New optimized bus structure to improve the roll-over test (UN R. 66) using structural foam (Terocore) with high strength steel

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ABSTRACT

Rollover resistant structures for coaches have been developed in the nineties, but recently, as the price of the steel has almost doubled only in the last year, the use of new materials for these superstructures has become more cost efficient. The price gap between high strength steel price and mild steel has been reduced and the use of this material is emerging into commercial
vehicle industry. High strength steel may lead to weight and cost reduction but a new energy absorbing mechanism has been identified with the use of structural foam.
On this study a solution using high strength steels and structural foam has been designed to improve the energy absorption and reduce the final weight of a current rollover resistant bus structure. Several parts of the bus structure have been manufactured with the final selection of structural foam and high strength steel. The prototype parts have been used for test and manufacturability.

INTRODUCTION

Public transport is being promoted by many governments in order to reduce road congestions and emissions. When a bus accident occurs it often becomes the focus of media and public attention, especially because the people involved had confidence in the transport and sometimes it is the only means of transport available to them. The most dangerous bus accident is the rollover crash; 75% of the fatal casualties in bus accidents are due to rollover accidents. A rollover accident involves high number of fatal casualties and causes great public anxiety. Bus safety is a key aspect for the bus industry and authorities. In 1987, with the aim of reducing the number of fatal casualties in rollover accidents, the UN Regulation 66 “UNIFORM TECHNICAL PRESCRIPTIONS CONCERNING THE APPROVAL OF LARGE PASSENGER VEHICLES WITH REGARD TO THE STRENGTH OF THEIR SUPERSTRUCTURE” was published. In the countries were Regulation UN R.66 is mandatory the number of death has decreased and currently many countries outside of Europe are requiring the rollover resistant structures**.**

ROLL-OVER TEST

The UN Regulation 66 defines the rollover test that the coach structure must fulfill. The main test is a quasistatic rollover test with a ditch of 800 mm.

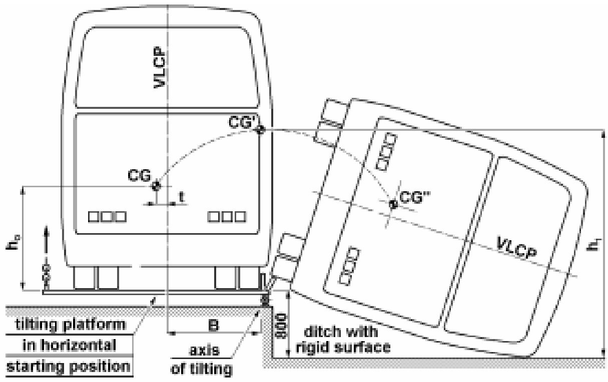

Figure 1. Rollover test set-up

This physics that lay under this test is based on energy balance. There is an initial Potential Energy at the unstable equilibrium position that will be transformed into Kinetic Energy when the vehicle is just hitting the ditch.
Once the vehicle is contacting with the ground, part of the kinetic energy will be transformed into deformation energy. The maximum deformation is restricted by the survival space so the deformation is limited.

Terocore™ STRUCTURAL FOAM

The quest to make vehicles lighter is not a new one.

Mass production pioneer Henry Ford noted in 1923 that **"Saving even a few pounds of a vehicle's weight means that it could go faster and consume less fuel.**
Reducing weight involves reducing materials, which in turn, means reducing costs". Over the last decades, the automotive industry has concentrated significant effort on car-body design optimization, also on overall quality and on weight reduction, in an effort to keep manufacturing costs to a minimum. With society demanding automobiles that provide higher fuel efficiency, safety for the occupants in collisions, and at the end of their service life can recycled with low environmental impact, the automotive material engineers are trying to meet the expectations through simultaneous use of design, material science and product-engineering as well as intelligent material combinations. Lighter materials are therefore getting more and more important in auto construction in order to save weight in the vehicle. To compensate for the weaker structures, automobile manufacturers are improving strength by reinforcing critical areas with heavier gauge steel or by using organic structural foams for panel, frame and body reinforcement. Through the proper use of structural foam in the design phase, both weight and cost savings can be derived through part consolidation and assembly process efficiencies. Although there are different types of organic foams, such as: Polystyrene Foam, Polyurethane Foam, Polyolefin Foam, Polyvinylchloride foams, Phenolic foam, Urea – formaldehyde foams, Polyvinyl Alchol-formaldehyde foam, 8. Epoxy foams, Acrylonitrile and Acrylate Copolymer foams, Pyranyl Foam and Synthetic Rubber and Silicone Foams; only few are used for structural reinforcement applications.
Currently there are two types of organic structural foams used in the automotive industry to reinforce metal sections. They are based on polyurethane or epoxy chemistry.

• Polyurethane's (PUR)

• Epoxies (EPOXY)

Henkel Technologies has developed several patented epoxy foam products that are marketed under the Terocore® trade name. Terocore® is an expandable epoxy based foam and is derived by embedding hollow microspheres (microballons) in a polymer matrix designated as a binder. Microballons can be made of glass, phenolic, carbon, ceramic, metallic and polymer
based materials.
Terocore®structural foam has been used in the global automotive industry since 1995. Terocore®products have caught the attention of structural engineers because these have low densities and high compression modulus. Terocore®reinforced structural members have increased durability, component stiffness/dampening, joint stiffness/dampening and are compliance requirement alternatives. In a number of applications, lightweight, high strength structural members are required and there is a need for providing strength without significantly increasing vehicle material or labor costs.

Terocore®products are available as either two component materials that cure under ambient conditions or one component products that require heat curing.

Terocore® 1401 is a two part epoxy syntactic foam product that is typically applied in the trim shop, although this material can be applied in the paint shop as well.
The use of structural foams for automotive structural reinforcement is still in its infancy, but development and application of these types of foams is growing rapidly. Figure 2. illustrates the wide range of possible application areas for structural foams in an automotive application. Many of the following applications are currently in use in production vehicles.

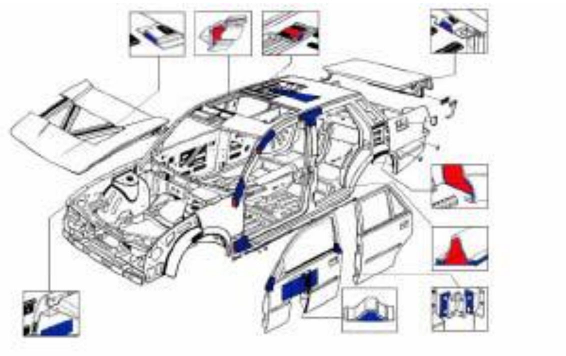

Figure 2. Terocore®Application Areas

COACH STRUCTURE

Almost all coach manufacturers use commercial closed section profile for the upper structure. Only city bus derivate vehicles may use another manufacturing technology, but even these vehicles will use closed section profile for the pillars, though maybe not standard shape. In the case of structures that are able to withstand the rollover test, the structure is formed of closed arcs.

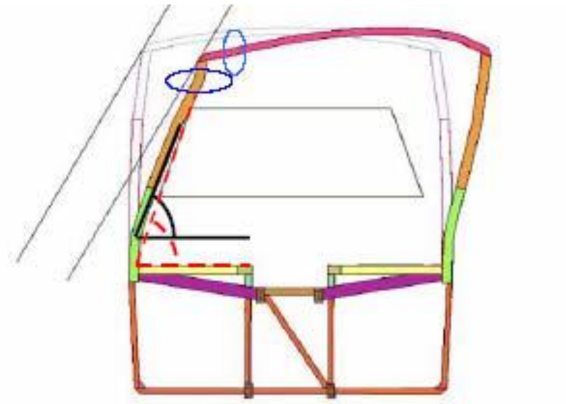

Figure 3. Behavior of the joint in a closed safety arc.

A closed arc is designed to control the deformation during the rollover and is composed by the joints, the pillars and a roof arc. The reason of the use of the joints is as follows:

The lower joint provides an elastic couple between the pillar and the floor cross members. The lower joint and the floor must be stiffer than the pillar; consequently the deformation will occur on the pillar. The higher the joint is the more deformation will be allowed before reaching the survival space. In figure 3 it is shown the effect on the deformation angle of a joint. The dashed line shows an angle smaller than the angle drawn in solid line. The solid line represents a higher joint than the dashed line.

The upper joint is also designed to have an elastic behavior. The main advantage of this joint is that the collapse appears on the pillar and the arc; so there are two areas where the energy can be absorbed.

Consequently with the closed ring design the energy absorption mechanism is localized on the pillars and the roof arcs.

ENERGY ABSORBING MECHANISM

As mentioned before, the pillars and the roof arcs are responsible for controlling the deformation and are usually made of closed commercial section. This kind of elements has a very special behavior during the rollover: the collapse.

The pillars are bending over the yield strength of the material and then the section becomes unstable and loses geometrical properties. The inertia moment is reduced as the compressed face of the section goes inside, and moreover the bending moment resistance is reduced.

3 point bending test is used to evaluate the collapse of the section. The result of the test is used to evaluate the ability of a section to deform. The shape of the collapse as well as the bending values are important parameters.

Figure 4. Collapse of closed section profile.

In the figure 5, it is shown the typical behavior of a closed section profile, where we can observe three different behaviours:

1.- Elastic behavior.

2.- Plastic behavior.

3.- Collapse behavior.

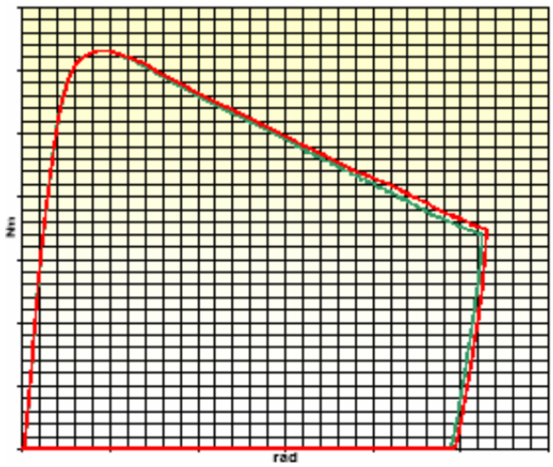

Figure 5. Bending moment vs angle for closed section profile.

During the elastic behavior the material is stressed below the yield strength and its slope depends on the shape of the section (inertia moment).

The plastic behavior starts just after the elastic one and finishes on the highest value of the bending moment. The material of the section is stressed beyond the yield strength.

Just after the maximum bending moment the initial geometry of the section is deformed and consequently the inertia moment reduced and the bending moment drops significantly. The ideal behavior is to have a positive slope that means the profile never collapse.

The thickness of the section is a key factor for the slope of the collapse. As the thickness increases the collapse behavior improves. Figure 5 shows examples of the collapse behavior for the same external section and different thickness.

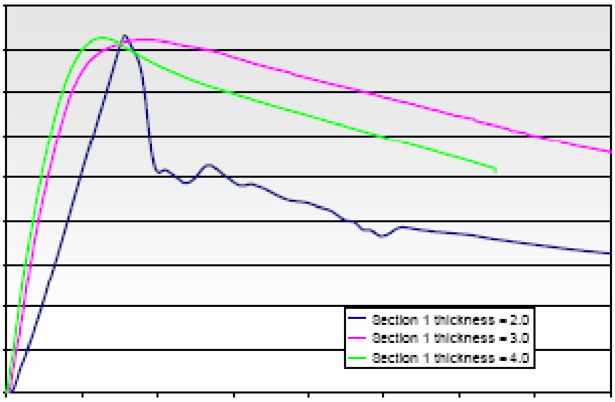

Figure 6. Unitary Bending moment vs angle for one closed section with different thickness.

SECTION BEHAVIOR WITH TEROCORE

It is under this situation when the Terocore® structural foam is a solution to stabilize the section during the collapse. The main objective of the use of the structural foam is to reduce the collapse slope with low thickness profiles, and no pretension to increase the maximum bending values. The steel will be responsible of the maximum values and the structural foam to avoid the collapse.

Initial studies were made with 3 mm thickness for the closed cross section tubes used already in safety arcs.
The original structural foam blended were used. The 3 point bending test was selected to evaluate the collapse of the section. The results of these tests are shown in figure 7.

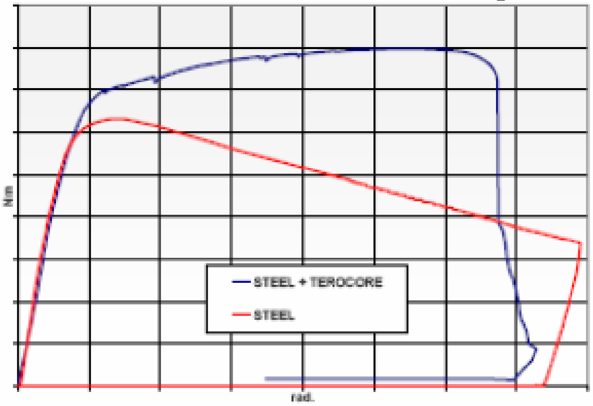

Figure 7. Bending moment vs. angle for one closed section with Terocore® and without it.

The bending moment curve shows a promising behavior of the section with the structural foam; but the steel was not resistant enough.

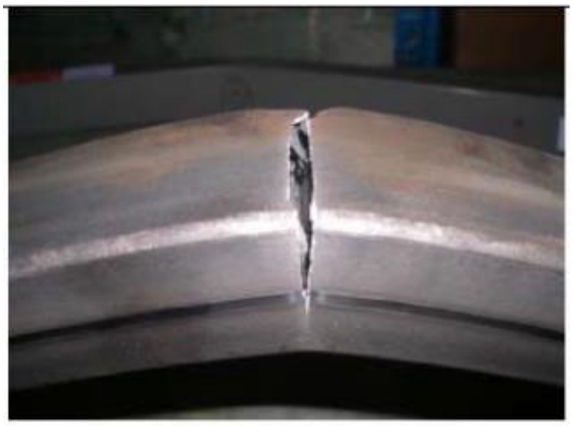

Figure 8. Crack of pillar tube with Terocore® in the interior

Even though the test values were good, this kind of failure was not admissible for a safety component. A vehicle manufactured in this way, has a lot chances to fulfill the rollover test according to the Regulation UN R66 but in case of real crash this pillar cannot withstand more load. This solution was abandoned.

Finite element model and simulations were carried out to correlate the material models and to propose countermeasures to the first designs.

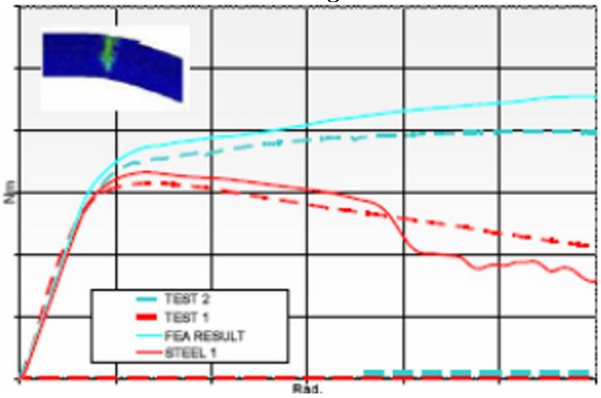

Figure 9. 3 point test correlation.

After the analysis of the simulation results, the use of higher strength steel was decided. Two different steel qualities were pre-selected for the next test series with thicknesses of 2 mm and 1.8 mm. One was a high strength steel S700M C according to EN-10149-2 with yield strength of 700 MPa, minimum tensile strength 750 MPa and elongation at break of 10%. The other steel selected was cold reduced dual phase steel with yield strength of 550 MPa, minimum tensile strength 800 MPa and elongation at break of 10%.

The results of this test were not as good as expected with the HSS steel the maximum bending value was high but the collapse slope was very steep. On the other hand the results obtained from with DP 800 steel were acceptable. The collapse slope was less steep. Figure 9 shows the results for 3 point bending tests.

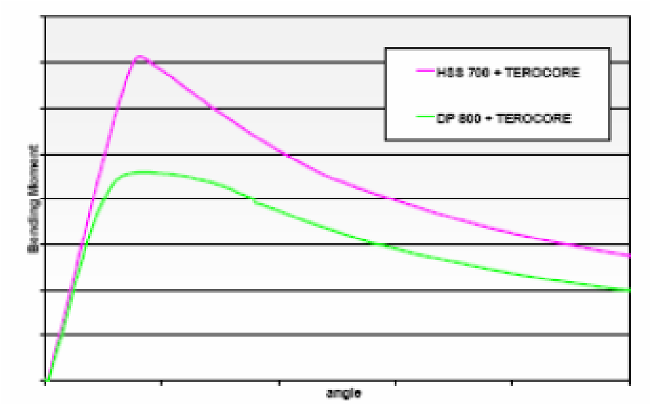

Figure 10. Bending moment curve vs angle

The steel behavior was improved and only small cracks appear on the HSS 700 steel localized at its fillet radius.
These types of steel present a behavior that allows us to have a remainder of energy after the full collapse of a structure.

Figure 11. Collapse shape for HSS 700+ Terocore® tube

Figure 12. Collapse shape for DP 800 + Terocore® tube

NEXT STEPS

The use of special steel allows reducing the thickness of the sections. The structural foam used for these test has improved the collapse behavior but no significantly. New foam formulation is needed to get stiffer compression values.

SECOND GENERATION OF TEROCORE®

After analyzing the results obtained with the standard Terocore® formulation and the use of higher quality steels, a new formula of structural foam was developed.

The new Terocore® should avoid the collapse of the section. Better performances in compression were required.

The steel properties were analyzed as well. The HSS 700 steel was kept as it showed a high bending moment and the Terocore® would improve the collapse behavior. For the Dual phase steel qualities two higher qualities were selected DP 1000 and DP 1200. These higher qualities were selected in order to increase the maximum bending moment of the section.

Figure 13. 3 point bending test with Terocore® 2

The results of these tests were good as no collapse was produced during the 3 point bending test. No cracks were found on the steel.

Figure 14. bending are for DP 1000 with Terocore® 2

The bending moment values also show the clear effect of the Terocore® as we can observe in figure 14. The structural foam is strong enough to avoid the collapse of the steel. The initial Terocore® formulation allowed the tube collapse and consequently the bending moment decreased; the new structural foam avoids the tube collapse and the bending moment keeps growing.

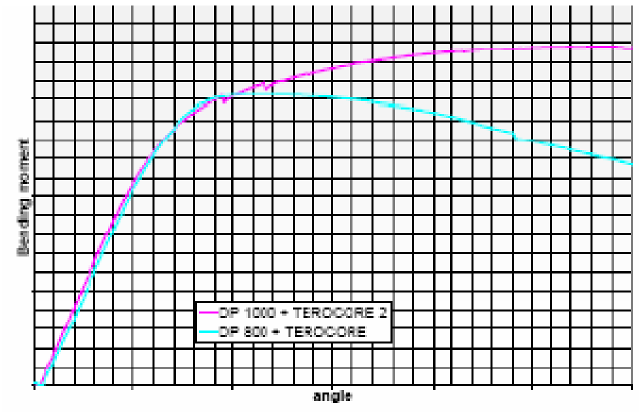

Figure 15. Bending moment vs angle for DP steel

The results with HSS 700 were also good. The structural foam behaves in a way to stop the collapse of the steel. In figure 16 we can clearly see the effect of the Terocore® 2 on the bending moment resistance.

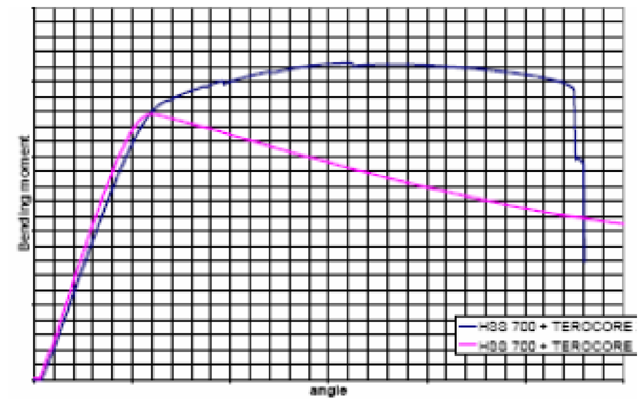

Figure 16. Bending moment vs angle for HSS 700 steel

INDUSTRIALIZATION TESTS

In parallel with structural studies, the manufacturability of this kind of solution was tested. The adhesion of the foam to the tube was checked in several conditions. Rough tubes and painted tubes were filled with Terocore® and after the foam was cured, a 3 point bending test was done. The results of these tests were satisfactory; consequently the application of the structural foam may be implemented before or after the paint process.

Figure 17. 3 point bending test result for painted and unpainted steel tubes.

The procedure for filling the tubes has also been checked. The two component material, which cures under ambient conditions has been selected for this study. This configuration has been considered to have the easiest implementation in a bus factory. Several tests were carried out to evaluate the number of holes and hole pitch to introduce the foam; some examples are shown in figures 18 and 19.

Figure 18. Cut section of a tube to check the foam distribution.

Figure 19. Bad filling example

VEHICLE IMPLEMENTATION

Following the lab tests which confirm that this solution works well, the next step was to implement it in a vehicle.

The vehicle to implement this solution is a vehicle which already fulfills regulation UN R.66.

This study is divided in two parts. One part has been developed with physical tests, in cooperation with a bus body builder. The other part has been carried out using simulation technologies.

The structure of a bus is mainly formed by tubes welded to each other. The 2 mm thick HSS tubes should be welded to the rest of the structure made of carbon steel and up to 4 mm thick. Moreover, as mentioned before, one important part of a safety arc is the joints. It is important to check if the traditional joint design is still effective with the Terocore® and HSS solution. The welding lines between the HSS or DP steel tubes and the joints should be compatible. Joint tests were carried out to check the joints and pillars. The test forces a displacement on the upper part of the pillar. This displacement goes beyond the limit declared by the Regulation UN R.66.

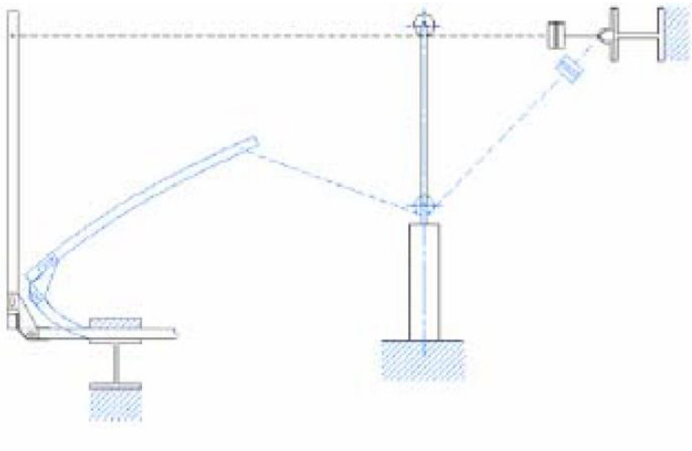

Figure 20. Joint test set-up

One part of the side of the bus, with its floor cross member, was manufactured at the bus body builder facility with the usual production tools. After the welded assembly was completely manufactured, the Terocore® was introduced inside the pillar.

These prototypes were made with HSS 700 steel and DP 1000 steel. No manufacturing concerns were found during the execution of the samples. The tests were performed at IDIADA HQ. Figure 21 shows a graph with the results. It can be deduced that there is no collapse.

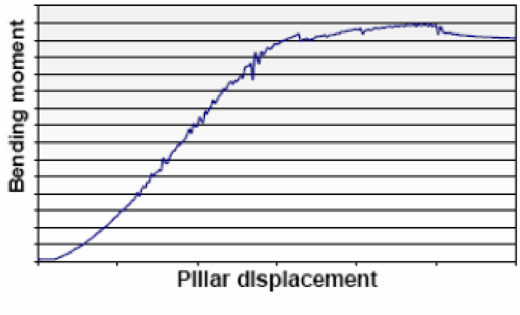

Figure 21. Joint test results

The joint after testing can be seen in figure 22. We can observe that the joint has behaved correctly; there is no plastic deformation. The connection of the joint with the pillar is OK. In addition, the welding lines between the different steels have behaved perfectly.

Figure 22. Joint test results

Finally, this study has been completed with the evaluation of all the work described above in a rollover section test. This evaluation has been made with finite element technology. A representative body section of a bus has been modeled and a traditional solution made with carbon steel has been simulated. The ballast of the bay section has been increased until the structure does not fulfill the Regulation in order to find the maximum energy absorption capability.

Figure 23. Bay section test with added mass

The final test weight of the bay section was 1887 kg. The results of the rollover test were unsatisfactory, since there was a small penetration of the structure in the survival space. Thanks to these simulations, it was possible to determine the maximum energy that the bay section can withstand. The simulation results can be seen in figure 24.

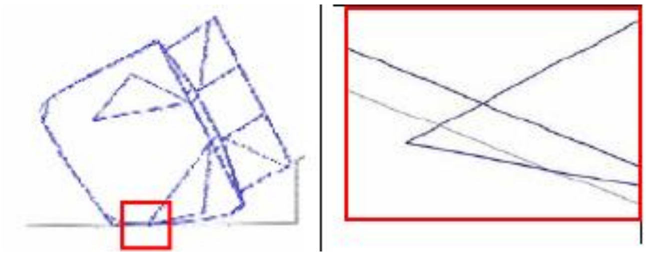

Figure 24. Simulation of the traditionally manufactured bay section.

The same simulation was also performed with DP 800 steel in the pillars and roof arc. The Terocore® was only introduced in the pillars and in the area close to the joints. Not the whole pillar length was filled with Terocore®. The ballast for the test remain the same.
The simulation results showed that this new structure was able to fulfill the test according to Regulation UN R.66.

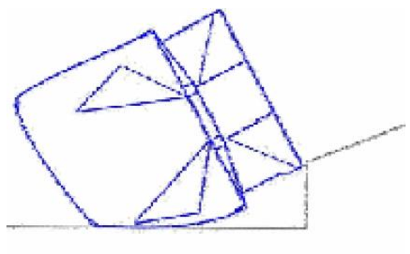

Figure 25. Simulation of the bay section withTerocore®.

This structure made with Terocore® and DP-800 was 75 kg lighter than the traditionally built one.

CONCLUSION

Previous studies were focused only on the introduction of structural foams or higher strength steels, independently from each other. These solutions do not work well individually, but an integrated design which incorporates the best properties of both results in an optimal performance. In the solution found under this investigation project, the steel is the responsible of the energy absorption and the Terocore® is responsible of the collapse shape, making it possible to make full use of the enhanced properties of the selected steel.

At the beginning of the project there were some challenges that have been successfully solved. The second generation of the rollover resistant safety arc has been proved to be effective.

The industrialization activities proved that the solution is easy to implement in the bus body builder's factories.

The design of the rollover resistant safety arc is a key aspect for the success of the implementation. Simulation tools are a must for optimal design of the joints and the placement of the Terocore®. The function of the Terocore® is to avoid collapse and must be placed only in the collapsible areas.

In our case study, the weight of the structure part has been reduced by 25% just by acting on the safety arcs.
We can foresee a weight reduction of up to 300 kg in the steel structure for a structure designed to fulfill Regulation UN R.66.

IDIADA is one of the most experienced engineering companies in the field of rollover resistance structures development, well known for its innovating solutions to improve safety in buses and coaches.

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