IMPROVED DESIGN FOR FRONTAL PROTECTION

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ABSTRACT

The requirements of frontal impact legislation and the comparative evaluations of consumer organisations have improved occupant crash protection. Passenger vehicle bodies have crumple zones developed through rigid flat barrier testing and improved passenger cell stability has resulted from consideration of offset deformable frontal impacts.
Pressures to minimise cost and weight, whilst still maintaining satisfactory crash performance, could potentially lead to vehicle designs in which the crash behaviour of the structure has been optimised for barrier testing. TNO has undertaken a collaborative research project with Alcoa Reynolds Aluminium to investigate how the energy from a variety of different frontal impacts could be reliably managed within the structure of a medium sized passenger vehicle. The concept structural design developed within this project is intended to provide an acceptable amount of energy absorption independent of the precise orientation of objects with which vehicle collision may occur.

INTRODUCTION

The potential for energy absorption within the front structure of a passenger vehicle may be optimised for specific loading e.g. high-speed rigid flat barrier impact. In many vehicles energy absorption is provided by the axial collapse of longitudinal frame members. These structural members work well when loaded as intended but may not always perform so effectively in vehicle crashes on the road. In the study described here the controlled bending rather than axial collapse of the main longitudinal members has been used to reliably manage the energy from frontal impact.
A demonstrator has been built as an illustration of the potential feasibility of realising these concepts. The project was named ECOFRONT, a reference to the use of lightweight materials in the vehicle's construction. The design was intended to enhance the predictability of the vehicle structural crash performance in frontal impact without the addition of extra weight. In developing the crashworthiness design concepts the overall vehicle weight has not been significantly reduced if compared to that of other Aluminium space frame vehicles.
The basic concept for the main structural longitudinal members is derived from that demonstrated in the "Cratch" vehicle developed by Professor Waltz of Zurich University in the early nineties [1]. Within the ECOFRONT project described here however, pre-bent Aluminium sections have been used within a much larger vehicle in such a way as to maximise their energy absorption potential .
The vehicle structural design is comprised of formed Aluminium extrusions and has been developed to provide crash protection in both low and high-speed impacts. Finite Element analysis has been used to lead the design process and the result of the design iterations necessary to incorporate recommendations from both this analysis and manufacturing feasibility investigations will be described.

CONCEPT DEVELOPMENT

The ECOFRONT structure has been developed using well-defined load cases so as to allow for design improvement against clear targets. The development load cases used to assess structural performance were the European legislative low speed pendulum impact test [2], the Allianz low speed damage repair ability test [3], the EuroNCAP offset deformable frontal impact test [4], and the Federal NCAP high speed rigid flat barrier test [5]. In addition to these typical vehicle development load cases simulation studies were performed to assess and modify the design's crash performance in impacts with different height vehicles and with differing amounts of vehicle to vehicle overlap.
The measure of vehicle crash performance in the two selected high-speed frontal impact load cases is normally occupant injury. The objective for this project was to develop a stable vehicle structure into

which a typical restraints system could be fitted. Occupant simulation and restraints development were not therefore performed to define an optimised structural and restraints solution. As a measure of design progress passenger cell intrusion and vehicle deceleration were monitored and used to influence the development of the detailed design.

The ECOFRONT project was started in 1999 as one of two parallel TNO projects. The other was the development a Diesel Electric hybrid drive system which when complete would be fitted within the ECOFRONT structure. Throughout the development of the structural design the vehicle package was adjusted to accommodate the evolving requirements of both the crashworthiness targets and the power train components for which space needed to be found. Figure 1. shows the representation of engine and generator packaged within the ECOFRONT prototype. The completed prototype demonstration vehicle includes a representation of the Diesel Electric components used within the vehicle packaging studies around which the vehicle structure was developed.

Figure 1. ECOFRONT package.

Initially the ECOFRONT structural concept was intended to take full advantage of free space available within the engine bay. The absence of drive shafts within the front of the vehicle made it possible to lower the front longitudinal section relative to that typically found with a front wheel drive vehicle. The width available within the engine bay made it possible to accommodate large Aluminium extrusions either side of the engine / generator for the main front longitudinal members. As the project advanced the constantly evolving package requirements associated with the new power train resulted in a less idealistic structure being realised. The resulting design being created as a consequence of being forced to address many of the space restrictions commonly associated with production vehicles. Figure 2. shows the vehicle front end package layout around which the structural concept was developed.

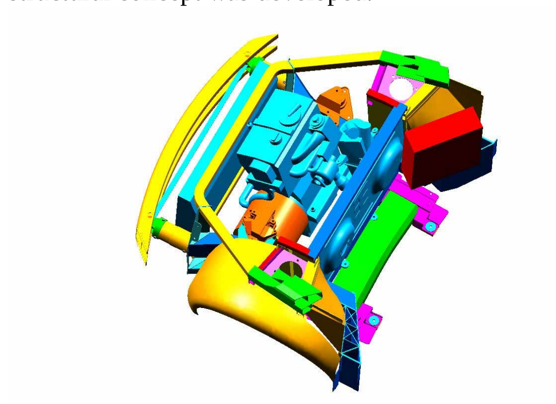

Figure 2. Engine and Generator installation

The structural concept used for development of the ECOFRONT design is based on three basic principles;

- Progressive absorption of impact energy at defined load levels.
- Multiple load paths from the vehicle front into the passenger cell.
- A robust structural design which if it collapses does so in a controlled manner.

The very front of the vehicle has been designed to offer some protection to vulnerable road users and is therefore relatively soft. This is represented by the green components as shown in Figure 3.

Collisions involving increased mass but low speeds such as may occur in parking accidents have been used for the development of the bumper beam.

At impacts up to 15km/h the bumper beam in conjunction with a sacrificial energy absorbing structure has been developed in order to minimise damage to the main vehicle structure and thereby minimise repair cost. This is represented by the red components shown in Figure 3.

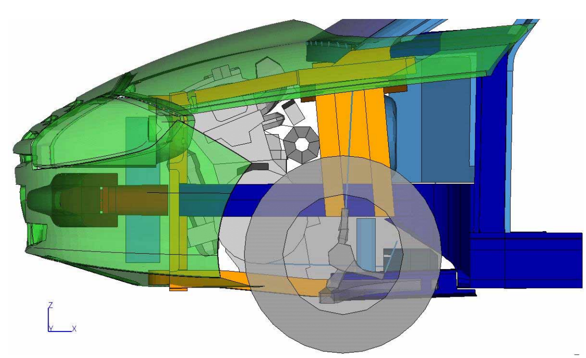

Figure 3. Energy Absorption and multiple load paths

Protection for the passenger compartment in high speed frontal impact has been provided by a combination of energy absorption from bending of the main longitudinal members and use of multiple load paths into the passenger cell in order to minimise the possibility of highly concentrated structural loading and structural collapse. The bending longitudinal members are represented blue and the additional load paths as orange in Figure 3.

COMPONENT PERFORMANCE

This section describes the function of each component of the ECOFRONT front structure and provides an overview of the final performance predicted for such a concept.

Bumper Beam

The ECOFRONT bumper beam design has more than one intended function with respect to vehicle safety. The Stretch bent Aluminium extrusion plays a role in pedestrian impact, low and high-speed impact.

In designing a passenger car front bumper system for pedestrian impact account should be taken of the maximum load levels thought to be acceptable for a lower leg. A stiff bumper designed only to provide structure and bodywork protection may produce high loading of a pedestrian's lower leg should impact occur. To ensure that the bumper does not create unacceptably high loading the area behind the bumper fascia can be designed, should space allow, to create loads within a lower leg that are of a suitable level to minimise injury [6].

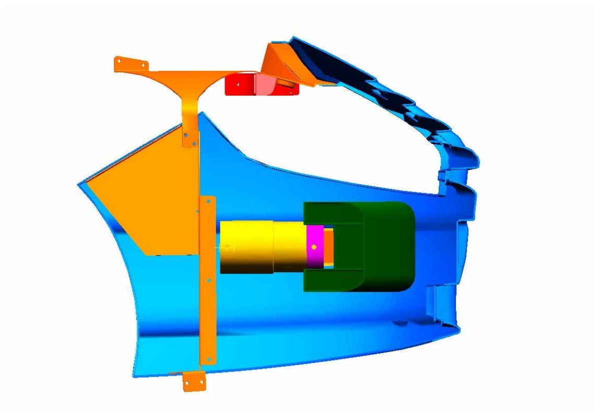

Figure 4. Bumper fascia and Beam

The ECOFRONT's polypropylene bumper fascia and reinforcement, as shown in Figure 4, were developed to provide some protection in collisions with vulnerable road users. Within this design concept the beam provides support for loads generated within the fascia during impact. The large Aluminium extrusion also serves to provide support should collision be severe enough to bottom out the impact absorber.

The consequence of adopting this concept however is that when the bumper is impacted by a stiff object such as may happen in a parking accident, or in the legislative low speed impact pendulum test, then the bumper fascia alone may not be sufficiently stiff to resist the impact. The ECOFRONT Aluminium bumper beam is able to manage any remaining impact energy once the fascia has absorbed that associated with a lower leg impact.

In low speed vehicle impacts as evaluated by the ECE R42 regulation and the Allianz 15 km/h offset rigid barrier impact, the ECOFRONT bumper beam is designed to react the impact loads. With the ECER42 loading the bumper beam behaves in an elastic manner with no permanent damage.

In the higher speed Allianz offset rigid barrier impact at 15km/h the bumper beam has sufficient initial stiffness to transfer load to a sacrificial low speed impact energy absorbing structure located behind the bumper beam. The sacrificial structure is designed to be "bolt on", thereby ensuring that vehicle damage repair costs are minimised. The components that would need to be replaced can be seen by the plastic strain shown in Figure 5.

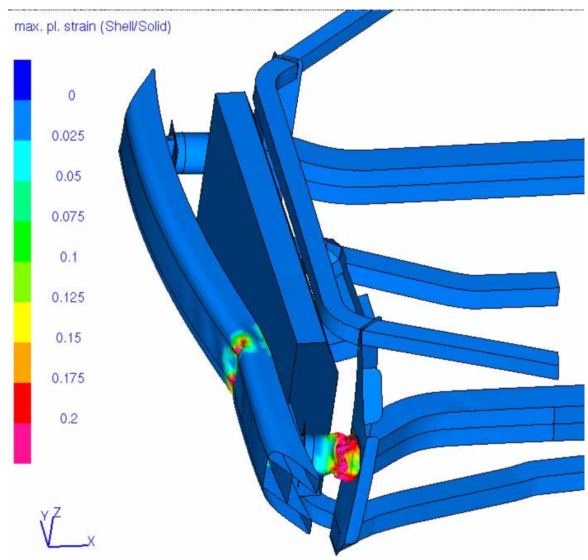

Figure 5. Damaged components in low speed impact

The design of the bumper beam was supported by Finite Element simulation. Material properties were supplied by Reynolds and although their 6000 series aluminium would have been suitable for low speed impact their 7000 series aluminium was eventually selected for the beam due to it's improved performance in vehicle to vehicle high speed impact simulations. The choice of this material had the added benefit of ensuring that impacts at low speed would be elastic.

To make the low speed energy absorbing system work effectively the energy absorbers needed to be loaded axially. The bumper beam is curved in plan so as to keep a constant offset to the front bumper skin providing a consistent level of protection to vulnerable road users across the vehicle front. On impact the initial curvature within the beam has a tendency to be removed. The beam straightens and as a consequence the beam mounts are pushed outwards. This outward motion puts the energy absorbing structure into bending and so energy may not be absorbed efficiently. To remove this possibility a strap was added between the beam supports. The strap, which is subjected to tensile loading as the beam attempts to straighten, maintains the geometrical relationship between beam and low speed impact energy absorbing structure sufficiently for them to be axially loaded and work efficiently.

Figure 6. Bumper beam and sacrificial energy absorbers.

The bumper strap can be seen in plan view in Figure 6. At higher impact speeds the bumper curvature will be removed but in the ECOFRONT structural concept axial loading of the support structure (main longitudinals) is not critical for the absorption of energy.
An Aluminium bumper beam was chosen in preference to plastic so as to maintain a consistent level of structural integrity within the front structure independent of the nature of vehicle impact.
It was important to have the front of the vehicle work as much as possible as a whole and not as a collection of individual components.
The possibility of sudden failure of a composite beam in some load cases would not have been consistent with this aim. The Aluminium beam connects the two sides of the vehicle together and does not fail in a sudden manner. It is therefore suitable to resist intrusion in both impacts with large surfaces and small diameter poles such as roadside furniture.

Sacrificial Energy Absorbers

Low speed impact protection, the damage repair ability load case, has been addressed within the ECOFRONT design by the provision of dedicated "bolt on" sacrificial energy absorbers. Each absorber has been designed as an invertube, a variable diameter aluminium tube that on impact collapses within itself to absorb energy.
At the forward end of this tube is a cap to distribute load around the end of tube and create the conditions for controlled axial collapse. This minimises the possibility of local bending failure arising from application of a concentrated load. Each cap has a pinned connection to both the bumper beam and the bumper strap. This pinned connection is present to ensure that irrespective of the impact condition, the tube is loaded in an axial manner and thereby absorbs energy during it's collapse efficiently. The invertube and end caps are represented in Figure 7.

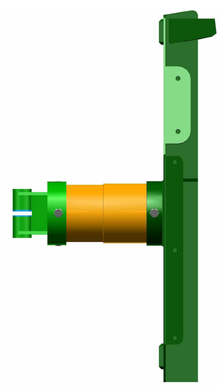

Figure 7. Sacrificial Energy Absorber

At the rear of each invertube is another cap, once again to ensure distributed loading of the tube and to act as an interface between the circular section of the invertube and the rectangular section of the end of the main front longitudinal member of the space frame.
The design as shown on the prototype has not been optimised for production but is just a representation of how the structural concept may be realised. Should such a sacrificial part become a production item it is appreciated that casting or moulding would need to be considered for the manufacture of such a part in order to minimise component cost.
The sacrificial structure is intended to absorb the energy associated with an offset rigid frontal barrier impact at 15km/h. Limiting damage to within easily replaceable items.
The structure was developed in conjunction with the packaging for the cooling system. Various design concepts for limiting the possibility of damage were considered including moving the whole radiator

assembly rearwards as the energy absorber collapsed. The final adopted solution placed the radiator in a static position as far rearwards as engine serviceability would allow. In doing this, the radiator was isolated from the main impact and as an additional benefit engine cooling was maximised as the shielding effect of the large bumper beam was reduced. Figure 8 shows the Finite Element vehicle crash model used to simulate the 15km/h impact.

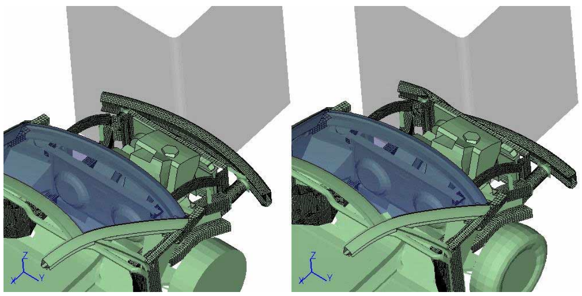

Figure 8. Simulated Allianz 15km/h 40% offset rigid wall impact

Concepts considered for development of the sacrificial structure included the axial collapse of a constant diameter tube, the collapse of a corrugated tube, the collapse of an invertube and the collapse of an extruded profile in which energy would be absorbed through bending of cantilever beams.

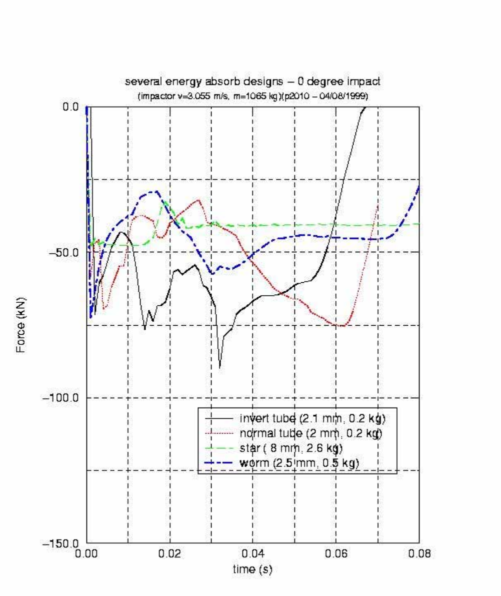

Figure 9. Low speed energy absorber comparison.

Each of these concepts was modelled at component level and simulated impacts with both a flat and angled rigid barriers were made to assess energy absorption and stability. A selection was made for the invertube concept based on a combination of both capacity to absorb energy and it's lateral stability. Figure 9 shows some output from component simulations performed to evaluate each concept. The wall thickness for the tube, 2.1 mm, was selected so as to ensure that the loads required to collapse the tube would be lower than the 75kN end load the main structural longitudinal was supporting early in the vehicle development. As the design of the longitudinal and it's support structure were later improved the margin between collapse of the sacrificial structure and the creation of damage in the main vehicle structure was increased.

Longitudinal Rail

The main structural longitudinal or rail section of the ECOFRONT design is intended, when subjected to impact loading, to absorb energy through bending. In plan each longitudinal section runs straight alongside the power train and is then bent outwards at the front of the engine. Figure 10 shows the main curved longitudinals in blue.

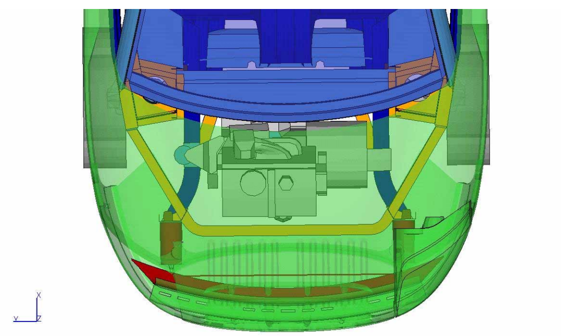

Figure 10. Structural frame

The choice of the outward longitudinal bend was made for the ECOFRONT in an attempt to create the possibility for two vehicles on collision to partially deflect one another. This would limit the amount of kinetic energy, which would need to be absorbed by the front structure. The mechanism to be investigated was named "anti-hooking", as it was intended to prevent one vehicle hooking into the other. This mechanism is described by the diagram in Figure 11.

Finite Element simulations showed that the bending mechanism within the longitudinal could be made to work successfully. It did not however prove possible to create the anti-hooking behaviour as originally intended. The simulations showed that to create the anti-hooking behaviour sufficient package space would need to be available between the bumper and the front wheel creating a long nose on the vehicle.

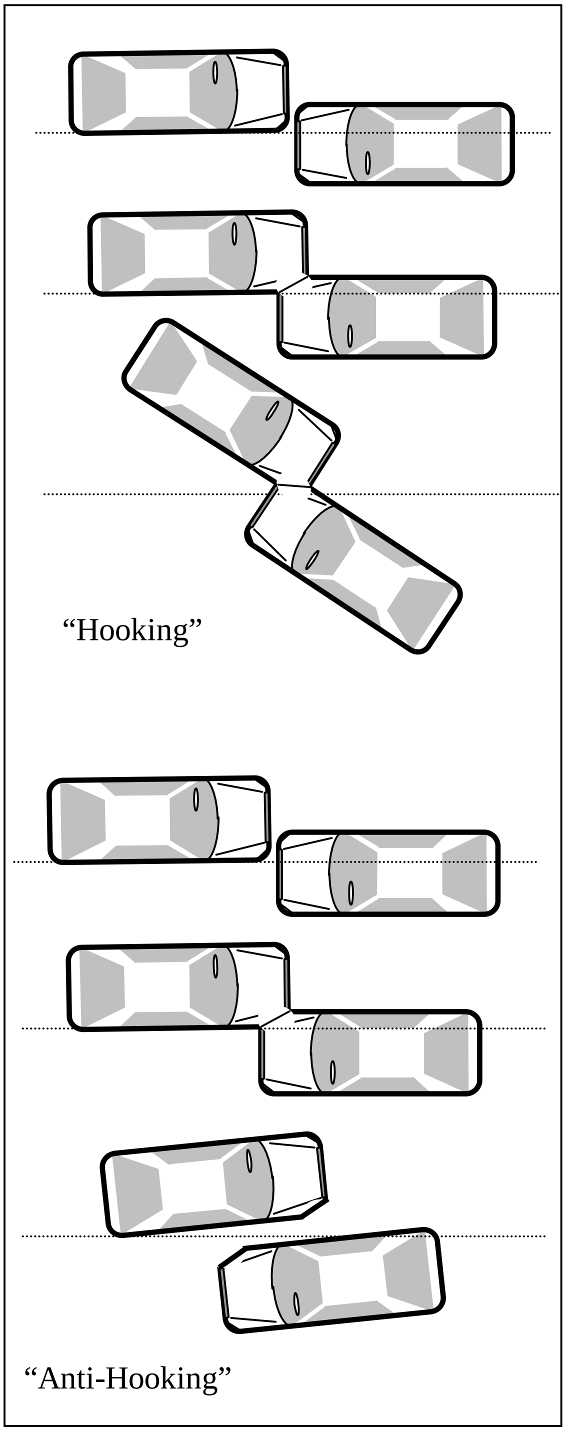

Figure 11. Anti-hooking concept, vehicle structure required to absorb less energy in vehicle collision

As the vehicle structure deformed in the simulations allowing the two vehicles to be redirected interaction occurred between the front wheels and suspension. It was found possible to create the desired structural response however the vehicle response was not as intended.

A straight longitudinal may collapse axially or may bend at a number of places along its length depending on the direction in which is loaded. With a possibility for uncertainty over the section’s collapse behaviour it cannot be guaranteed that a consistent level of protection for the vehicle passenger cell will always be provided.
The bent longitudinal concept has a significant advantage over a traditional straight longitudinal and that is the predictability of its collapse. A constant section bent longitudinal collapses at the pre-formed bend placed within the section and therefore can provide a more reliable level of energy absorption in frontal impact. The ECOFRONT longitudinal section is shown in Figure 12.
The material selected for use in the front longitudinal design was Aluminium. Absorption of energy through section bending is not as efficient as absorption through that of axial collapse. As a consequence the wall thickness of a section intended to absorb energy in bending needs to be increased compared to that of an efficient axial collapsing section. The difference in specific energy absorption of Aluminium compared to that of steel makes an increase in material thickness possible without significant increase in longitudinal weight. For a 1085kg vehicle the wall thickness selected for the main longitudinal was 4 mm.

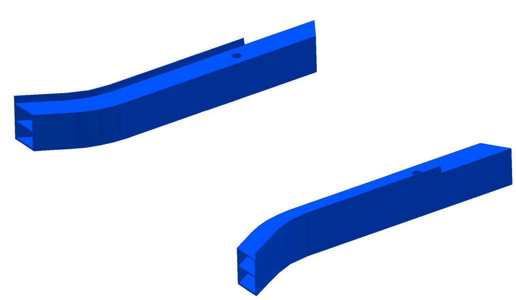

Figure 12. Stretch bent Aluminium extrusion for the main longitudinal sections

During the initial structural concept development for ECOFRONT a comparison was made between a possible bent Aluminium section and a longitudinal from a production vehicle. In this particular comparison the production car longitudinal effectively absorbed 16767 Joules of energy whilst the concept design absorbed 14250 Joules, however considering the weight of each section the specific energy absorption of the car longitudinal was 3280 J/kg, whilst that of the concept design was 4970 J/kg. An extruded aluminium longitudinal with sufficient wall thickness can therefore be designed to absorb as much energy as a traditional axially collapsing longitudinal without significant increase in weight if the wall thickness of the extrusion is optimised.

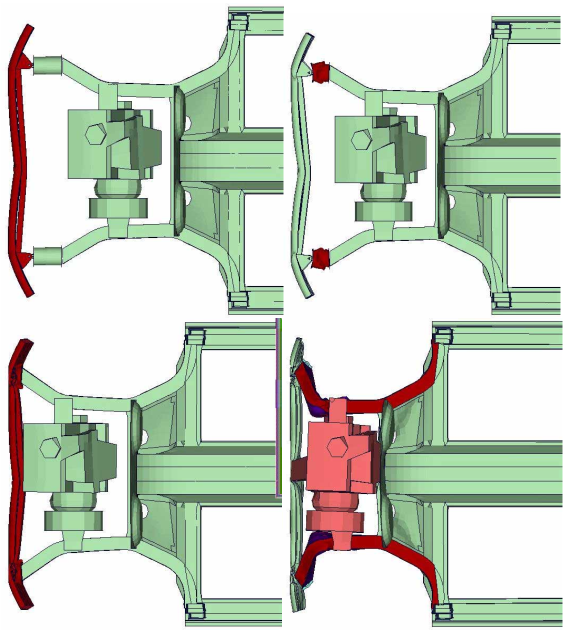

Figure 13. Collapse mechanism

Collapse within the ECOFRONT structure is intended to be progressive, bumper, sacrificial absorbers, bending of the longitudinal front and finally some bending of the longitudinal rear as shown in figure 13. Once the front portion of the longitudinal had been defined the loads developed within the section required support. The initial concept of one long extrusion with multiple bends was found not to be feasible for manufacture and a number of simulation and design studies were conducted in an attempt to support the loads generated within the longitudinal and transfer them into the main passenger cell.

As the manufacture of one formed extrusion was not feasible considering the level of tooling which could be afforded for this project the development of an additional component was started.

Longitudinal To A-pillar Link

The link extrusion makes a connection between the main longitudinal and lower A-pillar. On other Aluminium vehicles this connection has been designed in a number of different ways including the use of aluminium castings. For the ECOFRONT vehicle structural sections needed to be based on extrusions as at the time of developing the design that was Alcoa-Reynolds's main area of interest.

Rather than forming an extrusion in the same direction as the main longitudinal section and then attempting to stretch bend it was found that the structural integrity of the joint could be maximised by making the extrusion in a perpendicular direction. The challenge, which lay in this approach, was to define a joint of minimum weight but with sufficient load carrying capability. Initial concepts were not found to be capable of carrying sufficient load.

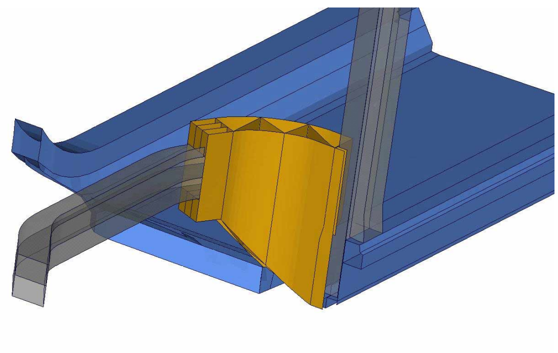

Figure 14. Concept longitudinal to A-pillar joint.

Once the overall exterior dimensions for the joint had been defined allowing for wheel envelope and foot clearance a series of Finite Element studies were conducted at component level to improve its load carrying capability.

Manufacturing feasibility was assessed by Alcoa-Reynolds and detail changes to the internal webbing made so that it could be extruded. The Link was designed with vertical flanges, which were then trimmed to ensure an interlocking connection to the lower A-pillar and Sill. Figure 14 shows the design of one of the first concepts for the connection between longitudinal and A-pillar.

STRUCTURAL DEVELOPMENT – LOAD PATHS

Concept Studies

The extruded aluminium space frame design of the ECOFRONT was intended to absorb energy and limit intrusion into the passenger cell in frontal impacts. Full vehicle Finite Element Crash simulations of early designs showed that whilst energy was being absorbed load was not being distributed effectively throughout the vehicle frame.

Initial simulations of a rigid, flat barrier impact at 56 km/h indicated low footwell intrusion levels of 25 mm with a peak deceleration of 70g for a 1085kg vehicle. Within this structure the predicted high deceleration was a function of engine to tunnel contact. Through the development of the structural design it was possible to reduce the peak vehicle deceleration by 10g and widen the deceleration pulse as a result of an improvement in energy absorption efficiency. The influence of the vehicle structure on crash performance was increased and the dependency on using the engine and generator to load the tunnel was decreased .

Figure 15. shows how the vehicle deceleration pulse was modified , the initial blue curve showing little structural involvement in the first part of the vehicle impact and the final red curve showing increased energy absorption by the structure with a corresponding reduction in peak deceleration. One consequence of increasing the contribution of the structure in the crash was a reduction in the time taken for the vehicle to stop. As the vehicle became stiffer the pulse duration became shorter.

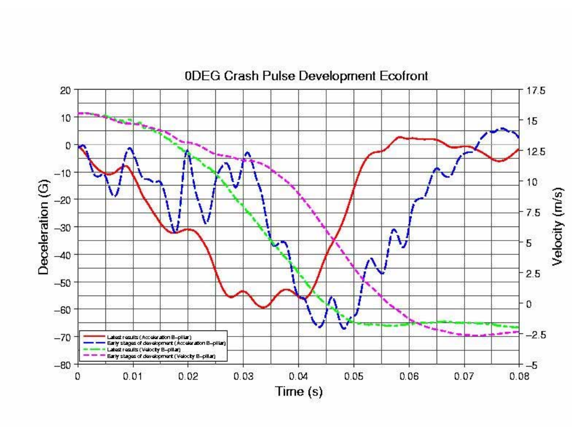

Figure 15. 56km/h flat rigid barrier impact, pulse development.

The soft front end structure has the potential to create a delay in an airbag sensor detecting a vehicle impact. Unfortunately a stiff initial impact was not found compatible with the vulnerable road user and damage repair targets. Airbag sensing on such a vehicle may need to consider additional remote sensing at the front bumper.

Once the front part of a vehicle is considered to have stopped in a frontal impact the rear can still be moving forwards creating passenger cell intrusion. In order to prevent excessive intrusion and the possibility of structural instability the passenger cell can be supported at a number of locations thereby minimising the possibility of high localised loads. To make this possible two additional load paths were added to the concept space frame structure.

A lower load path was defined by addition of a lower longitudinal member, not to act as a main energy absorber but to distribute load and create stability. Addition of this load path resulted in an increase in the loads measured within the Finite Element model's rocker section. Sudden vehicle deceleration which previously occurred as a consequence of contact between engine and tunnel was reduced.

In addition to the lower longitudinal an upper longitudinal or "shotgun" member was incorporated into the design. Connected between the radiator and shock tower this member is intended to provide some support to the lower A-pillar and also to interact with other vehicles should collision occur.

To create a reliable robust structural design load path and mass sensitivity studies were performed using the Finite Element model.

Doors were not included in the simulation model as a front end structural response dependent on their contribution was not desired. The longitudinal concept was not intended to require the doors to work in a particular manner for them to perform satisfactorily.

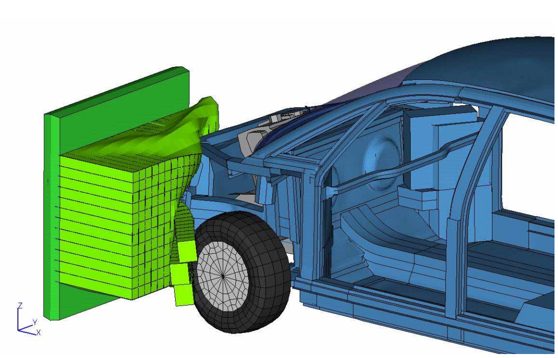

Figure 16. 64km/h offset deformable impact simulation.

In addition studies were performed simulating failure of the front suspension, and the influence of and dependency on the front wheel in offset frontal impact. As development progressed, intrusion was increased and the rate of vehicle deceleration reduced, balancing the two to find the best compromise to protect the vehicle occupant.

One of the full vehicle frontal impact Finite Element models used to develop the structural design is shown in Figure 16.

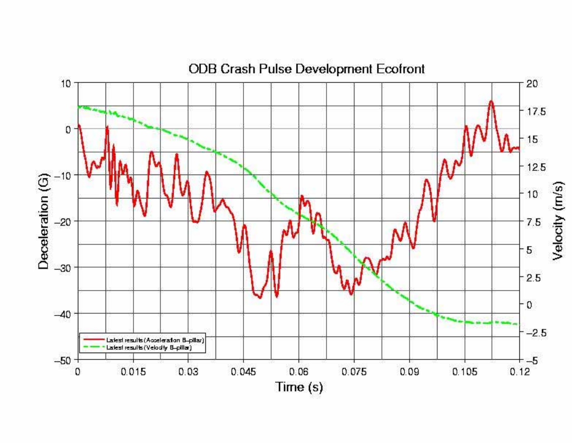

Figure 17. Final vehicle deceleration pulse.

From these initial simulations the design was developed to have multiple load paths from the front of the vehicle into the passenger cell. To satisfy the objective of having reliable predictable crash performance independent of the type of vehicle impact it was also decided not to be dependent on loading the passenger cell via the front wheel. Figures 17 and 18 show the vehicle deceleration and intrusion as predicted from the Finite Element simulations.

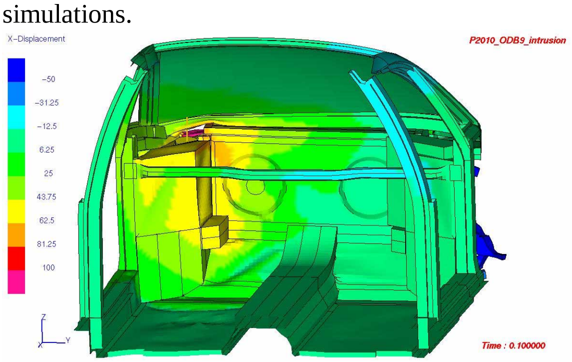

Figure 18. Maximum passenger cell intrusion .

Vehicle To Vehicle And Vehicle To Barrier Impact

Initially the shotgun was connected between the inboard side of the shock tower and another vertical member rising from the front of the longitudinal. This construction could be made stable and provided some support to the passenger cell in offset deformable frontal impact, however this concept did not address two associated crashworthiness concerns. The first is compatibility, the second is pedestrian impact. To generate a free area above hard items in the engine bay for the provision of some protection to vulnerable road users the original shotgun was packaged so as to maximise the distance between the structural section and the bonnet inner. The consequence of this was that the front of the shotgun was relatively close to the top of the main longitudinal. With little vertical offset between the main longitudinal and the shotgun there would be potential for a colliding vehicle to over ride the Ecofront vehicle thereby by-passing the energy absorbing members with the risk of penetrating the passenger cell.

Vehicle to vehicle impacts were then simulated using a more detailed Finite Element representation of the ECOFRONT design in an attempt to understand how greater interaction with a colliding vehicle could be achieved.

Vehicle to vehicle simulations were performed at forty and fifty percent lateral offset and at different longitudinal heights.

1) ECOFRONT to ECOFRONT
2) ECOFRONT to a bumper at a raised height to represent a typical height of longitudinal in front engine vehicles. This study was to investigate the possibility of typical production vehicles overiding the ECOFRONT structure.
3) ECOFRONT to a stiff bumper and support structure at a height comparable to that of a typical SUV.

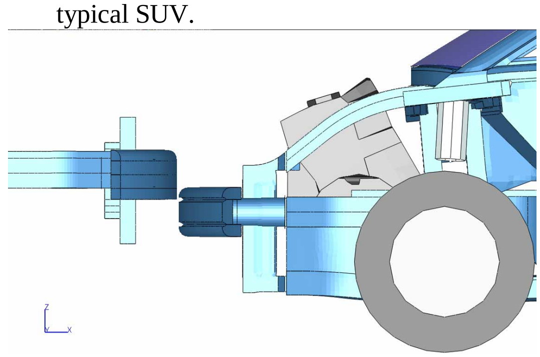

Figure 19. Vehicle to Vehicle impact

These simulation studies, model shown in Figure 19, suggested that passenger cell intrusion could be doubled within the ECOFRONT if it should have a collision with a higher vehicle and in doing so the energy absorbing structure did not interact with that of the other vehicle. In a simulated collision between an SUV structure and the ECOFRONT the raised bumper section intruded into the engine bay until it made contact with the structure around the shock tower. Passenger cell intrusion was increased by a factor of eight.

During these studies it was found necessary to relocate the rear connection of the shotgun to the outside of the shock tower and for the lower longitudinal to have the similar outwards curvature as the main longitudinal in order to reduce the possibility of them hooking into the colliding vehicle.

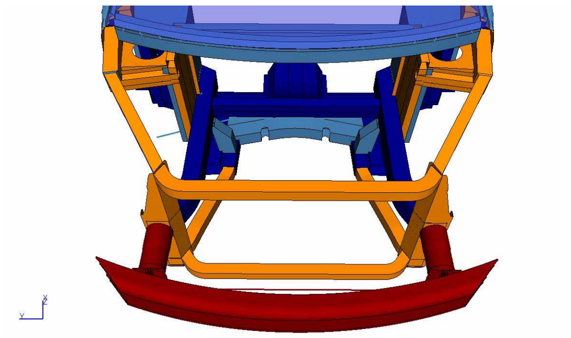

Figure 20 Three ringed concept.

The vehicle-to-vehicle impacts led to the creation of a three-ringed structural concept to create better interaction between the ECOFRONT and other vehicles in vehicle to vehicle impact. As can be seen in Figure 20 the upper ring passes from each shock tower via the radiator support frame, the middle ring is comprised of the main longitudinal, Invertubes and bumper beam, the lower ring is comprised of the lower longitudinal members and the radiator support frame. Each of the three rings are connected together by vertical panels added to create some interaction, "to catch" an intruding vehicle's structure and thereby limit passenger cell intrusion.

Proof Of Structural Concept

A prototype aluminium bumper beam, the invertube and main longitudinal have been subjected to component testing in order to validate the structural concept developed through Finite Element simulations.

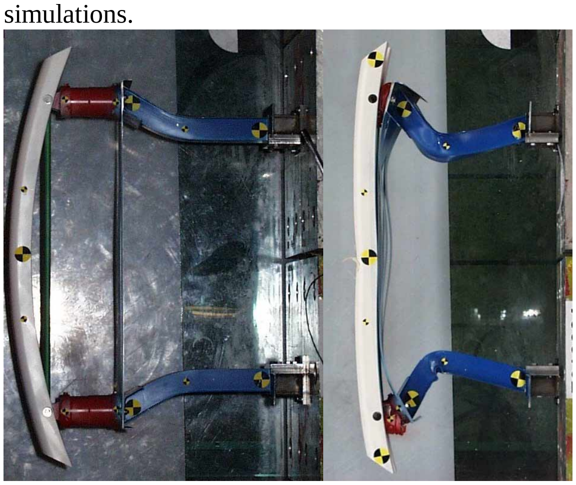

Figure 21. Physical component validation testing – longitudinal and front structural assembly.

Two tests were performed, one to study the load speed energy absorption design concept of the bumper beam and invertube, the other to investigate the behaviour of the main longitudinal as shown in figure 21. In both cases whilst the simulation models required some minor tuning to recreate the actual behaviour seen in the physical test e.g. Incorporation of slight inclination angle of impacting barrier, the prototype structure behaved as intended.

DISCUSSION AND CONCLUSIONS

The ECOFRONT demonstrator vehicle built as a result of these studies is only meant to be an indicator of what may be possible for the lay out of a vehicle structure given sufficient package space. Due to the boundary conditions for this project alternatives to aluminium extrusions were not investigated but in some cases alternative constructions may be preferable. The ECOFRONT prototype is of welded construction for simplicity but it is appreciated that for production vehicles adhesive bonding and mechanical fixings would in certain joints be preferable.

The ECOFRONT structural concept has not been subjected to a full vehicle frontal impact however the longitudinal, invertube and bumper section have been subjected to dynamic testing in order to verify the concept. This project suggests that the bending of Aluminium extrusions as a means to absorb crash loading in a controlled manner is feasible should package space allow, and as such it may be considered for adoption in mid or rear engine vehicles in addition to the hybrid front engined concept considered in this study.

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