness when it's made of PA66, but the improvement in the local stiffness is not needed because it is already higher than in the traditional metallic bed liner case.

Table 5. Maximum vertical displacement under local application of force

Position	Maximum displacement (mm)	
	Steel bed liner	Polyamide 66 bed liner
1	11,97	7,13
2	6,95	2,86
3	6,14	2,64

3.7 Proposal of a new design of parts

This stage of the work has the objective of, based on the results about the vehicle stiffness obtained in the previous section, design new parts made of PA66 GF40% searching for the following achievements:

- Reducing the weight of the vehicle, mainly by changing the steel traditionally used by polyamide 66 reinforced with 40% of glass fiber;
- Integrating the parts of the current configuration in a smaller number of parts, so that it could reduce the number of operations in the assembly process and at the same time be able to be processed by injection molding;

These achievements must be reached without a significant loss in the performance of the vehicle in terms of torsional, bending and local stiffness.

The parts are constructed observing the recommended optimum thickness of 3mm, which reduce the possibilities of sinks, voids and the fiber breakage (Hope e Vietor 2014). Also, the ribs are constructed considering that PA66 is a material with high shrinkage (Koeten 1993) and following the recommendation for rib thickness being 0.5 of the wall thickness (Beaumont 2016).

The parts are integrated like showed in Figure 13. They are modeled using the software NX 9 (Ming, Albin e Krishna s.d.) and the number of parts are reduced from 24, showed in Table 5, to 4 parts, showed in Figure 13. The mass is reduced from 48.2 kg, as shown in Table 4, to 20.96 kg, as shown in Table 6.
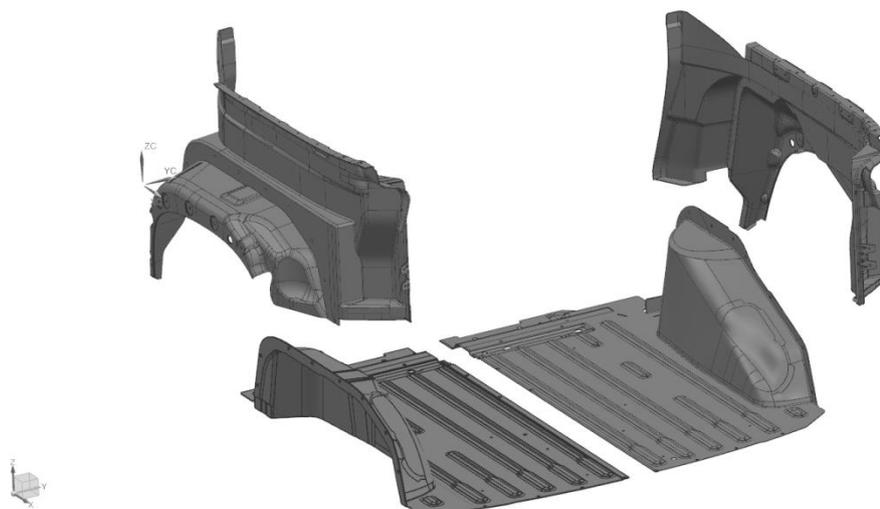
Figure 13. Proposed preliminary composite geometries

Table 6. Mass of PA66 40% GF parts

Part	Mass (Kg)
Right Side Panel	4,46
Left Side Panel	4,53
Right Cargo bed floor	6,09
Left Cargo bed floor	5,88
Total	20,96

At a primary design, the parts have a draft angle equal to 2 degrees, which allows them to be molded by injection, with minimal adjustments if necessary. From Figure 13 both side panels were designed to allow extraction in y direction, while both sides of the floor could be extracted in z direction.

Also, as previously stated, the parts are designed with constant thickness of 3mm, reducing the risk of voids and sinks due to shrinkage or pressure loss during the flow of the melted reinforced polymer.

3.8 Assembly of the designed parts in the vehicle

After designed, the parts showed in Figure 13 were inserted in the model, substituting the ones showed in Figure 4. To isolate the effect of the materials and the geometry, it was assumed that the connections are as similar as possible to the old model, keeping the existing adhesives and maintaining the rigid elements where there were spot welds that could also represent fasteners in the case of composite materials.

Like the study made about the injection molding process, the connections must be detailed in a further study, but it was considered in a way to avoid the parts attachment to be unfeasible in a first moment, so that the project can be carried out in the future.

3.9 FEM analysis

After insert the parts at the model, the same virtual tests are performed: bending stiffness test and torsional stiffness test. The local stiffness test is not repeated because the geometry at the cargo bed floor is essentially not modified respect to the geometry tested at the first time.

3.9.1 Torsional stiffness test

The torsional stiffness test is run again. The constraints are the same present in Figure 5 and the results are plotted in Figure 14.
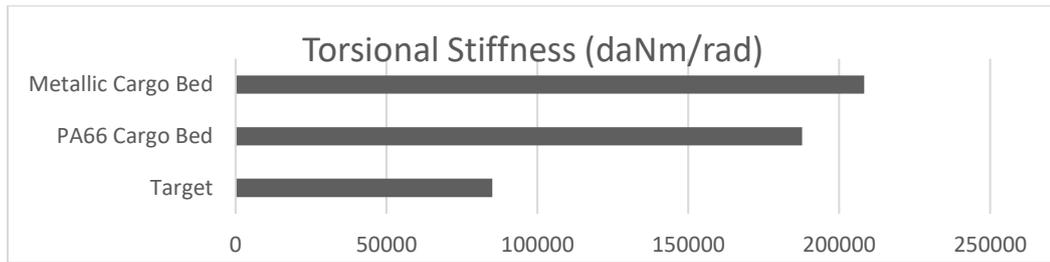
Figure 14. Torsional stiffness using the designed components

As can be seen, the torsional stiffness of the whole vehicle decreased just 10% from the original value, from 208234daNm/rad to 187672daNm/rad. This value is still much higher than the target considered at the project stage, 85daNm/rad, which makes the PA66 a potential material to be used in replacement of the cargo bed steel structural components.

Observing the Figure 15, we can see that the increase of the thickness makes the force be transmitted through a larger area, reducing the stress at the components. Also, integrating the parts, the number of stress concentration points as corners and welds are reduced. In this reference study, a point which concentrates a large amount of tension in the original structure is dissipated trough the new geometry. The value of the stresses calculated are multiplied by three to make easier the visualization, which doesn't affect the comparison. This means that the maximum stress determined in the torsional virtual test of vehicle with composites in its structure values approximately 14,1 MPa. Considering that the material is fragile and doesn't yield and that its tensile strength is about 215MPa, the torsional situation simulated submits the car to a situation where the composite undergoes less than 10% of its load capacity.
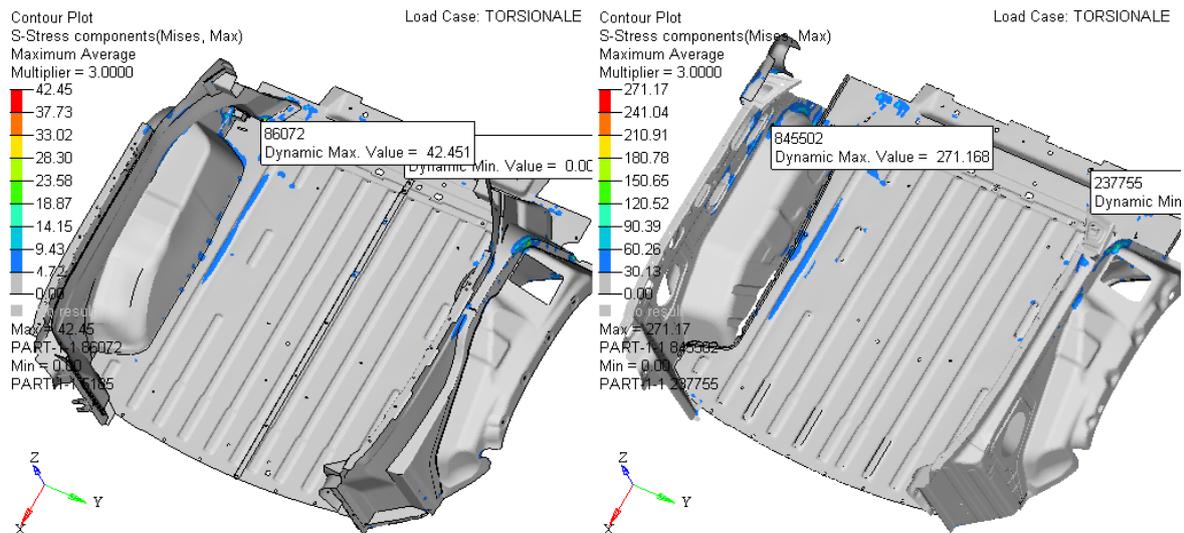

Figure 15. Stresses in composite and metallic parts when the vehicle is submitted to torsional stiffness virtual test

Analyzing the parts that were not changed, shown in Figure 16 , we can see that the tension values are approximately the same. This fact means that the change in the material of the cargo bed probably will not imply in serious penalties in the resistance of the other components in terms of their tensile strength and durability.
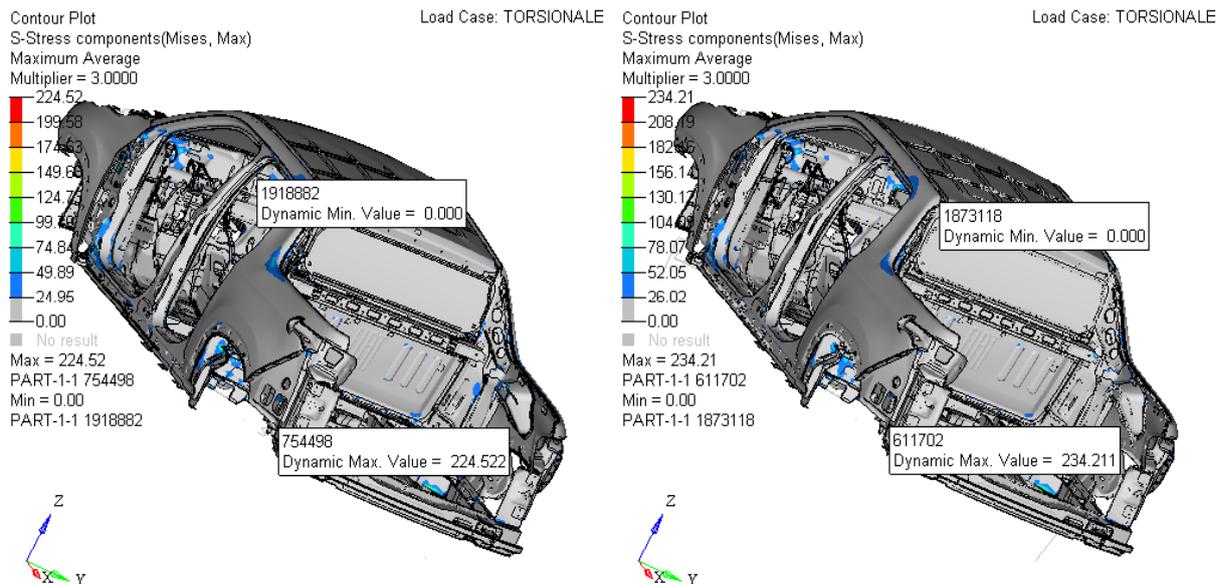
Figure 16. Stresses in the rest of the vehicle when equipped with composites (left) and steel (right)

3.9.2 Bending stiffness test

The bending stiffness test is also carried out again, taking as reference an FCA internal standard. The result for the bending stiffness can be observed in Figure 17. The pickup with PA66 parts can be seen on the left side of the picture. The simulation shows that the bending stiffness of the pickup equipped with composite parts decreased only 3.2%, from 673,4daN/mm to 651,4daN/mm. These values are higher than the target value stipulated at the primary design stage, 600daN/mm.
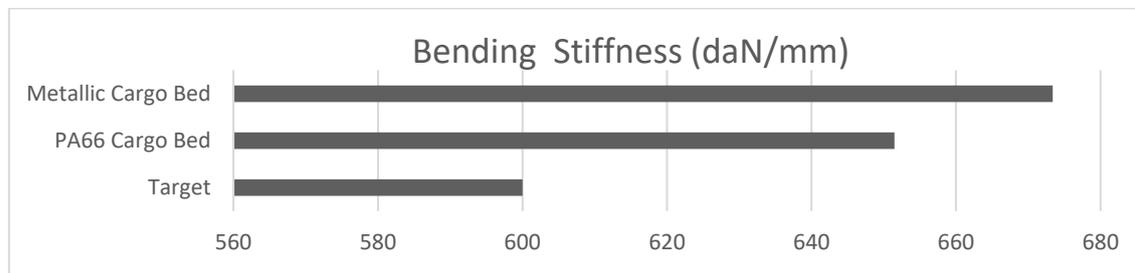

Figure 17. Bending stiffness of the PA66 Cargo Bed compared to the design target

The stress which the composite parts are submitted are much lesser than the stress in the steel parts due the thicker wall and the existence of a smaller number of stress concentration. In the left side of Figure 18, we can see the maximum stress in the composite parts is equal to 7,47 MPa, considering that the values are multiplied by 3 to make the visualization easier. This value represents 3,5% of both yield and tensile strength, considering that the material is fragile. In the right side of Figure 18 we can see that the maximum stress in the steel parts is equal to 57,5 MPa, which represents 13,6% of the yield strength and 11,27% of the tensile strength, knowing that one of the steel grades used is the FEE 340 F.
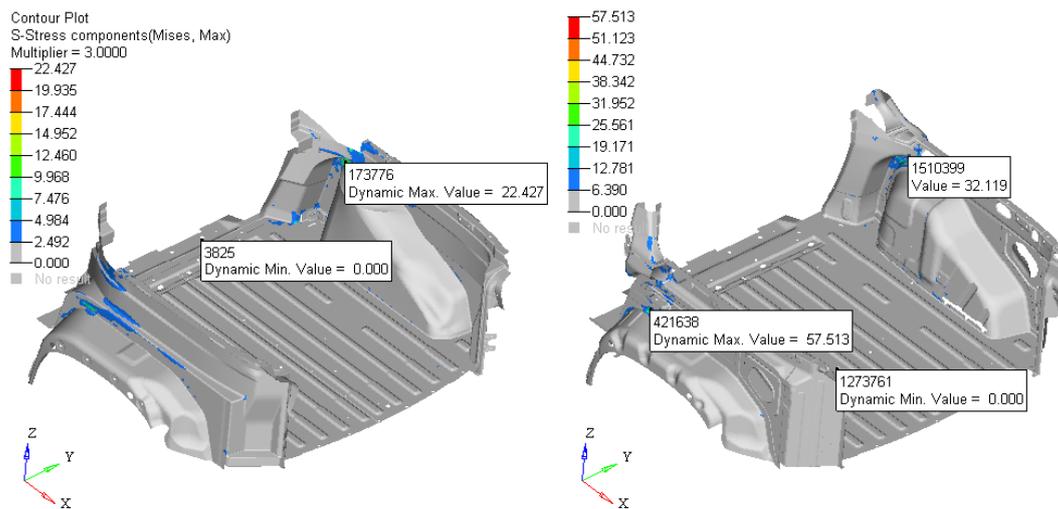
Figure 18. Stresses in composite and metallic parts when the vehicle is submitted to bending stiffness virtual test

Considering the other parts of the vehicle shown in Figure 19, we can see that the unmodified parts of the vehicle are submitted approximately to the same stresses, even though in the left side of Figure 19, the vehicle cargo bed is PA66 reinforced with 40% of glass fiber. This means that the use of the composites would not cause additional damages in the other components. This result is very similar to that found in the torsional simulation.
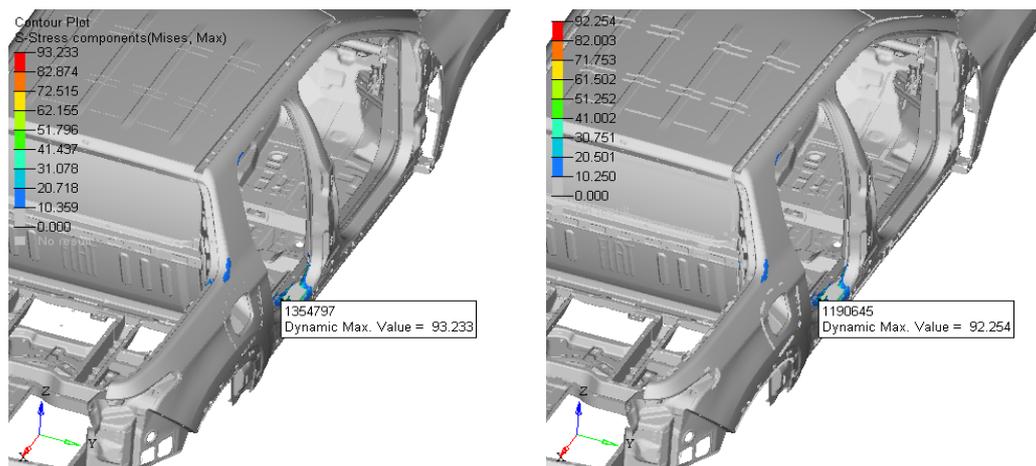

Figure 19. Stresses in the rest of the vehicle when equipped with composites (left) and steel (right)

3.10   Conclusions

Completed benchmarking phase, it was observed that the most effective way to reduce weight is the complete replacement of the metal panels by composite materials. Some vehicles, like pickup C, have composite panels just covering a metallic structure, which annuls part of capacity of composite materials to reduce weight.

Considering the options available to replace steel panels, PA66 reinforced with 40% of glass fibers was chosen because it has a higher ratio between resistance and density, allowing the biggest reduction of weight. This choice was made between materials that already have an application in FCA or can be easily found among the suppliers. It doesn't consider cost of the material, but the higher cost of the reinforced polymers can be balanced by the reduction of parts and operations in assembly. It must be noted that future analysis must include tests at high temperatures, that is a common situation of cargo beds. For this purpose, Nylon 66 is still a good candidate because can support heat without significant loss of properties.

Performing the virtual torsional and bending stiffness tests, it turned out that if the current parts were substituted by composites, without changes in their geometry and applying thickness of 3mm, the global torsional and bending stiffness would drop just 10%. These results make PA66 40% a potential substitute for steel parts, considering that, in terms of stiffness, the values determined are higher than the values settled at the project phase. The local stiffness

virtual test applied on the floors of the cargo bed showed that the composite floors presents less deformations compared to the traditional steel floors. This improvement was achieved probably due the increase in thickness of the component.

Integrating the parts, the number of components decreased from 24 to 4, giving the possibility of cost saving by reducing the number of operations in assembly process. Also, the integration was accomplished in a design similar to one that would allow processing by injection molding, which gives the analysis more feasibility.

The integrated parts where placed in the vehicle structure and the torsional and bending tests were carried out again. The mass was reduced from 48,2 kg to 20,96kg, which means a weight-saving of 56% comparing to the traditional structure. When the torsional and bending virtual test were performed with the integrated parts, the components in composites caused a drop of approximately 10% in the torsional stiffness and 3,2% in bending stiffness, keeping the vehicle's performance above the target values. The stresses calculated at the composite structure represents smaller fractions compared to those in the metallic parts, which means that, in the case of static bending or torsion, the steel probably would brake easier than the composite. This is due the thicker panels of the composites, that distribute better the stresses. Also, integrating the parts, makes possible the elimination of welds and other connections between them, reducing points where the stresses concentrate. The stresses in the unmodified parts of the vehicle remained the same in the case of the steel and the composite parts, showing that the adoption of reinforced polymers would not affect other components. The local stiffness analysis was not repeated because the floor's geometry is essentially the same of the original.

As stated previously, further analysis must be done in terms of thermal resistance of the composite components, detailing of the connections with the vehicle's structure, injection process, cost of the changing and other specific load analysis, but at a primary analysis, it can be seen that PA66 40% can promote a substantial weight reduction without compromising the vehicle performance. Further studies can also optimize the design of the PA66 parts, reducing even more the weight of the components.

4. ACKNOWLEDGEMENTS

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6. RESPONSIBILITY NOTICE

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