POLITECNICO DI TORINO

Automotive engineering master’s degree course

Master’s degree thesis

A door opening system: from case studies to the design of a hinge system for small series vehicles

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1. Abstract

1.1 Thesis project description

The thesis focuses on the analysis and the design (with the appropriate case studies) of door assemblies of small series vehicles (Automobili Amos Delta Futurista) and prototypes (SCG 004S).
The curricular training had the goal of setting a design method for the door system of small series vehicles, with the following components that derive from it: hinges, latches, door panels, weatherstrips.

The project begins with the study of the overall door systems, focusing on the several components that constitute the assembly, and underlining the differences that can be encountered from one vehicle typology to another. For that reason, it is important to define the most known types of doors that exists nowadays in the market, which differ not only on shapes and kinetics, but also on the materials adopted and the several production processes.

Starting from the analysis of different case studies, the objective is to evaluate the problems occurred in design terms on the door systems, and to perform the "lessons learned" useful to decide in the future which design choices to follow.
Taking as reference those studies, the thesis flows into the definition of the specifics and the design requirements for different application cases:

- Typologies of vehicles: passenger, race, sport cars.
- Doors typologies: conventional hinges, gullwing doors, scissors doors, sliding doors,….
- Production technologies and materials: aluminium, steel, carbon fibre, magnesium.

After having design a completely new solution for the SCG004S door, the final goal of the thesis is to create a design normative for the company Podium Advanced Technologies of the door systems, considering all the structural and design analyses performed.

1.2 Podium Advanced Technologies – my job during the curricular training

Podium Advanced Technologies in a consulting engineering company, which is uniquely positioned to offer a comprehensive set of services in automotive high performance development, covering conventional, hybrid and full electric powertrains, supported by a unique hand-on experience in all facets of international motorsports (such as endurance races).

During my curricular training in Podium I have focused not only on my thesis project, but also to some projects that, for secrecy reasons, I will not show in this document.

Even if Podium Advanced Technologies works for many clients, the two most important that spread Podium name around the world are Automobili Amos and Scuderia Cameron Glickenhaus (SCG). Automobili Amos has commissioned the engineering study to Podium on the Delta Futurista, the vehicle that I will analyse later in the thesis. While at the same time I performed some structural analyses on the door assembly of the road legal car of SCG, the 004S.

Following on person (as a spectator) the assembly processes of these two vehicles allowed me to evaluate design and structural considerations in an easier way, studying the rise of the cars from zero.

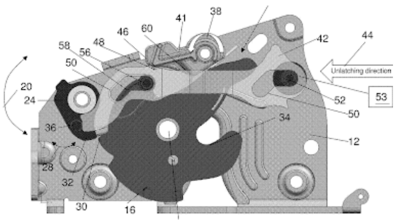
2. Doors typologies: design and production processes

In this chapter I am going to describe the overall design door system, starting from the different components that compose the assembly and underling all the most important door types known nowadays. What I am going to do is to perform a detail analysis of the system, taking as reference all the aspects related to the door, such as:

1. Car door system main components.
2. Lateral doors function analysis.
3. Door type classification.
4. Example of Door design decision matrix .
5. Door material classification.
6. Side door structure - families.

2.1 Car door system components

The main door system components to take in consideration during the design processes are:

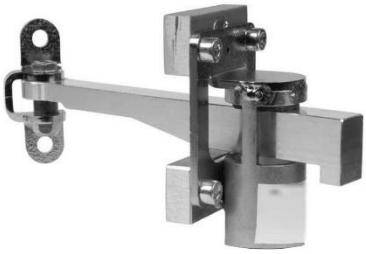


- **Door locks and latches:** most vehicle doors are secured closed to the vehicle body with latches which may be locked to prevent unauthorized access from the exterior. Vehicle door latches on practically all vehicles today are usually operated by use of a handle, which requires the user to pull with some force towards themselves rather than push.
  A door lock includes a mechanical module with movable parts usually fitted to the door and a striker, usually fitted to body side. It is anyway possible to exchange both components position by other opening devices that in any case must allow the door to open after a crash.

- **Door hinge:** facilitate passenger entry/exit by providing an axis of rotation for the door, a mechanism to control the door motion, and a mechanism to prevent over travel of the door when opening to prevent damage to adjacent components.

- **Door switch:** simple on/off mechanisms connected to the interior light (or warning light) to inform the driver when the door is not closed.

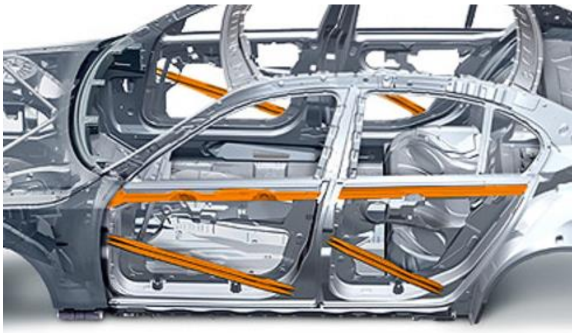
- **Windows:** most car doors windows retract downwards into the body of the doors and are operated manually or electronically.



- **Door brakes:** they have the function to slow the door down if it is opened with a strong pulse, as in case of a gust of wind or misuse. In fact, the door may reach the final opening position with still a relevant amount of kinetic energy, the absorption of which results in higher loads that depend on the stiffness of the stop. If the stop consists in just a hinge tooth, its stiffness can cause either the door, the hinges or the body side to yield, and sometimes the door can even hit the body pillars or fenders.

- **Door handles (exterior/interior):** necessary mechanism to open the door from outside or inside.

- **Anti-intrusion bar:** passive safety device which must protect passengers from side impacts. The role of an anti-intrusion bar is to absorb the kinetic energy of the colliding vehicles that is partially converted into internal work of the members involved in the crush. These bars are generally made of high strength steels (HSS). However, some studies indicate that stainless steel 304 might be a better choice, because of its larger plastic field and a larger amount of potentially absorbed energy before fracture.



- **Door module:** An automotive door module is an arrangement of a rubber-sealed carrier, onto which an array of automotive door components such as the window sliding mechanism, the wing mirror arrangement, loud speaker, wiring harness, door latch inner and outer release cable, door locks and various switches are fitted.

2.2 Lateral doors functions analysis

Before starting the analysis of the specific systems, it is important to define the lateral door differences between a road legal vehicle and a race vehicle for what concerns the requirements to fulfil during the design stages.

The lateral doors functions of a road legal vehicle are:

1. To ensure easy entry/exit inside/outside of the vehicle's cockpit.
2. To protect the cabin from air, water and dust in bad weather conditions, using seals that also ensure easy closure and opening (low weather strips load reactions).
3. To provide the presence of anti-intrusion bars in the door frame (Figure 1) to protect the driver in a safer way in the event of a side collision.
4. To prevent unauthorized access from outside through door locking and locking systems.
5. To improve thermal and acoustic comfort by isolating the driver and passengers from adverse external conditions.
6. To ensure adequate comfort for both arm support and immediate control availability while the vehicle is in motion.
7. To provide a pleasant look that mixes with the stylistic theme of the vehicle.
8. The door has to open/close automatically with an electro-hydraulic implementation system (above all in those cases that the driver's position does not allow the door to open and close manually).
9. Appropriate door closing speed at the level of ease of closing, sound level and plays pairings.

Figure 1: Door frame components

The lateral doors functions of a competition vehicle are:

1) To prevent air and dust from entering the cabin.
2) The door **does NOT** require a high-quality door seal (still ensure a good protection from water and unsolicited driver air comfort).
3) The door ***does NOT*** require a large opening of the door (the ergonomic and comfort aspect of the entrance/exit from the cockpit due to the presence of roll cages is not important).
4) To guarantee the possible presence of polycarbonate side windows: ensure a light but less rigid structure than the glass variant.
5) The door ***does NOT*** require space for cranks.
   Note: You can insert a sliding portion on the window (Figure 2).

Figure 2: Sliding portion on the window

2.3 Door types classification

In order to focus on the door assemblies of the vehicles designed in Podium, it is necessary to analyse each typology (Figure 3) in a proper way, defining their mechanisms but above all the advantages and disadvantages encountered.
From this brief classification we can underline the main characteristics of the doors, in order to make the right choices during the design phases of new vehicles: focusing on their stiffness, aesthetic appearance, innovative design, materials and structure type [10].

In the following list I have reported all the most famous types of doors known nowadays, which they will be studied in a detail way for what concerns the design processes, underlining the advantages and disadvantages of each type (indicating the vehicles that adopts those doors):

1. *Conventional.*
2. *Suicide.*
3. *Swan.*
4. *Scissors.*
5. *Butterfly.*
6. *Gull wing.*
7. *Sliding.*
8. *Swing Sliding Door (SSD).*
9. *Canopy.*
10. *Dihedral Syncro-Helix actuation doors (Koenigsegg patented).*

Figure 3: Side doors typologies

2.3.1 Conventional doors

A conventional door (Figure 4), also known as a regular door, is hinged at the front-facing edge of the door frame, and so it allows the door to swing around almost a vertical axis, outward from the body of the car. These doors are relatively safe, except if they are opened during forward motion of the vehicle: the wind resistance will work against the opening door and will effectively force its closure. The operation of ingress and egress via doors from the vehicle, or standing outside an opened vehicle door can represent a safety issue particularly at night, if the passengers are not alert.

Conventional doors are mainly constituted by 2 hinges almost vertical to the ground (inclined to avoid self-closing): one upper and one lower. Between them it is located the door brake to reduce damages to the door assembly, slowing down the door just before it completely opens.

- **Advantages**:
    - Good safety, since the doors do not unlatch when driving.
    - Simple and well-known technology.
    - If the door is unlikely opened during forward motion, the wind resistance will work to keep the door closed.

- **Disadvantages**:
    - Requires more lateral free space for the maximum opening to ingress/egress from the car.
    - Front door much longer than rear door, this leads to unusual proportions.
    - When the door is completely opened, the vehicle leads to safety issues above all at night: for that reason, nowadays opening door lights are introduced.

Usage: it is widely used for almost all types of vehicles, for its simplicity and since it is a mature technology in which are well known each advantage and disadvantage. For that reason, almost all passenger cars have adopted this typology.

Figure 4: Fiat 500

2.3.2 Suicide doors

A suicide door is the slang term for an automobile rear passengers' door hinged at its rear rather than front, as conventional doors. But such doors are rarely found on modern vehicles, primarily because they are perceived as being less safe than a front-hinged door. In the era before seat belts, the accidental opening of such doors meant that there was a greater risk of falling out of the vehicle compared to front-hinged doors, where airflows pushed the doors to close rather than opening them further (for that reason they are called "suicide").
Suicide doors can be characterized by a B pillar and independent rear door: the rear door is latched to the B pillar, that has a structural function. There is a play between the front and the rear door, which is covered by weather sealing in order not to let water and air entry inside the vehicle.
In recent years, in case of lack of the B pillar, rear-hinged rear doors that cannot be opened until the front doors are opened (**slave doors**) have appeared on several vehicles, including extended-cab pickup trucks. The rear door is slave of the front since, due to the absence of the B pillar, the front doors must lay on the rear when they close in order to seal completely the side of the vehicle from water and air ingress.

Remark**:** In case of a pillar less solution, the rear door frame, which is slave of the front door (cannot be opened until the front door has opened), has a structure that must resist to side crashes: it is like the B pillar that is moved to the rear door (for structural issues). This solution leads to have a bigger cross section of the rear door with respect to the front door, with 2 latch strikers for the rear assembly: one on the roof and one on the doorsill to allow the locking action; while the striker of the front door is placed on the side of the rear.
For what concerns the front seat safety belt, two solutions are adopted:

- Safety belts mounted on the **rear door frame**: rear door cannot be opened until the front passenger has released the safety belt, otherwise it brings safety issues.
- Safety belts mounted at the **top of the rear door frame**, while at the bottom to the car body. The mechanism is called slide bar, since at the bottom the safety belt anchorage slides backward when the rear door opens and slides frontward when the door closes (just because of the mechanical tension of the belt).

- **Advantages**:
  - To make entering and exiting a vehicle easier, allowing a passenger to enter by turning to sit and exit by stepping forward and out.
  - Better installing procedure of child seats in the back.
  - It allows for a design without B pillar (B-pillar less solutions), creating large opening for the ingress and the egress.

- **Disadvantages**:
  - When front doors are directly adjacent to rear suicide doors, exiting and entering the vehicle can be awkward if people try to use the front and back doors at the same time.
  - Aerodynamic factors forcing doors to open. Safety issues when a vehicle hits the door, since it could lead to passengers' damages.
  - Requires more lateral free space for the maximum opening to ingress/egress from the car.
  - In case of absence of B pillar, the rear door is slave since it cannot be opened until front door is opened.

Usage:

- Suicide door with B pillar and independent rear door:
    - Opel Meriva (Figure 5).
    - Rolls Royce Phantom (Figure 6).
    - Lincoln Continental.

Figure 5: Opel Meriva

Figure 6: Roll Royce Phantom

- Suicide door without B pillar (pillar less solution):
    - BMW i3 (Figure 7).
    - Mini Clubman, 2007 (Figure 8).
    - Madza RX-8.

Figure 7: BMW i3, safety belt mounted on rear door frame

Figure 8: Mini Clubman, safety belt attached to the doorsill at the bottom

2.3.3 Swan doors

Swan doors are a type of doors sometimes seen on high performance cars or concept cars. They operate in a similar way to conventional car doors but unlike regular doors, they open at an upward angle. This design helps the door to clear curbs, especially on lower sports cars, by opening slightly upward and away from the curb.

- **Advantages**:
  - To give the car a stylish look.
  - Convenient in tight parking spaces.
  - To avoid curbs.
- **Disadvantages**:
  - Due to the design of the door, it can make it uncomfortable for the driver to close the door when in a tight space.

Usage:

- Aston Martin V8 Vantage (Figure 9).
- Jaguar C-X75 concept (Figure 10).

Figure 9: Aston Martin V8 Vantage

Figure 10: Jaguar C-X75 concept

2.3.4 Scissor doors

Scissor doors are automotive doors that rotate first sideways (on XY plane, swing-out angle α) of few degrees and then vertically at a fixed hinge at the front of the door (on XZ plane, lift angle β), rather than outward as with conventional door (Figure 11). A common scissor door conversion (for regular production cars that originally come with regular doors) kit includes model specific redesigned door hinges and gas filled shocks.

The conventional type rotates to 90° towards the vertical direction, but there are different types of scissor powered doors:

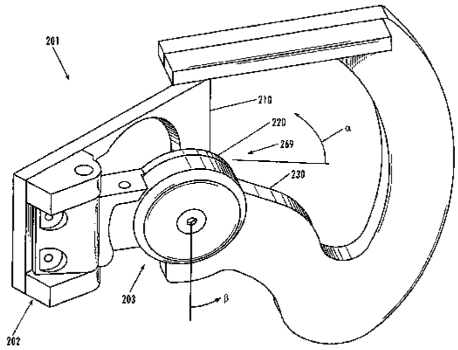


Figure 11: Scissor doors hinge

- **Vertical Lift System:** VLS doors have a scissor door configuration. The biggest change is that they are designed to initially open slightly outward before opening upward to allow the top edge of the door to clear the door frame and A pillar. VLS doors are not the same as butterfly doors as VLS doors move outward only of a small degree compared to butterfly doors.
- **130°:** scissor doors can rotate up to 130°. Such scissors have the benefit of not obstructing the entrance or exit to the car as much as conventional scissor doors.
- **Scissor-conventional door hybrid:** Some aftermarket example scissor doors are also designed so they can open either vertically or horizontally, as the user chooses. Such doors allow the user to gain the benefits of both types of door, choosing to open the door in whichever style is best suited to the situation.

- **Advantages**:
  - Offers the possibility of operating the car with the door open (impossible for conventional doors).
  - Reduces the dooring hazard to cyclist.
  - The hinge is placed in a similar location to a conventional door, so a convertible version of the car is possible with the same door style.
  - Useful when parking in tight spaces since the doors stay within the car's track throughout their range of movement.

- **Disadvantages**:
  - High cost of manufacturing the door hinge.
  - If the height of the parking lot ceiling is insufficient, a car door may come in contact with it when it opens.
  - In rollover situations, emergency egress may be more difficult than with conventional doors, or impossible (unless explosive door bolts presence, which remove the door).
  - Impediment of access/egress much more than gullwing and conventional doors.

Usage: scissor doors have become a trademark of the **Lamborghini high class vehicles** (Figure 12), but they are used even by other sportive companies for many cars (such as Bugatti).

***Remark*:** Not every Lamborghini car has scissor doors, for example the Lamborghini Gallardo and the Lamborghini Huracan present conventional doors because of the synergy with Audi company (the chassis is similar to Audi R8).

Figure 12: Lamborghini Aventador

2.3.5 Butterfly doors

Butterfly doors are a type of car door (similar to scissor doors) seen mainly on high-performance cars. While scissor doors move straight up via hinge points at the bottom of a car's A pillar, butterfly doors move up and out via hinges along the A pillar. This makes for easier entry and exit, at the expense of requiring more clearance than needed for scissor doors, above around the front pillar.

- **Advantages:**
  - Due to being on automatic door gliders, they can open and close on their own.
  - Convenient for parking in tight spaces.
  - Big space for ingress and egress.
- **Disadvantages:**
  - Hard to get out of the car after a rollover accident.
  - The door can come in contact with the ceiling of a parking garage if the height of the ceiling is not sufficient.
  - Complex technology: has more structural constraints.

Figure 13: McLaren P1

Usage: modern prototypes and supercars such as:

- All McLaren vehicles (Figure 13 and Figure 14).
- Toyota Gt-One.
- Ferrari Enzo.
- Ford Gt (2nd generation).
- SCG 003S.
- SCG 004S.
- Mercedes-Benz SLR McLaren (Figure 15): is one of the few open-top cars to use butterfly wing door, and this is made possible by having hinge points along the side of the A-pillar instead of at the top.

Figure 14: McLaren Senna

Figure 15: Mercedes-Benz SLR McLaren

2.3.6 Gullwing doors

A gull-wing door is a car door that is hinged at the roof rather than the side, and it is characterized by a simple rotation around the longitudinal axis (Figure 16). The name of the doors come from the evocation of an image of a seagull's wings, when they are opened upwards.

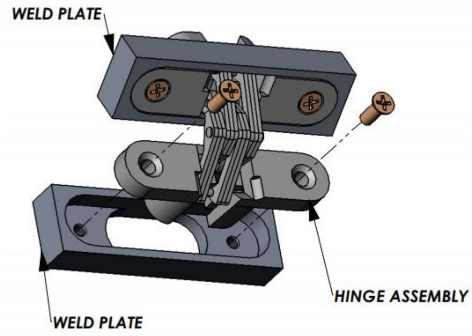


Figure 16: Gullwing door hinge

- **Advantages:**
  - The design is a very practical one in a tight urban parking space.
  - When properly designed and counterbalanced, they require little side-clearance to open (about 27.5 cm) and allow much better entrance/egress than conventional doors.
  - Due to being on automatic door gliders, they can open and close on their own.

- **Disadvantages:**
  - During rollover events, when the vehicle comes to rest on its roof, the exit by the doors would be impossible, requiring a large windscreen opening to escape. This problem was solved by the Mercedes SLS, by fitting the hinges with explosive bolts that would blow up in the event of a roll over.
  - Door can encounter the ceiling of a parking garage if the height of the ceiling is not sufficient.

Usage:

- Mercedes-Benz 300SL.
- Mercedes-Benz SLS AMG (Figure 17).
- DMC DeLorean.
- Tesla Model X (also called "Falcon doors").

Figure 17: Mercedes-Benz SLS AMG

Remark: Falcon doors represent a modification of standard gullwing doors, patented by Tesla for its Model X (Figure 18).

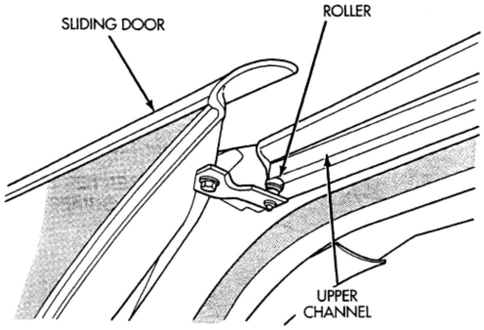
The key difference between gullwing doors and falcon wing doors is that the latter are double-hinged (it has 2 hinges as well along the door belt to swing the lower part of the door) and when working alongside a host of sensors, automatically adjust the angle at which they will open if there are cars parked next to it.

- **Advantages:**
    - Reduce space on the side and on the top (avoiding contacts with cars around and the ceiling of a parking garage).
    - Easier ingress/egress inside and outside the vehicle.
- **Disadvantages:**
    - High cost technology: the design and the production are expensive.
    - Higher risk during the design process because it is an innovative technology.

Figure 18: Tesla Model X (Falcon doors)

2.3.7 Sliding doors

A sliding door is type of door that owns trolleys on its frame, that allow the door to slide horizontally and outside, following the route defined by the nearly rectilinear rails/channels mounted on the body side. Doors of this type are usually adopted on commercial and industrial vehicles with straight body side surfaces to provide a large entrance or exit for passengers and goods loading.



Sliding doors are characterized by 3 guides/rails at different heights that allow the door to move sideways of few centimetres and to slide until the end of the stroke, where a block stops it and keeps it in a stable position.
The three guides are located on:

1. **Lower position**: it is placed on the sill and supports the weight of the door, guiding it as well during its sliding mechanism.
2. **Central position**: it is placed on the body side at the beltline height (in that case the trolleys are fitted to the door), or on the door (in that case the trolleys are hinged to the body).
3. **Upper position**: it is placed on the vehicle roof.

Usually a car body side has very different curvatures at different heights: for that reason, only two rails are frequently used, one at the belt line level and one on the sill. The third trolley is located inside one of the two rails, in such a position to avoid door rotation around the axis determined by the other two trolleys.

Two guides out of three are load bearings: the lower and the central, or the lower and the upper.
The main advantage of vertical reaction on the lower rail relates to the higher strength and stiffness of rocker panel, compared to the roof frame.
Regarding two rails comparison with three rails, the horizontal reactions are much higher in the case of two rails, due to lower lever distance. For instance, in the case of two rails, the horizontal reaction is inversely proportional to the distance between the rails.

Remark: Different pillar less solutions of sliding doors exist nowadays, so that allow an easy access of passengers or goods inside the car.
They are characterized by:

1. Two doors per side: the rear sliding door is slave of the front door (Ford B-max), with the front passengers’ safety belts mounted on the rear door frame.
2. A single sliding door, such as the Peugeot 1007, that covers both front and rear compartment. Unlikely this configuration was an unsuccess, since this technological innovation resulted bad from an aesthetical point of view, because of side rails.

It is important to note that side sliding doors never feature self-closing while the vehicle is stationary on up to a 20° slope. Moreover, if the door is opened on a slope, it must engage a brake, capable of absorbing the whole kinetic energy of the door, without permanent yield of frames and rubber dumpers.

- **Advantages:**
  - Allow easy access to the car (above all in B-pillar less solutions).
  - Great for use in tight parking spaces.
  - Facilitate the loading of goods.

- **Disadvantages:**
  - Vehicle style appearance is negatively influenced by the presence of rails and guides (this represents the main reason of the unsuccess on high-class cars).
  - Door mechanism has a narrower tolerance than conventional hinged door.
  - Weight.
  - Complexity.
  - Cost.

Usage:

- Minivan: Ford B-max (Figure 19) that has a rear sliding door; Peugeot 1007 (Figure 20) characterized by a single sliding door which covers both compartment; Fiat Ulysse; Toyota Sienna.

- *Pocket doors:* is a sliding door that slides along its length and disappears, when open, into a compartment in the adjacent wall (Figure 21). Used in some delivery **vans and train carriages**.

- *Buses:* has a pantographic hinge that moves the door panel outwards from its plug socket and then parallel to the side of the bus to clear the opening. This arrangement makes a very good airtight and soundproof seal and it is commonly found on coaches.

- *Passenger trains:* high speed trains use sliding plug doors because they can be made airtight, soundproof and reduce aerodynamic drag.

- *Commercial and industrial vehicles:* Fiat Ducato (Figure 22); Fiat Doblò.

Figure 19: Ford B-Max, sliding door without B pillar with conventional door at the front

Figure 20: Peugeot 1007, sliding door with B pillar and a single side sliding door

Figure 21: Kaiser Darrin (pocket door)

Figure 22: Fiat Ducato (commercial vehicle)

2.3.8 Swing Sliding Doors (SSD)

Swing sliding door is a concept hypothesis not already installed on current vehicles (Figure 23). Its mechanism is very simple: front door swings first and then slide frontward, while rear door swings as well but then slides rearward. Both doors have 2 lower links to body (they should provide kinematic and weight support) and 1 upper link to roof structure (has only a kinematic function), as shown in Figure 24. No B pillar is needed, and for that reason rear door can be opened just once the front door has opened (rear door represents a slave door).

- **Advantages**:
    - Very innovative and unique opening system.
    - Good ergonomic, since ingress-egress is granted with limited side space free (less than 50 cm).
- **Disadvantages**:
    - High production costs and higher number of tools to be used.
    - Technical complication if front door shall avoid clash with front wheels steered.
    - Quality and reliability risks, which lead to an increase of warranty costs.

Usage:

- AA Tuono (concept car).
- Other concept cars.

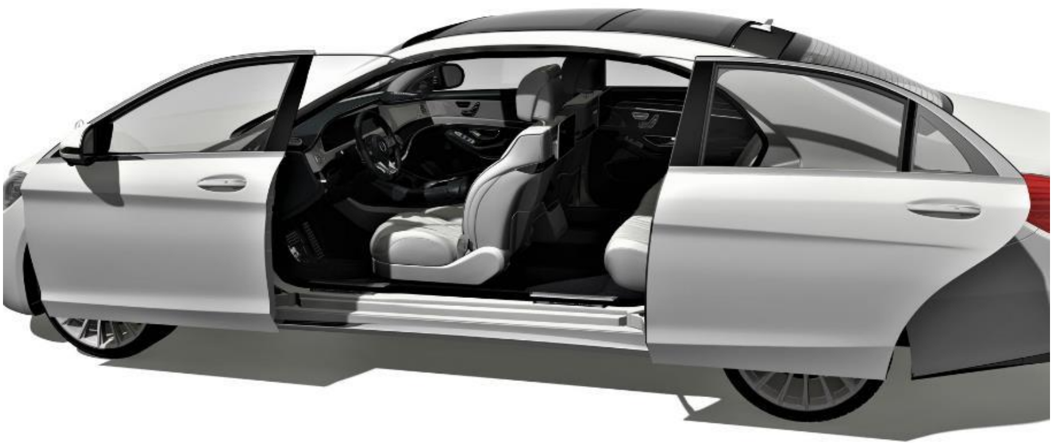


Figure 23: General concept car

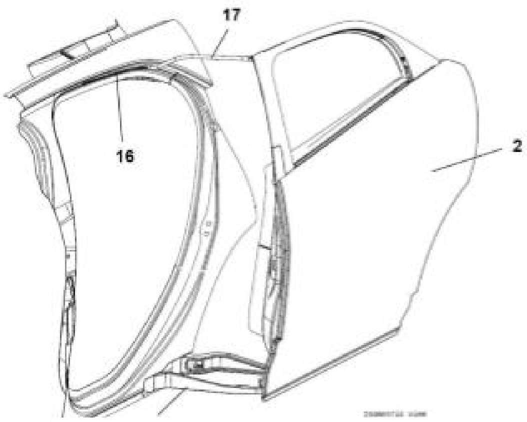


Figure 24: Detail of the rear door

2.3.9 Canopy doors

A vehicle canopy is a type of door which sits on top of a car and lifts up towards the front by means of special actuators, to provide access for passengers. There are no established sub-types of canopies, so they can be hinged at the front, side, or back (hinging at the front is more common).

- **Advantages:**
  - They open vertically: they do not obstruct the road, pavement and cars around when opened, different from conventional doors that open out of the car's track.
  - No A-pillars since there are no side doors: the windscreen can extend from the front to the back of the car, giving the driver a field of view of more than 180° minimizing blind spots.

- **Disadvantages:**
  - Provides substantial greenhouse effect, so it is necessary to provide an air-conditioning system.
  - Entering and exiting the vehicle result difficult.
  - In bad weather conditions, it is impossible entering and exiting without getting the interior wet.
  - In the case of a rollover effect, exiting the vehicle would be impossible (except breaking the glass).
  - Lead to production/assembly complications, it can have reliability risks.

Usage: rarely used on production cars, sometimes used on concept cars.
- Le Mans Prototype endurance race cars.
- Sterling Nova (Figure 25).
- Pininfarina/Maserati concept car: Maserati Birdcage 75th (Figure 26).

Figure 25: Sterling Nova

Figure 26: Maserati Birdcage 75th

2.3.10 Dihedral Synchro-helix actuation doors

The dihedral door is a hybrid of the scissor car door type, with the only difference being that the dihedral door opens by moving outward, while at the same time rotating 90° around the doors hinge (Figure 27). Their hinges are located on the A-pillars, supporting the entire door and mechanisms.

The mechanism is all automatized: the door can be opened by just pressing a button.

- **Advantages:**
  - Easier ingress/egress inside the car.
  - Unique look.
  - Minimize the space taken between the cars and avoids both street curbs and garage ceilings.

- **Disadvantages:**
  - Parking too close to a high curb can damage the door and with the doors being carbon fiber, the repair bills can be extremely costly.
  - Complex and expensive mechanism design.

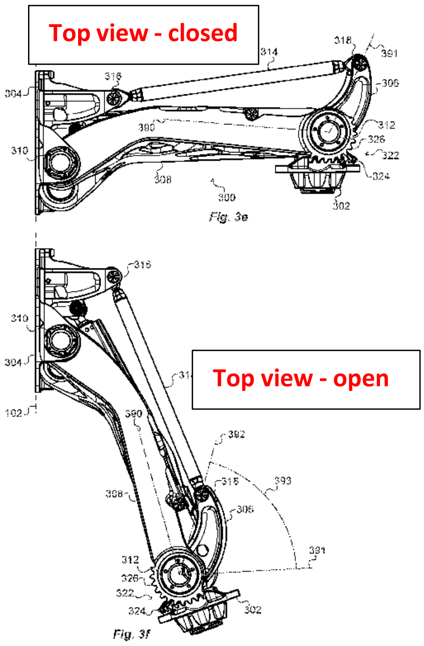


Figure 27: Koenigsegg door hinge

Usage: these doors became a trademark of Koenigsegg company, patented by Koenigsegg itself (Figure 28 and Figure 29).

Figure 28: Koenigsegg One

Figure 29: Koenigsegg car door detail

2.4 Example of door design decision matrix (Suicide vs. SSD doors)

How shall we decide between different types of automotive doors? In case that the use of unconventional doors is preferred, it is not easy to decide, so it is appropriate to turn to well-structured and motivated decision-making procedures. Later on, we could see an example of a decision matrix defined to allow to make a well-motivated and logical decision between Suicide and SSD door system on the electric SUV concept AA Tuono.

2.4.1 Automobili Amos Tuono

Taking as reference the project commissioned by Automobili Amos (AA) to Podium Advanced Technologies, we can define an example of decision matrix focused on the side doors.
This pre-concept vehicle is called Automobili Amos Tuono, a High-End Full electric four door SUV. This project leads a great focus on a new system of side doors, in order to be more creative and unique but at the same time to have high ergonomic, during the ingress and egress into and from the vehicle.

The two main requirements for the door system are:
- **Structural strength**: high static and dynamic stiffness.
- **Style level**: innovative system from aesthetical point of view.

The design evolution choices on the side doors of AA Tuono are:
1) A single sliding side door which covers both front and rear passengers' compartment. This solution was hypothesized B-pillar less.

   Advantages: more ergonomic for the front compartment.
   Disadvantages: difficult ingress and egress in/from the rear compartment since the sliding door cannot go too much backwards (safety reason: when parking with cars or walls which are behind the vehicle).
2) Two sliding doors: one for the front and one for the rear.

   Advantages: more ergonomic for the front and rear compartment.
   Disadvantages: problems at style level because of the presence of trolleyed guides on front fenders and rear sides.
3) Conventional front door with vertical hinge, while the rear door is hinged on the back so it represents a suicide door, with the rear door which is slave of the front (can be opened once the front door has opened). B pillar less solution is preferred.
4) SSD (swing slide doors) doors in collaboration with Automotive Idea.

The decision matrix, illustrated in the Table 1, is defined taking in consideration the last two solutions, in order to find the best design choice, in particular:

- *Conventional front door and suicide (reverse) rear door.*
- *Alternative door opening: Swing Slide Door.*

	Current door opening (suicide rear door)	**Alternative door opening (SSD)**
Concept Examples		
Solution description	• Traditional front doors with 2 gooseneck hinges. • No B pillar. • Rear door with reverse opening. • Strong B pillar on rear door replaces the body B pillar. • Rear door is a slave (can be opened once the front door has opened).	• Front door swings first and then slides frontward. • Rear door swings first and then slides rearwards. • No B pillar. • Both doors have 2 lower links to body (kinematic and weight support) and 1 upper link to roof structure (kinematic only). • Rear door is slave (can be opened once the front door has opened)
Pro (+)	• Lower development and production costs.	• "Wow effect" for selling purposes. • Very innovative and unique opening systems. • Good ergonomic (ingress-egress with limited side space free: less than 50 cm).
Concerns (-)	• Need of more lateral free space. • Front door much longer than rear door (which leads to unusual proportions).	• High production costs and higher number of tools. • Technical complication if front door has to avoid clash with front wheel steered. • Quality and reliability risks (increase of warranty costs). • Additional tooling cost. • Additional Development and Validation cost.
Conclusions	• Solution with good balance benefit-concerns. • Original system (no B pillar, rear reverse door) with interesting advantages but with limited technical risks.	• Additional sales justify additional costs? • No need of door handles, this leads to save additional costs and weight. • Automatic opening of doors by means of smartphone or other remote controllers.

Table 1: Decision matrix table (Suicide door vs. SSD door)

KEY POINT: are additional sales for SSD doors sufficient to justify the additional costs/investments and additional technical risks?

These are the SSD doors solutions that are hypothesized to overcome the concerns:

1) ***Problem:*** *Clash between the door and the steered wheel.*

   Solutions:
   i. Front wheels to be automatically aligned, or a warning should be displayed on the display in a position to get the attention of the driver.
   ii. To use classic hinged doors at the front.

2) ***Problem:*** *Collision of the door with the front side mirrors.*

   Solutions:
   i. To make the side mirrors foldable: let them turn on the pivots to get closer to the side of the vehicle.
   ii. To mount them on the door.
   iii. Door lateral displacement high enough to overcome problems.

Considering all the advantages and the concerns of these two solutions, the best choice is to make a mix of the two.

This is because finding a solution to the two problems of the SSD door previously defined could be expensive and difficult, since the steered wheel and the side mirrors represent two big constraints. Therefore, the best thing to do to keep the costs “low” and to avoid technical complication is to keep the front door as a traditional door with 2 front gooseneck hinges. While the rear door can face this innovative and unique opening system (SSD), in order to bring the “Wow effect” suddenly to the concept. Rear door is slave of the front door, since a pillar less solution is adopted (No B-pillar) to get more space during the ingress.

2.5 Side door structure families

Different families of door structures are known all around the world, which change from the several assembly technologies exploited. This is due to the fact that the main goal is to reduce the weight and cost production, and at the same time to chase a good stiffness for the door without highly increasing the times of production. Most of the times, all these design choices are trade-offs between many hypotheses, considering the size and the precision of the final product as well [1].

The most used types of door structure used nowadays are:

1) Unitized stamped doors.
2) Sash doors.
3) Hybrid doors.
4) Frameless window doors.

2.5.1 Unitized stamped doors

These doors are made of two large stamped sheets, the outer and the inner panel, both carrying a part of the window frame. The panels are usually assembled by hemming: the outer panel being down flanged and then hemmed over the inner, following a structural adhesive extrusion on the panel border and with a limited number of spot welds. The assembly also includes several reinforcements including window frame channel which is spot welded to both panels or to one panel, hemmed over the other or hemmed over both panels.

They represent the cheapest solution, considering all the components of the doors (weather strips included), and the most precise and strong: for that reason is widely used in cheap passengers vehicles (Figure 30). However, they are not the preferred choice of designer, due to the size of the window frame.

Figure 30: Fiat Panda (unitized stamped door)

2.5.2 Sash doors

The sash door assembly (Figure 31) is made up of two stamped panels (inner and outer) below the belt line and a sash assembly made of roll-formed, bent and welded profiles making up the window frame. The sash is welded to the inner panel before the hemming of inner and outer panels; in case of heterogeneous panel, screwing or riveting and adhesive bonding can be adopted, instead of hemming [2].

The sash door uses a strong, narrow cross-section window frame; it is more expensive than unitized stamped doors while the cost is less than the hybrid solution, but inconveniences include embedding of the sash in the inner panel below the belt line, due to the lack of stiffness and the need to braze the sash to the inner panel in the belt line.

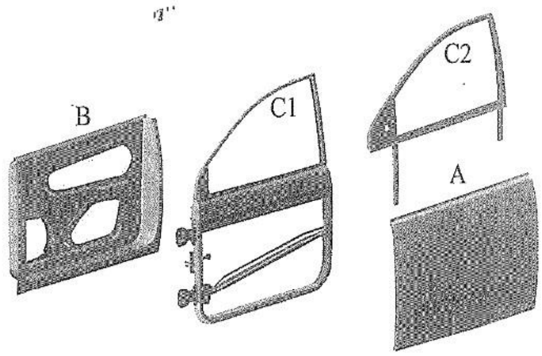


Figure 31: Sash doors

2.5.3 Hybrid doors

The hybrid door (Figure 32) is a mixture of the above solutions, as the stamped inner panel includes the window frame, while the outer panel is extended just up to the belt line. Before hemming the main panels, a roll-formed or stamped channel is usually welded to the inner panel to obtain a boxed window frame to be adequately stiff in torsion [2].

In terms of dimensional quality and performance, it is the preferred choice by designers because the window frame is narrower and can be completely covered by aesthetical weather strips.

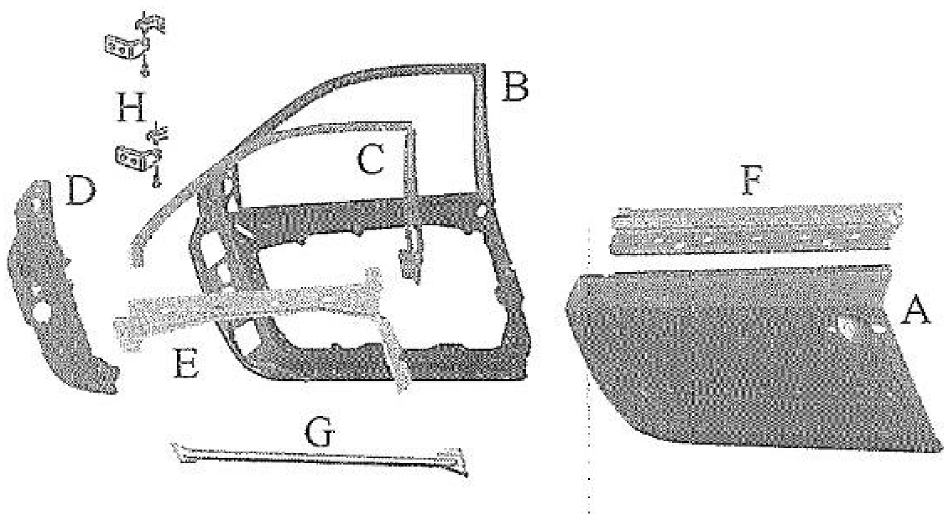


Figure 32: Hybrid doors

2.5.4 Frameless window doors

In this solution, the window frame is completely missing (Figure 33), with glass sealing being provided by body side and roof weather strips. It is typically used for spider and convertibles vehicles, but it is sometimes present on sedans or coupes too. The amount of sheet metal for these doors is the lowest, but waterproofing relies entirely on the glass-weather strip matching on the body side, mainly on the belt line node transition. In fact, for convertibles, weather strip contact in this area moves from window glass to door inner panel in a very short space, with high curvature and section discontinuity.

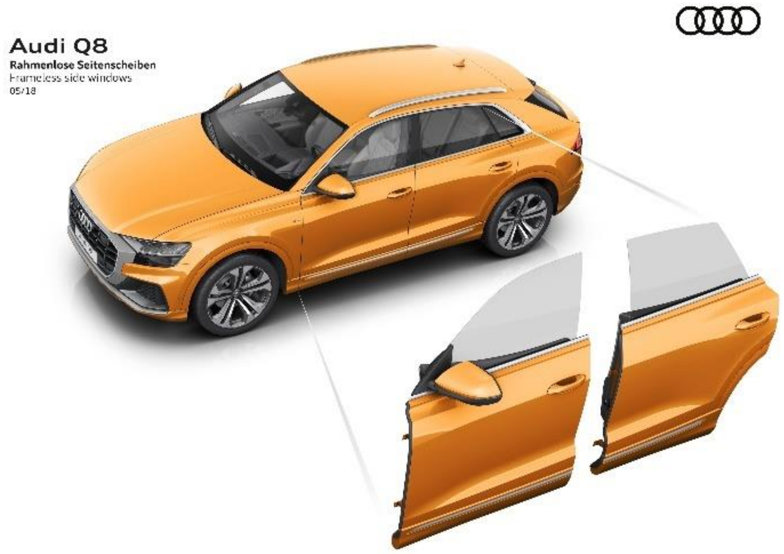


Figure 33: Audi Q8 (frameless window door)

2.6 Door materials classification

In the following I will describe a classification of the typical door's materials, analysing their characteristics in terms of properties and their application on the door assembly: panels, frames, etc… The classification of materials is absolutely important during the design phases of the vehicle components (in this case for the doors), since they allow the company to underline the main differences in terms of stiffness and production costs that the overall system can reach.
The materials typically used by Podium and worldwide applied are:

1. *Steel.*
2. *Aluminium.*
3. *Carbon fiber.*
4. *Magnesium.*

On common passenger cars, doors are usually made of sheet steel panel stamped elements, but even aluminum and hybrid doors have been manufactured.

Hybrid doors have, for example, a steel or cast magnesium or aluminium or thermo set resin inner panel, covered by a drawn steel or aluminium sheet outer panel, or by a thermo set or thermoplastic injected outer panel. A thermoset structural adhesive lays on the outer panel flange of the door in order to generate a reliable link between the inner and the outer panel, to avoid a sliding risk just after the hemming process. **Hemming** process, as shown in Figure 34, consists first in the insertion of the inner panel in the outer panel, then the outer panel 180° folding over the inner panel is performed after putting structural adhesive extrusion in between.

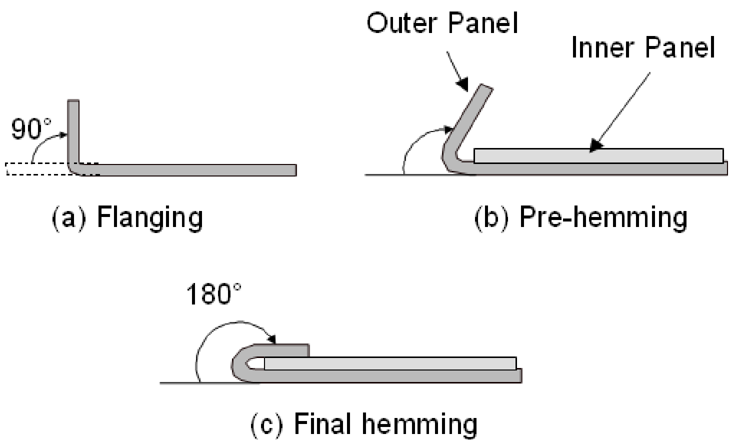


Figure 34: Hemming process

2.6.1 Steel

Steel is an alloy of iron and carbon containing less than 2% carbon and 1% manganese and small amounts of silicon, phosphorus, sulphur and oxygen. Steel is the world's most important engineering and construction material, and it is widely used in automotive applications. After forming, parts appear perfectly smooth and do not require manual finishing.

Some of these steel grades (Dual Phase and Multiphase) have the property of changing their ductility because of plasticity during the forming stage, meaning they are sufficiently drawable in the stamping stage but then increase hardness and yield strength when the body is painted [3].

Properties:

- *Tensile strength*: 200-600 MPa.
- *Density*: 7600 kg/m^3.
- *Elastic modulus*: 190-210 GPa.
- *Elongation at break*: 10-32%.

Advantages:

- Good formability and printability (cold printing).
- High yield and tensile strength.
- Good elongation and fatigue resistance.

Disadvantages:

- Weight, it is heavier than aluminium, magnesium and carbon fiber composites. Its mass is 7.8 kg per square meter of sheet gauge 1 mm.
- Susceptibility to buckling.
- Bad corrosion resistance (require accurate protection).

There are many applications of steel alloys, but not all of them are exploited in automotive field, above all for what concerns the door assembly. The most important types, for vehicles' door frame or panels application are:

a) TRIP steels.
b) Dual Phase steels (DP).
c) Bake Hardening steels (BH).

a) TRIP Steels

TRIP (Trasformation Induced Plasticity) steels are coil steels with ferritic/bainitic/austenitic structure, so they guarantee good cold forming [4]. During deformation, a percentage of energy is used to transform a certain amount of metastable austenite in martensite; this phase enhances the mechanical properties while the residual austenite acts as "energy absorber" in case of violent deformation (impact).

The TRIP steel has a lower initial work hardening rate (work hardening is the strengthening of a metal by plastic deformation) than the DP steel, but the hardening rate persists at higher strains where work hardening of the DP begins to diminish. This brings to have higher yield and tensile

strength with respect to Dual Phase steels, while the elongation remains in the range of DP steels (10-40%), as it can be seen in the diagram in Figure 35.
TRIP steels therefore can be engineered or tailored to provide excellent formability for manufacturing complex parts or exhibit high work hardening during crash deformation for excellent crash energy absorption.

Current production grades of TRIP steels and example automotive applications are:

- TRIP 350/600 → Frame rails, rail reinforcements.
- TRIP 400/700 → Side rail, crash box.
- TRIP 450/800 → Dash panel, roof rails.
- TRIP 600/980 → B-pillar upper, roof rail, engine cradle, front and rear rails, seat frame.
- TRIP 750/980 → Door frame.

NB: the number next to TRIP denomination represents the value of yield strength.

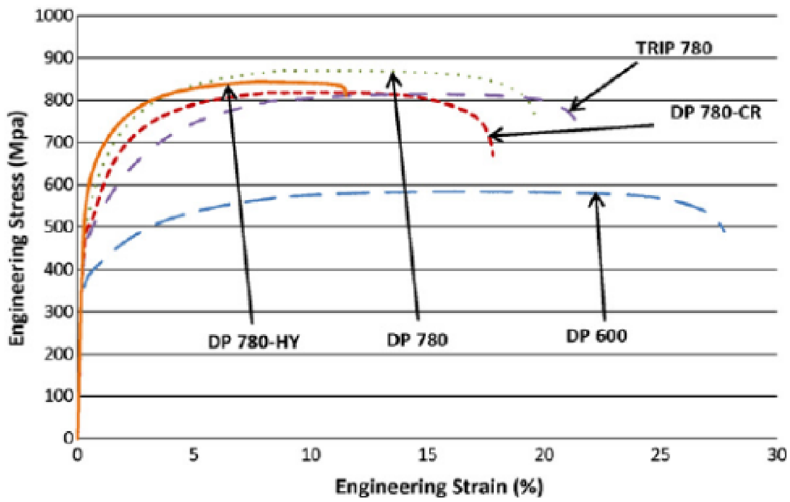


Figure 35: Stress-strain diagram comparison between TRIP and DP steels

b) *DUAL PHASE Steels (DP steels)*

DP steels are high strength steels that has a ferritic-martensitic microstructure as it can be seen in Figure 36 (*this is the reason of "Dual Phase" name*). It is produced from low or medium carbon steels that are quenched from a temperature above A1 (temperature at which below the austenite becomes perlite) but below A3 (lowest temperature at which austenite exists) determined from continuous cooling transformation diagram. This results in a microstructure consisting of a soft ferrite matrix (white area in Figure 36) containing islands of martensite as the secondary phase (black area in Figure 36), this latter phase allows an increase of the tensile strength.

The soft ferrite in the final DP material is exceptionally ductile and absorbs strain around the martensitic islands, enabling uniform elongation with high work hardening rate and fatigue strength.

DP steels have high ultimate tensile strength (UTS) in the regime of 400-1200 MPa combined with low initial yielding stress (provided by the ferrite phase), high early-stage strain hardening and macroscopically homogeneous plastic flow. These features render DP steels ideal materials for automotive-related sheet forming operations.

Advantages:

- High strength.
- Low yield to tensile strength ratio (= 0.5).
- High initial strain hardening rates.
- Good uniform elongation.
- A high strain rate sensitivity (the faster it is crushed, the more energy it absorbs).
- Good fatigue resistance (due to low carbon content).
- Can be strengthened by static or dynamic strain ageing through the "*bake hardening effect*".

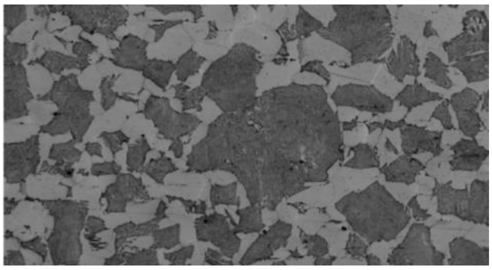


Figure 36: DP microstructure (white=ferrite; black=martensite)

As they combine high strength and good formability at low production costs, DP steels are often used for automotive applications: *door panels*, *wheels* and *bumpers*.

The alloying elements used in Dual Phase steels have different types of effects:

- Carbon: used in the range between 0.06-0.15 of weight percentage, it acts as an austenite stabilizer, strengthens the martensite and determines the phase distribution.
- Manganese: cheap element, used between 1.5-3 of weight percentage, it allows the stabilization of the austenite. It is a ferrite solid solution which rises the mechanical properties and retards the ferrite formation.
- Other elements: Silicon promotes the ferritic transformation, while Chromium and Molybdenum (used up to 0.4 of weight percentage) can retard pearlite and bainite formation. Additionally, microalloying elements such as Vanadium or Niobium can be used as precipitation strengtheners and to refine the microstructure.

c) *BAKE HARDENING Steels (BH steels)*

The composition and processing of these steels are designed to promote a significant increase in yield strength during low-temperature heat treatment, particularly paint curing. Bake hardening is a controlled aging phenomenon related to the presence of low percentage of carbon and/or nitrogen in solid solution in the steel.

The steel is soft during cold forming stage but picks up strength during subsequent paint baking stage. This leads to an increase of the Yield strength of the Bake Hardened steel.

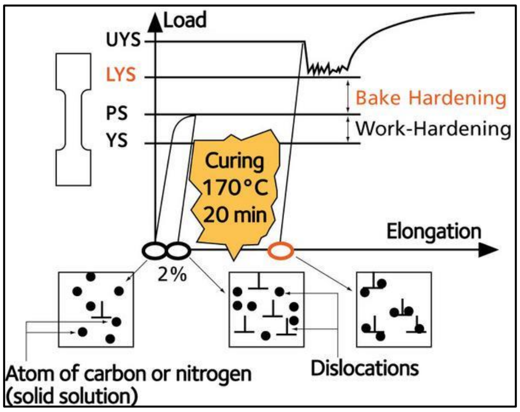


Figure 37: Bake hardening mechanism

The BH2 parameter is used to evaluate the resulting increase in dent resistance.
It is given by:

BH2 = LYS - 2% PS

in which LYS is the lower yield stress measured after heat treatment and PS is the yield stress after initial 2% plastic pre-strain, as it can be seen in Figure 37.
The diagram illustrates the bake hardening mechanism and shows the displacement of carbon atoms in solution during heat treatment (typically 20 minutes at 170°C to block the dislocations generated by forming). This ultimately increases the metal's yield strength.

Advantages:

- Excellent drawability-dent resistance combination in all strain modes. Their drawability is essentially equivalent to that of interstitial-free steels of similar yield strength.
- They enhance vehicle weight reduction.
- They improve vehicle aesthetics.

Bake hardening steels thus offer a suitable response to automotive bodywork requirements. Steels in the BH range are designed for visible (Door, hood, tailgate, front wing, roof) and structural (underbody, reinforcement, cross member, lining) parts.

2.6.2 Aluminium

Aluminium is widely used in automotive industry because of its good mechanical properties (such as light-weight), and it is classified in several categories: cast, extruded and rolled alloys, each meant for different parts and positions in vehicles, including door frames and panels.

Properties:

- *Tensile strength*: 125-420 MPa.
- *Density*: 2660 kg/m^3.
- *Elastic modulus*: 70 GPa.
- *Elongation at break*: 5-15%.

Advantages:

- Strength rating little bit lower than steel, but it is lighter (lower density leads to fuel energy saving).
- High corrosion resistance.
- Good yield strength.
- High dent resistance.
- Recyclability.

Disadvantages:

- Formability is lower than steel (deep draws are to avoid).
- Difficult to repair after collisions on panels and frames.
- More expensive than steel.

The two main aluminium series alloys adopted in automotive fields are:

a) 5XXX series
b) 6XXX series

a) 5XXX SERIES

A 5XXX series Aluminum alloy (Al-Mg) is specific for the body in white, which is the stage in the automobile manufacturing in which a car body's frame has been joined together. The 5XXX series aluminum alloy is not heat treatable, but it is just strain hardenable. These aluminum/magnesium alloys have the highest strength of the not-heat treatable alloys and they are readily weldable. Therefore, they represent the best candidate aluminum alloys for car doors.

b) 6XXX SERIES

A 6XXX series Aluminum alloy (Al-Mg-Si) would be a suitable replacement for the current mild steel panel, since the strength rating is typically the same as mild steel, but it is lighter. To match steel stiffness, the aluminum panel must be up gauged 1.5 times the thickness of the steel part it is replacing.

In USA, the alloy A6111 *(Si 0.7-1.1%, Mg 0.5-1%)* is often used for outer panels in gauges of 0.9-1.0 mm which combines high strength with good formability. In Europe, EN-6016 *(Si 1.2%, Mg 0.4%)* is preferred and applied in gauges of 1-1.2 mm. It shows a superior formability and filiform corrosion resistance and allows flat hems even on parts with local pre-deformation. However, the bake-hardened strength of 6016 is significantly lower that of A-6111.

Deep draws are to avoid as the formability of aluminum is generally lower than that of steel.
Spot welding could be replaced with SPR (Self Pierce Riveting) and other bonding methodology, even without the use of adhesives. Typically, SPR's can replace spot welds at 1:1, but using structural adhesive can help reducing the number of SPR used too, which is a good advantage in terms of labor.
Sheet aluminum passivation coatings are anticipated to improve long term adhesion performance when required.

2.6.3 Carbon fiber composites

Carbon fibers are a type of fibers about 5–10 micrometres in diameter and composed mostly of carbon atoms. Carbon fibers are usually combined with other materials to form a composite: when permeated with a plastic resin and baked, it forms carbon-fiber-reinforced polymer which has a very high strength-to-weight ratio, and it is extremely rigid although somewhat brittle.

In automotive field, it is mostly adopted on supercars/hypercars components in order to reduce weight but maintaining high strength, and consequently gain better performances.

Properties*:*

- *Tensile strength*: 3.45-7.06 GPa.
- *Density*: 1740-1870 kg/m^3.
- *Elastic modulus*: 230-441 GPa.
- *Elongation at break*: 1.5-1.7%.

Advantages:

- Lighter than aluminium and 8 times stronger.
- High thermal and electrical conductivity.
- High fatigue strength.
- Very high stiffness.
- Optimal dampening capacity.

Disadvantages:

- Expensive.
- Suitable for low volume of production.
- Working times are extremely long.
- Repair costs are high.

The most famous and used carbon fiber production technologies are:

a) *Pre–preg.*
b) *Pultrusion.*
c) *Automated tape laying.*
d) *Automated fiber placement.*
e) *Compression moulding.*
f) *Lamborghini forged composite technology.*

a) PRE-PREG

The processing of carbon fibers starts from the raw material, which is worked with epoxy resins until a prepreg material is obtained [5]. Then it is cut in carbon fiber sheets which, through the sheet wrapping technology, are used for various technologies such as sport and construction industries.

The pre-preg process begins from the unwinding of the carbon coils. The yarns (made of thousands of filaments) are flattened and placed side by side to give the shape of a carbon ribbon with unidirectional fiber. The latter then flows into an impregnating machine which allows the epoxy resin to penetrate. The product obtained is called Pre-Preg and it is wrapped in coils that can be stored in cold chambers at a temperature of -18°C.
Thanks to this exclusive pre-preg technology, it is possible to produce thin layers with a perfect distribution of the stresses. Weight, inertia and thickness are reduced, with an optimal ratio between these factors. The result is a great homogeneity in the design component.
Then the pre-preg material is cut in small sheets, which are wrapped (Sheet Wrapping) in succession on a mould, creating the subsequent layers of wrapping requested.

The unidirectional pre-preg use allows the fibers to be applied in various direction in order to maximize their structural efficiency. Then it is requested the autoclave polymerization process, which further increases the quality and mechanical characteristics of the product because it avoids possible vacuum area and let the material be more compact.

The use of pre-preg drastically reduces the time and cost of processing of composite materials.

b) PULTRUSION

The pultrusion is a continuous process used in order to produce reinforced polymeric extrusions (Figure 38).

The reinforcing fibers (carbon fibers) are taken from the creel and passed through an impregnation bath where they are tied to the resin matrix. Then the traction pulls the fibers already impregnated with the resin, passing them through a comb as a guide and feeding them into a preforming station. These are introduced into a heated mould (curing die) having the section shape of the desired final product. The high temperature of the die favors the polymerization of the resin itself (curing process).

On leaving the oven, the profile is transported to a cutting area where it is suitably cut by blades that size it. At the end of the pultrusion machine we find the traction system, located quite far from the curing oven, in order to allow optimal cooling of the profile and to avoid deformations during the clamping phase.

The profiles present good traction resistance along fiber direction, while on transversal direction the properties are quite low since they are in function of the resin. Therefore, in order to increase the mechanical properties, it is necessary to use textile strips.

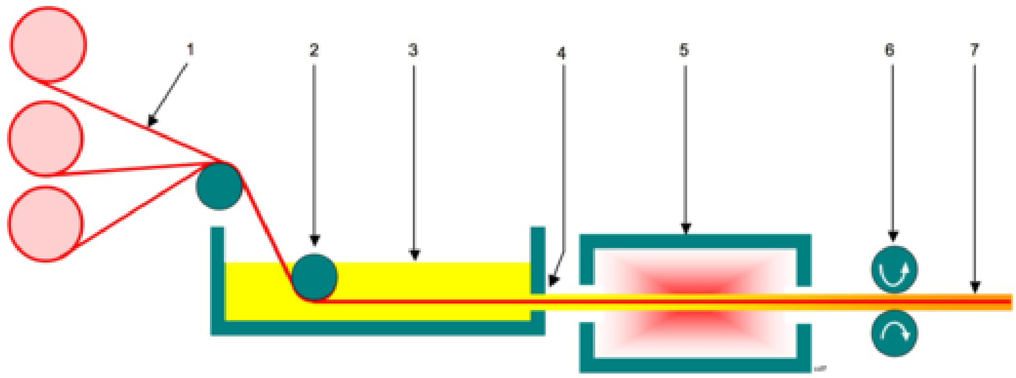


Figure 38: Pultrusion process

Where:

1) Fibers
2) Roll
3) Impregnation bath of the fibers with the resin matrix
4) Impregnation bath exit
5) Curing in the die
6) Traction system
7) Composite material with carbon fibers

c) *AUTOMATED TAPE LAYING*

Automated Tape Laying (ATL) is one of the most well-established automated manufacturing techniques for composites materials, used especially in automotive industries. Wide unidirectional tapes are laid onto a part mould using a loaded roller system with varying degrees of articulation, depending on the complexity of the part being manufactured [6].
Although not necessarily a fiber placement technique, modern ATL systems have precise control of tape start, cut, and orientation, allowing them to add more complex reinforcement than simply adding additional plies to the laminate. This technology is cheaper than pre-preg process.

d) *AUTOMATED FIBER PLACEMENT*

AFP is an advanced method of manufacturing composite materials. It is an automated composite manufacturing process (Figure 39) of heating and compacting synthetic resin pre-impregnated non-metallic fibers on typically complex tooling mandrels. The fiber usually comes in the form of what are referred to as tows, which is typically a bundle of carbon fibers impregnated with epoxy resin. The tows are fed to a heater and compaction roller on the machines head and, through robotic type machine movements, are placed in courses across a tool surface.

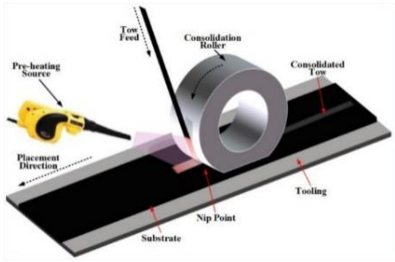


Figure 39: AFP process

AFP is used in order to increase rate and precision in the production of advanced composite parts. AFP machines place fiber reinforcements on moulds in an automatic fashion and use several separate small width tows of thermoplastic pre-impregnated materials to form composite layups.

e) *COMPRESSION MOULDING*

Compression moulding is a closed-mould composite manufacturing process that uses matched metal moulds with the application of external pressure. In the compression moulding process, an engineered composite layup is placed in the open mould cavity, the mould is closed and consolidating force is applied. The pressure remains on the mould throughout the curing cycle, which occurs in an oven [7].

The combination of heat and pressure produces a composite part with low void content and high fiber volume fraction (a near net shape finished component). Compression moulding often yields composite parts that have optimal mechanical properties.

The type of moulding process is an appropriate fabrication system for producing uniform quantities of complex, high-strength composite structures of carbon fiber or fiberglass. Compression moulding allows for the manufacturing of intricate components with features (such as holes) that would otherwise have to be machined post-mould. This process has the big advantage of leading bigger productions with respect to the prepreg methodology, but the latter process allows to have higher stiffness on its pieces.

f) LAMBORGHINI FORGED COMPOSITE TECHNOLOGY

Forged Composite is an advanced composite material designed by Lamborghini to give major impetus to technological innovation in composite materials [11].

The Forged Composites moulding process (Figure 40) is made up of few phases: cutting of the material (a pre impregnated roll of short carbon fiber immersed in a resin film), measurement of the weight of the load, preparation of the load, positioning of load in mould, moulding cycle (heating at 135°C and pressure at 80 bar) and then the removal of the component.

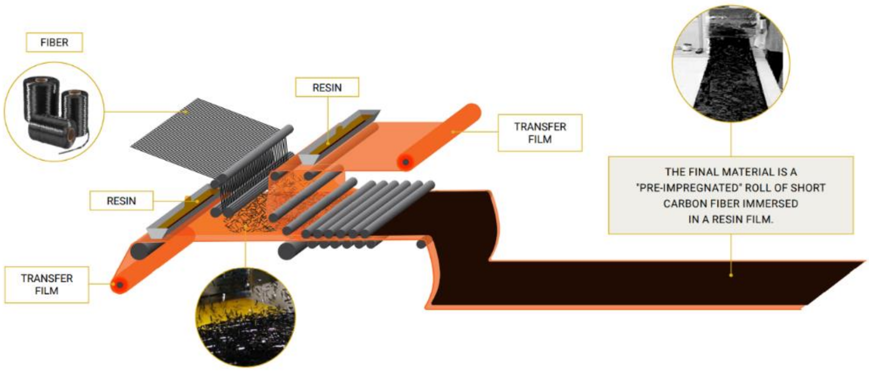


Figure 40: Forged composite process

Forged Composites is perfect for creating complex forms with undercuts by means of combined moulds (mould and matched mould), high-quality steel and surface finish, automatic removal systems and multi-axis pressure. The process is highly localized, letting the distribution of the heat possible.
Variations in section are possible without having to laminate additional material, any thickness can be created; at the same time it is possible to do mechanical machining (such as drilling or trimming) because the material is hardly affected by cutting. This process is ideal for the use of fasteners (load-bearing capacity).

Advantages:

- ***HIGH:*** production volume, design freedom, integration, automated process.

- ***LOW:*** production expenses, number of components, labor.

2.6.4 Magnesium

Vehicle weight reduction is one of the major means available to improve automotive fuel efficiency. High-strength steels, aluminum (Al), and polymers are already being used to reduce weight significantly, but substantial additional reductions could be achieved by greater use of low-density magnesium (Mg) and its alloys. Magnesium alloys are currently used in relatively small quantities for automotive parts, generally limited to die castings.

Magnesium is an attractive material for automotive use, primarily because of its light weight: 36% lighter per unit volume than aluminum and 78% lighter than iron. When alloyed, Mg has the highest strength-to-weight ratio of all the structural metals and it could increase strength if solute heat treated and aged.

In order to reduce door weight, door with cast magnesium inner panel and aluminum outer panel have been tested. However, a second goal to achieve is to reduce the door module cost, by integrating in the cast panel some components such as hinges, usually split on traditional steel doors.
Example: Spider door frame has an estimated total cost lower than traditional doors, while the mass is reduced of 48% with respect to steel door.
Automotive applications require also good ductility for many components (such as doors), especially the energy absorbed in case of an accident is a very crucial issue. One direction in the magnesium alloy and process development for wrought alloys is to optimize the energy absorption of the material.

Properties:

- *Tensile strength*: 170-270 MPa.
- *Density*: 1900 kg/m^3.
- *Elastic modulus*: 41-45 MPa.
- *Elongation at break*: 6-20%.

Advantages:

- Reduces door weight.
- Possibilities of components integration to reduce door module cost (example: hinges in the cast panels).
- Good dampening capacity.

Disadvantages:

- Less strong and resistant than steel and aluminium.
- Less ductile than steel.
- It is flammable and explosive: once ignited, heats up at extremely high temperatures (temperatures that easily melt aluminium or steel) and it has low high temperature strength.
- Poor corrosion resistance.

In the *Table 2* I have illustrated all the main advantages and disadvantages of the materials which are indicated as the best choices for door frames and panels.

Material	Pro (+)	Concerns (-)
Steel	• Good drawability and printability • High yield and tensile strength • Good elongation and fatigue resistance	• Heavier than aluminium, magnesium and carbon fiber composites • Susceptibility to buckling • Bad corrosion resistance: require accurate protection
Aluminium	• Strength rating little bit lower than steel, but it is lighter (lower density leads to fuel energy saving) • High corrosion resistance • Good yield strength • High dent resistance • Recyclability	• Formability is lower than steel (deep draws are to be avoided) • Difficult to repair after collisions on panels and frames • Paint problems • More expensive than steel
Carbon fiber	• Lighter than aluminium and 8 times stronger • Mostly adopted on race cars' components to reduce the weight and reach better performance • High thermal and electrical conductivity • High fatigue strength • Optimal dampening capacity	• Expensive • Suitable for low volume of production • Working times are extremely long • Repair costs are high
Magnesium	• Reduces door weight • Possibility of components integration to reduce door module cost. • Good dampening capacity	• Less strong and resistant than steel • Less ductile than steel • Flammable: once ignited, heats up at extremely high temperatures (temperatures that easily melt aluminium or steel) and it has low high temperature strength • Poor corrosion resistance

Table 2: Materials box comparison

3. Analysis of Podium Advanced Technologies projects and lessons learned

In this chapter I will analyse the door assembly projects already designed by Podium: Delta Futurista and SCG 004S (Figure 41). SCG 004S is the sport road legal version of 004C, the race car which joined the 24 hours endurance race of Nurburgring this September, arriving in the first 15 positions.

After having analyzed the current projects, I was suggested by the tutor to underline the problems occurred (structural or style manners) and to find some solutions to adopt afterwards, by means of the lessons learned specifics. Different considerations should be taken for the 004S since it is not already realised on the market (it is still a prototype) and I am going to think new solutions for the door assembly (by means of CAD and FEM structural analyses on Catia and Hypermesh) in order to overcome the problems explained as follows, and to find a solution that can be used for both race and road legal vehicles.

However, at first, it is important to define which is the assembly already chosen as the current one, and I will take as reference that project. Afterwards, all the proposed configurations that will be described are those analysed by my colleagues the months before my training start.

My duty is, firstly, to explain the problems occurred with those solutions, finding all the reasons because they were discarded; secondly, I am going to explain my suggestions with the classics “lessons learned” to improve the overall structure.

The Automobili Amos Delta Futurista is already on the market, therefore my “lessons learned” are just some suggestion to improve the Deltas not already produced since the overall design phases are done and only small modifications could be performed on it.

Figure 41: SCG 004S prototype

3.1 Automobili Amos Delta Futurista

Delta Futurista is a restomod vehicle (Figure 42 and Figure 43), since it is a car which took the chassis of the previous version of the past, and was is completely redesigned: both at mechanical/dynamic and bodywork level. In this project, the “donor cars” are the Lancia Delta Integrale 16v, and not the “evo” since that version has more historical interest and Automobili Amos decided to preserve it.

Podium Advanced Technologies took the chassis of the clients’ Deltas Integrale and re-engineered completely the vehicle, giving them a more aerodynamic and sportive shape and more structural strength. The engine power is updated as well, increasing the power up to 330 HP which, combining with a total mass of 1250 kg, makes the Delta Futurista as sportive as ever.

In this chapter I will present my personal analyses that I performed on the doors of the Delta, studying the vehicle in person during its assembly process with the production and technical coordinator of this project.

Figure 42: Delta Futurista (front and side)

Figure 43: Delta Futurista (back)

The analyses performed on the Delta Futurista covered four main areas of the current project of door assembly, considering even the volume occupied around it in order to define the clearances necessary not to damage the door:

1. Miniskirt compartment.
2. Door weather strips sealings.
3. 3 door switch.
4. Internal tab of the door lock.

3.1.1 Miniskirt compartment

The Lancia Delta Futurista owns the same chassis of the Lancia Delta Integrale, therefore this provides a huge constraint during the design phase. In fact, for what concerns the door system, the two hinges are already mounted on the vehicle frame and are slightly inclined inward and frontward.

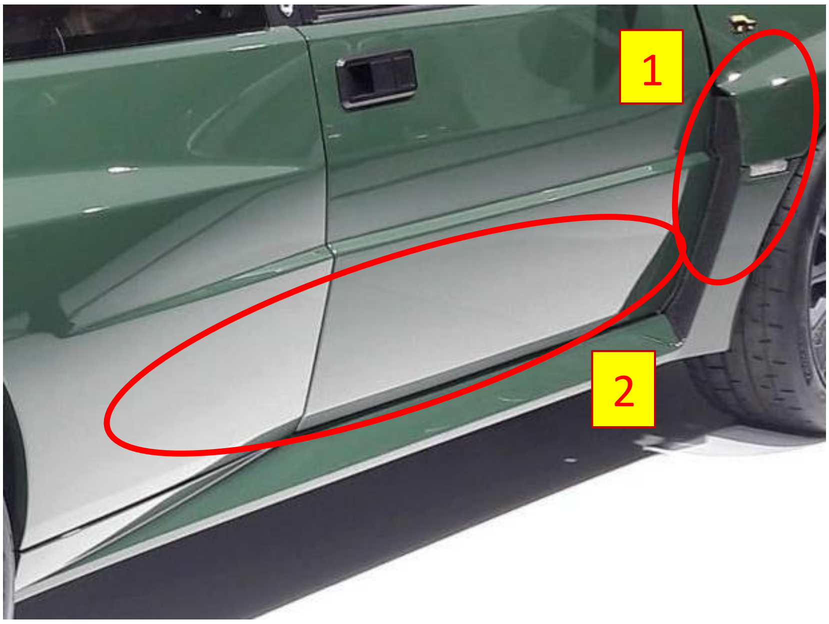


Figure 44: Delta Futurista, miniskirt detail

The presence of the two hinges in an already fixed position has created big problems for the compartment of the miniskirt, which is integrated with the fender in order to form a unique system, that has to cover the two hinges paying attention to the volume around (so as not to obstruct the opening of the door). As it can be seen from the Figure 44, the door is surrounded by that system, which it is made up of the fender (number “1” in the Figure 44) and the miniskirt (number “2” in the Figure 44). It is preferable to use a mechanical plug as main reference point to center the miniskirt. The design of this extremely "flashy" miniskirt is due to the need to assign innovative aesthetic style to the vehicle, in order to be good looking.

The problems that we have encountered are that it occupies a big volume in the lower body area, but even on the sideways since it has to cover both hinges attached to the frame.
This solution allows to have an innovative aesthetic style on the Delta but, since of its large volume, it can cause problems at clearance level with the door during its opening (just 1 mm of tolerance between the door and the side component of the miniskirt).

Therefore, we decided that it is necessary to increase the clearance between the miniskirt and the door so as not to risk a collision between the two components. However, we have to think about a trade-off on that component, because the play between the miniskirt and the door must not be too high, in order to improve the visual appearance and the structural stiffness of the door (Figure 45).

- **Current tolerance**: 1 mm.
- **Optimal tolerance**: ≥ 3 mm so as not to ruin the door during opening operations.

Figure 45: Tolerance between the door and the miniskirt

3.1.2 Door weather strips sealings

Delta Integrale sealings with a "V" cross section (Figure 46) are maintained to reduce design and production costs. One of the main reasons for the preservation of the seals of the Delta Integrale is certainly of historical and aesthetic value. Keeping the sealings of the “old” Delta cuts the costs of redesign a new type, that must fit with the current door shape.

Figure 46: Delta Integrale 16v weather strips door sealings

The main problem that we observed is that the old design weather strips do not guarantee an excellent seal from water, air and dust during bad weather conditions. The sealings generate a problem in the opening and closing of the door, this is because the driver needs to apply an elevated effort in order to operate these two actions. Therefore, there is a great margin of improvement in reducing the applied force, working on the seals reactions.

A solution that we thought can be adopted on the Futurista is to insert sheets of nylon between the seals and the window (internally) to cover more the water entrance in the cabin, causing the flow to drain down (inside the door panels) and finally outside the car, so as not to touch the electrical system, cases, etc... in the door panel.

Figure 47: "Two bulbs" door sealing

If design choices of the door allow, using "two bulb" seals (Figure 47) instead of those with a "V" cross section decreases the ingress of air and water into the cabin.
Adopting this type of weather strip helps to decrease the reactions of the seals, in order to close the door with less effort and decrease the opening load on the handle.

The target is to find a trade-off between the reactions to keep a good protection from air and water ingress, and the reactions to open and close the door without difficulties.

3.1.3 3 doors switch

The Delta Futurista abandons the Integrale project for what concerns the number of doors, passing from 5 doors for the car of 1989 (Figure 48) to 3 doors in the modern one (Figure 49), thus "covering" the rear doors and integrating them with the body of the vehicle. The reasons for this choice are due to the desire to further stiffen the structure and to give an aesthetic continuity with the rear (in order to improve its visual appearance).

Figure 48: 5 doors Delta Integrale v16

Figure 49: 3 doors Delta Futurista

The 5-door volume shapes are maintained, creating "problems" in the plays between the door and the body (> 4-5 mm), making it too obvious from an aesthetic point of view that gives a bad perception of the vehicle shape.

The tolerance of 4-5 mm is present because of tolerances management: therefore, it is due to manufacturing causes instead of style choices (Figure 50). The union of components of the old Delta with the pieces of the new Delta (realized with soft tools) generates these tolerances. The goal is to try to ensure a stylistic image of the vehicle shapes and lines more elegant, implementing a more flush door with the rear body reducing the plays: so as not to make it look open when it is closed, but at the same time not to ruin the door.

- **Current tolerance**: 4-5 mm.
- **Optimal tolerance**: ≤ 3 mm.

Figure 50: Clearance between front door and the rear body

3.1.4 Internal tab of the door lock

The same tab of the Lancia Integrale's internal lock is maintained to reduce design and production costs (Figure 51). The preservation of the Lancia Integrale components also has a historical and aesthetic value, recalling and keeping alive the "myth" of Delta.

The main problem is the difficulty in the descent and ascent to the end of the ride when the lock is activated and deactivated, caused by the high friction with the guide.

The main goal to solve this issue is to reduce the friction which is formed between the tab and its guides. This can be done by improving the efficiency of the spring connected to the actuator so that the tab can rise and descend quickly.

Figure 51: Internal tab of the door lock

A summary box of the current projects just analysed is shown in *Table 3: Delta Futurista lessons learned summary box*, considering the problems that I have encountered and the design suggestion in the "lessons learned" column.

CURRENT PROJECTS	PROBLEMS	LESSONS LEARNED
Miniskirt composed of two pieces and covers both hinges.	Large volume, it can cause problems at plays level with the door during the opening.	Try to increase the play between the miniskirt and the door so as not to risk a collision between the two components.
Seals with a "V" section maintained by Delta Integrale.	• They are old-fashioned, they do not guarantee great protection from air, water and dust. • Closing reactions too high: excessive effort in opening and closing the door.	• Place sheets of nylon between the seal and the window so that the water drains down without touching electronic components in the door panel. • Decrease the release reactions of the seals, in order to close the door with less effort.
Switch from the 5-door Delta Integrale 3-door to the Delta Futurista to stiffen the body.	Aesthetic problems from the point of view of excessive plays between door and body (> 4/5 mm).	Try to ensure a stylistic image of the vehicle shapes and lines more elegant, implementing a more flush door with the rear body reducing the plays.
Maintained the same tab of the internal lock as the Delta Integrale.	Difficulty in the descent and ascent to the end of the ride when the lock is activated and deactivated, caused by the high friction with the guide.	• Improve the efficiency of the spring connected to the actuator so that the tab can rise and descend quickly. • Reduce friction between the tab and its guides.

Table 3: Delta Futurista lessons learned summary box

3.2 Scuderia Cameron Glickenhaus SCG 004S

3.2.1 Target

The goal is to perform an analysis of innovative door system that allows to have, at the design stage, a good compromise between a racing vehicle SCG 004C (Figure 52: "C" stands for Competizione, competition in English) and a road legal variant SCG 004S (Figure 53: "S" stands for Stradale, road legal in English), continuing to respect the structural (and not) targets set.

Figure 52: SCG 004C (Competizione)

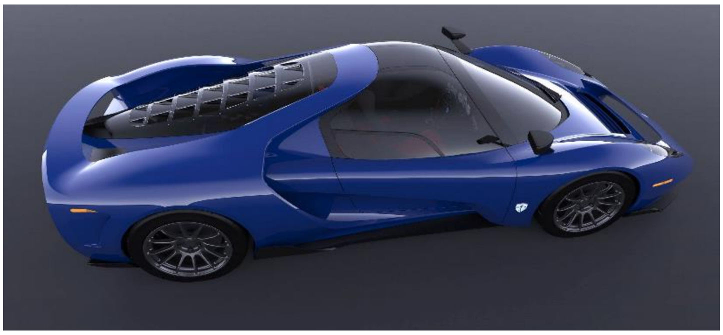


Figure 53: SCG004S (Stradale)

3.2.2 Structural requirements and specifics on door assembly: SCG 004 Competizione and Stradale

In order to evaluate the structural performances of each of the two vehicle types, it is necessary to define the main differences in terms of functional specifics. These different specifics represent the final targets of the two vehicles: by knowing them in advance, it is possible to define at the beginning of the design phase which are the main goals to fulfil.

SCG 004C:

- Prevent air and dust from entering the compartment.
- It does **NOT** require a high-quality door seal (still ensure good protection from water and air → driver comfort not requested).
- It does **NOT** require a large opening of the door (the ergonomic and comfort aspect of the entrance/exit from the cockpit due to the presence of roll cages is not important).
- Polycarbonate side windows are preferred: ensure a light but less rigid structure than the glass variant.
- It does **NOT** require space for windows regulators.
  NB: A sliding portion on the window can be inserted (Figure 54).

Figure 54: Sliding portion of the window

SCG 004S *(Figure 55 and Figure 56):*

- Ensure easy ingress/egress inside/outside the vehicle's cockpit.
- Protect the compartment from air, water and dust in bad weather conditions, using seals that also ensure easy closure and opening (low weather strips reactions).
- Require the presence of intrusion bars to protect the driver in a safer way in the event of a side collision.
- Prevent unauthorized access from outside through door locking systems.
- Improve thermal and acoustic comfort by isolating the driver and passengers from adverse external conditions.
- Provide a pleasant look that mixes with the style of the vehicle body.
- The door needs to be opened and closed automatically by means of electro-hydraulic implementation system: the arrangement of the seats 1 (driver) + 2 (passengers) does not allow the driver (in the central position) to open and close the door manually (Figure 57).
- Windows regulators necessary to allow the lifting and lowering of the window (at least 200 mm).
- Provide an appropriate speed in closing the door at the level of ease of closing, sound and pairing of plays.

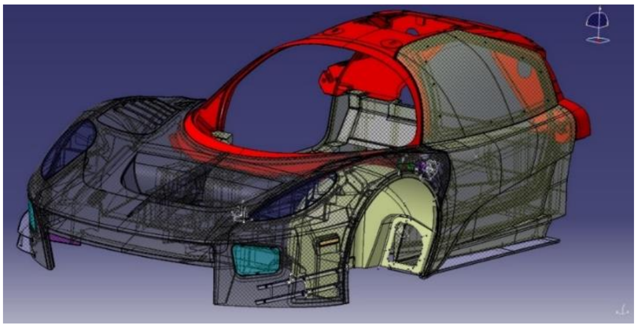


Figure 55: SCG 004S 3D model in Catia (door system)

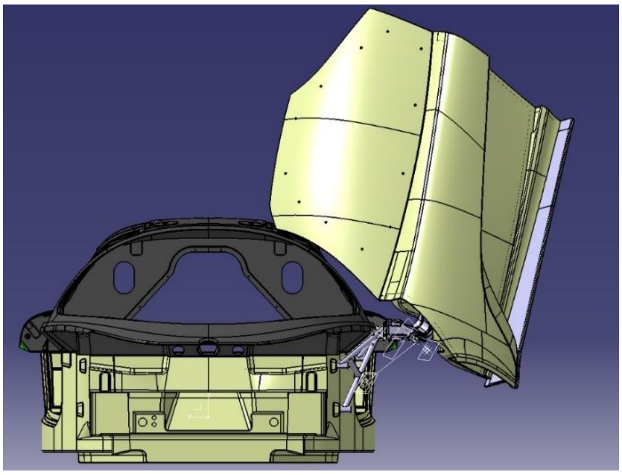


Figure 56: SCG 004S 3D model in Catia (door completely opened)

Figure 57: SCG 004S seat arrangements

3.2.3 Structural targets of the door assembly to satisfy

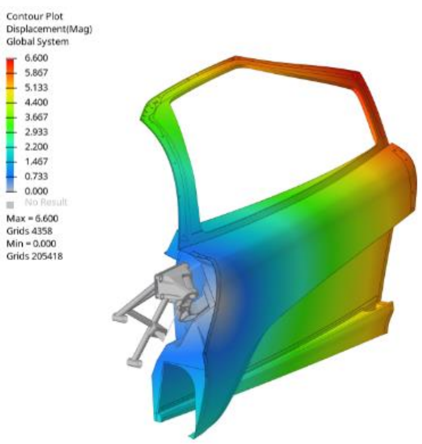
Structural targets are necessary to give a technical reference, to evaluate first in a virtual way and then in physical tests the technical validity of the door.

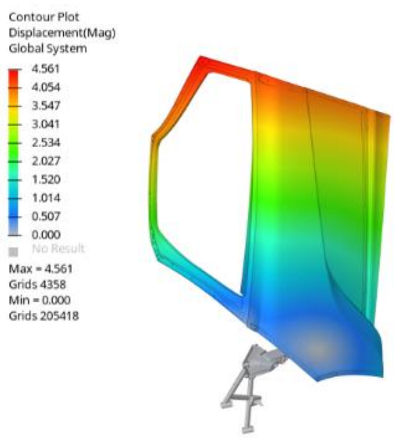
The *Table 4* lists the five main structural targets to ensure the proper door functionalities. The values reported (defined as targets) have been defined taking into account the values found in the technical literature but adjusted, in order to take as reference types of unconventional hinged doors: the SCG004 mounts **butterfly doors**, which are in carbon fiber material.

Load identity number	Load type description	Door position	Reference target
1	Door total deformation on gravity	**Open**	< 2 mm
2	Door total deformation on gravity	Closed	< 2 mm
3	Door deformation due to a load of 385 N applied to the door latch, Parallel to hinge axis	**Open**	< 20 mm
4	Door deformation due to a load of 385 N applied to the door latch, Parallel to hinge axis	Closed	< 20 mm
5	Static torsional stiffness due to a torque of 10000 Nmm at door latch	Closed, door hinge locked	> 450 Nm/deg

Table 4: Unconventional hinged door structural requirements

Target: Ensure high structural stiffness, which allows to achieve the features described above and to verify the static structural requirements of the vehicle. It is important to keep in mind that the torsional stiffness and the lock load deformation are evaluated on the door latch node, while the deformation due to gravity is a maximum value.





3.2.4 Current project – Overall door system

Since the two 004 vehicles (Stradale and Competizione) have different requirements for what concerns the door assembly, it is necessary to design in the proper way the components that made up the overall system (in Figure 58 we can see the 3D model of the road legal version, which is the one that is taken as reference in the performed analyses).

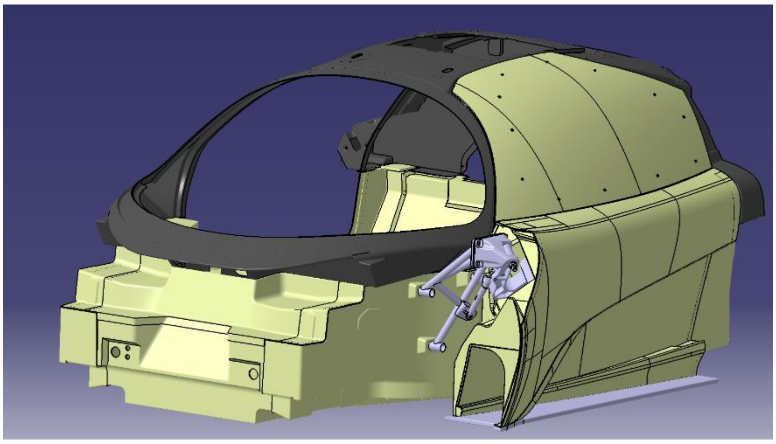


Figure 58: SCG 004S 3D model in Catia software

The type of door is unconventional, since it is a butterfly carbon fiber door: it means that it moves up and out, up to 70°, via hinges mounted on the lateral frame. For that reason, a framework system is exploited and mounted on the lateral chassis of the vehicles by means of 3 attachment points.
The road vehicle should be provided with a window frame, in order to ensure the presence of a window regulator to move the lateral windows. The window regulator is of difficult design, since the presence of intrusion bars or door inserts on the side of the vehicle does not leave space for their installations.
The hinge arm is a gooseneck type, with two reinforcements on its sides in order to make the structure more rigid.

A big drawback for this kind of vehicle door is that it is not left space for windows regulators, which are necessary in the road legal variant, according to its specifics and requirements. The descent of the windows (at least 200 mm) has to be guaranteed since the driver and the passengers should adapt it to every weather condition, for example in summer when it is hot outside and the driver requires fresh air when the vehicle is in motion.
From the structural analysis, we have evaluated a low static stiffness of the system as well, since the door assembly hardly reaches the reference displacements and strength requirements defined as targets, above all in the road legal version. This is due to the fact the SCG 004S door assembly was designed without taking in consideration the structural targets at prior.

So, what to do to solve these problems? At first, we need to define all the requirements previously specified of the road legal version (Stradale) and the race one (Competizione), to take them in consideration during every design phase.

Secondly, it is important to give the structural targets (such as a static torsional stiffness of at least 450 Nm/deg) in order not to find a low-stiffness structure, which it does not work properly. Therefore, it should be performed a breakdown of all subsystems in order to design the system in such a way that it respects the structural requirements and the requested functionalities.

3.2.5 Current project and its possible variations – Single components

The single components that constitute the current door assembly, and the possible variation hypothesized to get the structure stiffer, can be defined in 5 main design fields:

1) Attachment points and support structure:
   - Tubular framework system.
   - Composite structure mounted on cabin.
   - Composite structure mounted on frame.
2) Door structure inserts.
3) Structural modifications on door assembly.
4) Geometric modifications on hinge arm.
5) Lateral windows.

1) Attachment points and support structure:

➢ Tubular framework system

The attachment points of the hinge are located on the vehicle frame (putting the frame in connection with the door via a tubular framework system as it is seen Figure 59), preferring the lower part of the chassis and not the body. This is done since, fastening the hinge on the lower part of the frame (Figure 60), we can reach a higher structural resistance because the chassis is stiffer and more resistant than the body.

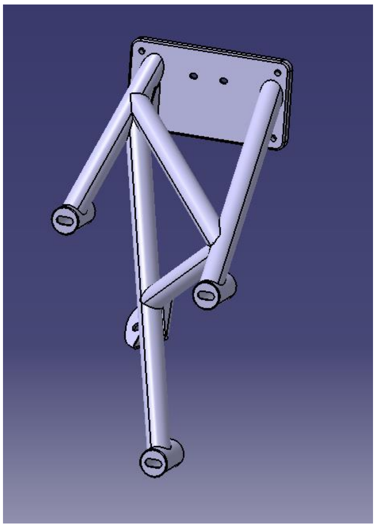


Figure 59: Framework attached to the frame

Structure (closed door)***:***

- **Torsional stiffness:** **294.1 Nm/deg** (*Required: > 450 Nm/deg*).
- **Door total deformation in gravity:** **6.6 mm** (*Required: < 2 mm*).
- **Door deformation with 385 N on door lock, parallel to door hinge axis** *(complete system, closed):* **60.1 mm** (*Required: < 20 mm*).

The biggest problem of this solution is that the system has low static torsional stiffness, so it is not capable of supporting high loads.

Some solutions that can be adopted to overcome those problems are:

1) **Keeping the attachment points** on the frame and let the structure be stiffer, that could represent a good choice from design point of view, since it preserves the constraints already present on the vehicle. All these hypotheses are done not to revolutionize the overall project.
   - **Advantages:** Simplicity in the solution, no geometry modifications needed.
   - **Disadvantages:** Low structure stiffness. (**NB**: Stiffness can be increased by adopting a composite structure instead of frameworks).

2) An alternative at maintaining already defined constraints could be **creating new fasteners** on the vehicle frame or directly on the bodywork, but just if it would lead to a higher stiffness.
   - **Advantages:** The main advantage is the increased rigidity and strength of the structure.
   - **Disadvantages:** Overturning the entire geometry of the project, since it is requested to go looking for new constraints that give a better rigidity to the structure. Another drawback is the excessive intrusion into the body/cabin part (which is a less structural component than the frame).

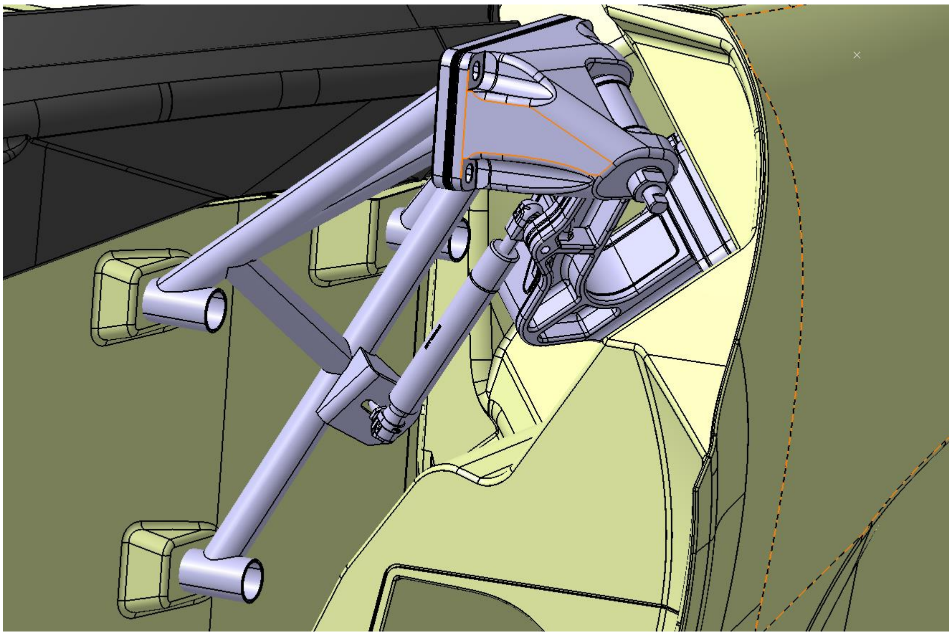


Figure 60: Complete hinge system attached to the frame

This is the structure that is currently adopted on the vehicle, later on some hypothetical solutions are studied in order to improve the structural strength of the system. These analyses had been performed by my colleagues before the beginning of my training.

I have taken their solutions and analysed in a more detailed way, underlining the problems encountered and the possible “lessons learned” from each configuration. Afterwards, in the chapter “Case study: design project of the door hinge assembly of SCG 004S” I will show the personal solutions that I have hypothesised, illustrating the work I have performed on Catia and Hypermesh (with the corresponding results values).

➢ Composite structure mounted on cabin

It was hypothesized to insert a composite structure mounted on the cabin (Figure 61), resulting in changes to the geometry. The reason behind this idea is to reduce the used volume, in order to save space and let the vehicle be lighter.

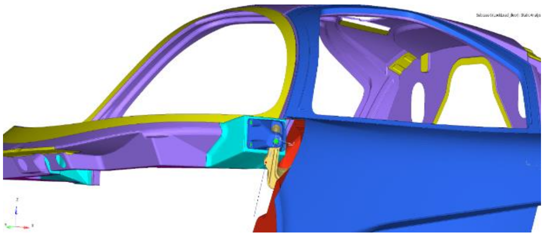


Figure 61: Composite structure mounted on the cabin

Structure (closed door)***:***

- **Torsional stiffness: 340 Nm/deg** (*Required: > 450 Nm/deg*).
- **Door total deformation in gravity: 3.4 mm** (*Required: < 2 mm*).
- **Door deformation with 385 N on door lock, parallel to door hinge axis** *(complete system, closed):* **22.5 mm** (*Required: < 20 mm*).

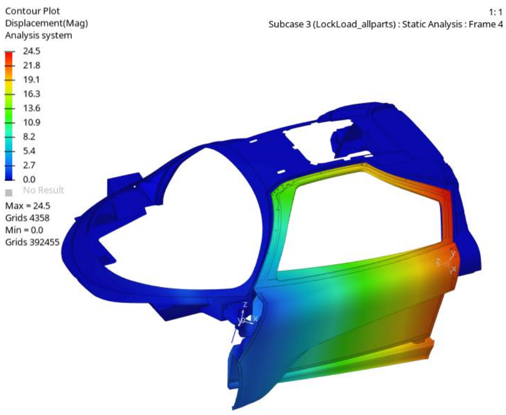


Figure 62: Hypermesh structural analysis – Lock load displacements

Two main drawbacks are defined, starting from this configuration: the first one is that the composite structure creates major problems because it consists of overlapping skins that, in addition to complex realization, have a high cost.
Having a composite structure does not mean a higher strength at first glance, as it can be evaluated through FEM analyses (Figure 62 shows the door displacements due to the lock load). In fact, this is mainly due to the pre-selected attachment points: in this case we have a low stiffness, since the cabin is less rigid than the frame; an anchorage in the lower part is further preferred because the frame is more structural.

The idea to improve the structure is to leave the hypothesis of creating a composite structure which is mounted on the cabin, since this structure does not guarantee a proper stiffness to the door system. The cabin is less rigid than the chassis, so the door assembly cannot be attached to the body in order to be stiffer.

➢ Composite structure mounted on frame

Inserting a composite structure mounted on the vehicle frame was considered in order to increase the overall strength, keeping the anchorage points already defined (Figure 63). The reason behind this idea is to gain more structural stiffness with respect to the composite structure mounted on the cabin, since the cabin is more subjected to deformations.

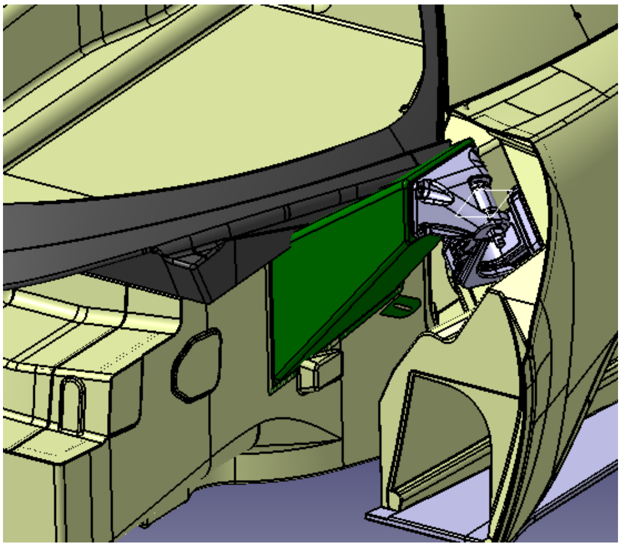


Figure 63: Composite structure mounted on frame

Structure (closed door)***:***

- **Torsional stiffness: 332 Nm/deg** (*Required: > 450 Nm/deg*).
- **Door total deformation in gravity: 3.2 mm** (*Required: < 2 mm*).
- **Door deformation with 385 N on door lock, parallel to door hinge axis** *(complete system, closed):* **16 mm** (*Required: < 20 mm).*

The composite structure creates major problems because it consists of overlapping skins that it is of difficult and complex realization, and at the same time it has an high cost of production.

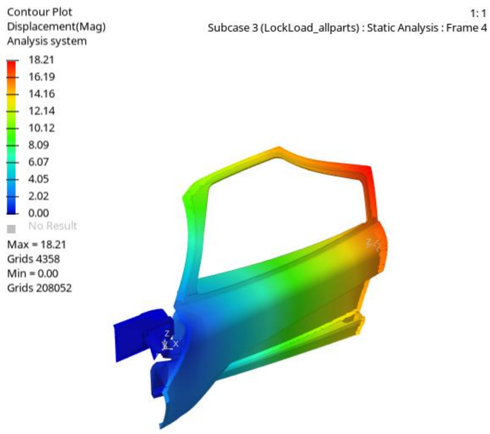


Figure 64: Hypermesh structural analysis – Lock load displacements

But this is not the only drawback, since this big structure occupies a large volume inside the door hinge assembly area. And even considering the big amount of volume occupied, as we can see from the values of the structural analyses that had been already performed by my colleagues, we have a low torsional stiffness. This is mainly due to the fact that this structure covers the bending action of the door (when the loads are applied), but not the torsion due to the moment application on the door latch. Even though the static torsional stiffness is less than the target, we have good results in terms of displacements due to gravity/lock loads (Figure 64 shows the door displacements due to lock load).

The composite structure between the door and the frame allows to have a good stiffness of the entire system, but it increases the production costs since composite materials are more expensive than steel and aluminium structures. A good design opportunity could be keeping this structure attached to the frame, but using different materials (such as steel) without losing the stiffness gained with carbon fibre material.

2) Door structure inserts

An attempt to improve the stiffness and strength of the structure was made by assuming the integration of a **door insert** on the door panel (as it is seen in Figure 65). The reason is that it is requested to increase the structural stiffness (reducing the torsional rotation) and reaching the structural targets in terms of displacements, and then to exploit all the available space for the door assembly.

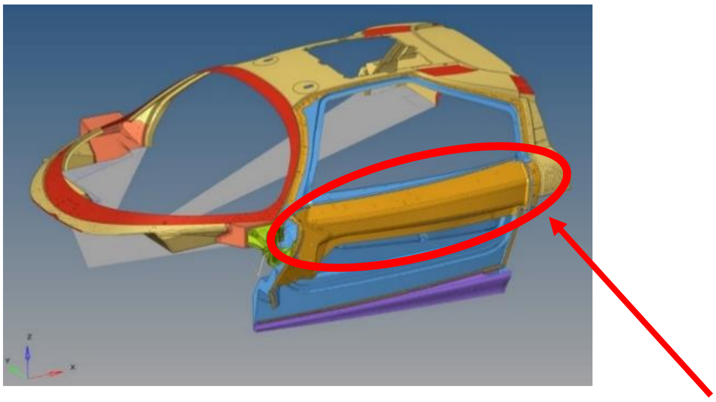


Figure 65: Door insert mounted on the door frame

Structure (closed door)***:***

- **Torsional stiffness: 200 Nm/deg** (*Required: > 450 Nm/deg*).
- **Door total deformation in gravity: 3.3 mm** (*Required: < 2 mm*).
- **Door deformation with 385 N on door lock, parallel to door hinge axis** *(complete system, closed):* **21.1 mm** (*Required: < 20 mm*).

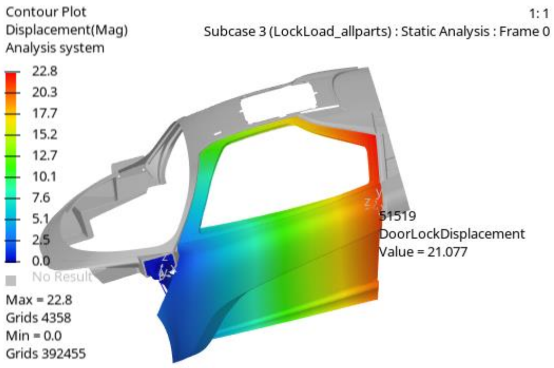


Figure 66: Hypermesh structural analysis – Lock load displacements

Even if the values computed by the structural analyses in Hypermesh (Figure 66) seams compatible with the required target of the unconventional doors, we can encounter some problems. The first one is that inserting this additional structure on the side of the door leads to have a large volume, that could create interferences with many components installed inside the door.

For example, adopting this solution leads to a lack of the windows regulators since there is no space for them to be mounted, therefore lifting and lowering of the side windows are not granted.

Apart from that, this door insert does not bring satisfying results from what concerns the torsional stiffness, in fact we can see that the value that is computed (200 Nm/deg) is less than the half of the searched value (required: > 450 Nm/deg).

Something that could be done to improve the overall structure is to try to ensure enough space for the lowering of the windows in presence of the door insert. It can be useful putting the insert more sideways in order to ensure at least 2-3 cm for the lateral window location. The windows regulators can be placed under the door insert, as it can be seen in the sketch I have realized in Figure 67.

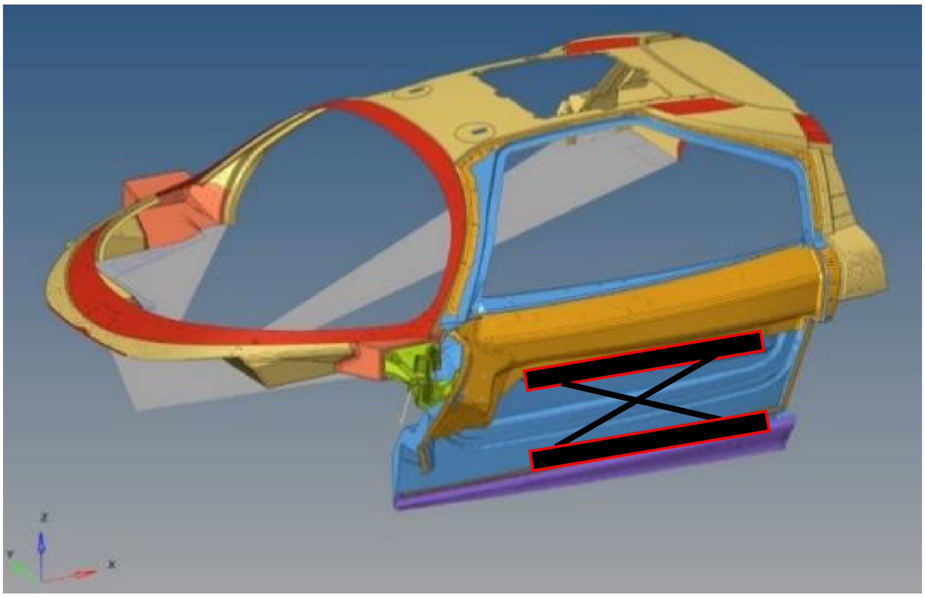


Figure 67: Door insert concept with windows regulators sketch below it

3) *Structural modifications on door assembly*

Door hinge arm is modified in steel, while the composite structure in mounted on the cabin (the cabin is modified as in Figure 68). This is done to increase the stiffness of the structure in order to reduce the total displacements during the loads' applications.

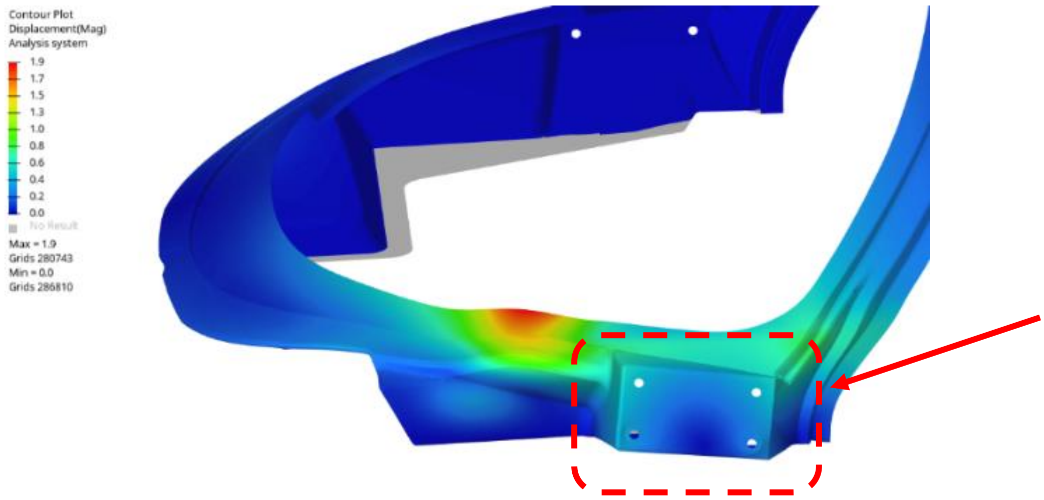


Figure 68: Geometric modifications on cabin

Structure (closed door)***:***

- **Torsional stiffness:** **220 Nm/deg** (*Required: > 450 Nm/deg*).
- **Door total deformation in gravity:** **2.195 mm** (*Required: < 2 mm*).
- **Door deformation with 385 N on door lock, parallel to door hinge axis** *(complete system, closed):* **10.978 mm** (*Required: < 20 mm*).

This is not the best solution in terms of cost, since this assembly is extremely expensive: 20 mm of composite material (6 mm CFRP + 8 mm Honeycomb + 6 mm CFRP) is really high.
But there are other problems as well, in fact the structure occupies a large volume, and it is difficult to produce (since it has a complex and costly realization).

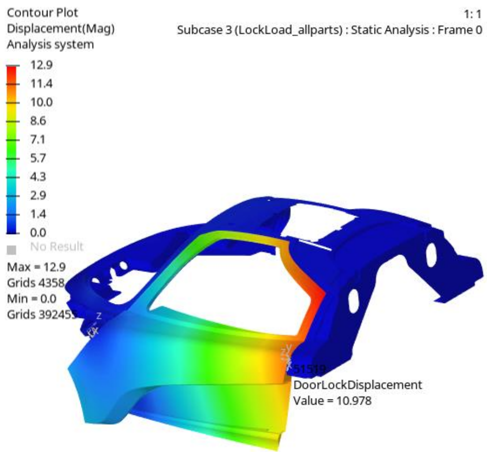


Figure 69: Hypermesh structural analysis – Lock load displacements

It should be preferable not to mount this structure on the cabin (as it can be seen in this configuration) since, it is true that from one side it reduces the displacements (as it is seen in Figure 69), but on the other side it does not have a good torsional stiffness because the body is not as structural as the chassis, therefore it deforms easily.

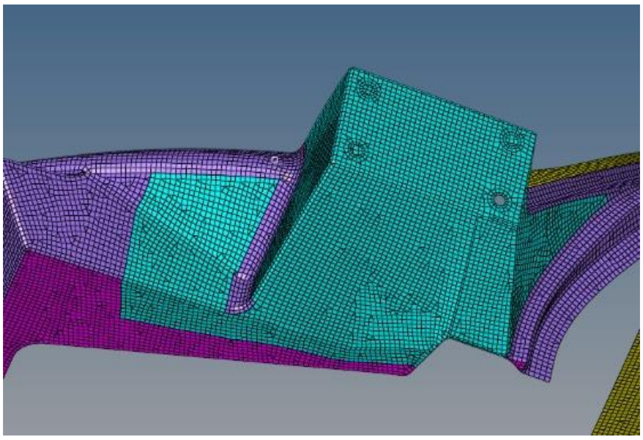


Figure 70: Composite structure in carbon fiber, mounted on the cabin (20 mm)

From this analysis we can say that it is more convenient mounting the composite structure on the frame, following the 3 attachment points, and not on the cabin since the latter is less rigid and resistant to side impact.

Another lesson learned from the current configuration is that the composite structure should be reduced in dimensions (even if it is stiffer), since 20 mm of carbon fibre material it too expensive (Figure 70). The goal is to find a good trade-off between the structure's cost and stiffness.

4) *Geometric modifications on hinge arms*

During this stage we increased the cross section of the gooseneck hinge arm (from 55 mm as in Figure 71 to 99 mm as in Figure 72), while two additional supports are inserted on the sides. This increase on the cross section is realized to make the hinge system more rigid in torsion, as we can see in the result *Table 5*. In this configuration, not only the hinge arm geometry was modified, but it was adopted again the framework system made of tubes, which is the solution currently used on the SCG 004S.

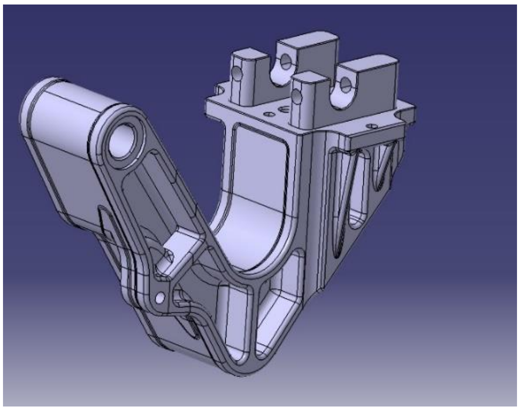


Figure 71: Baseline version of hinge arm

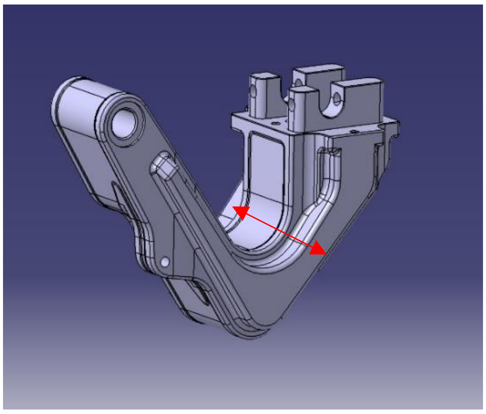


Figure 72: Updated version of door hinge arm (bigger cross section)

Structure *(closed door)*:

- **Torsional stiffness**: **332 Nm/deg** (*Required: > 450 Nm/deg*).
- **Door total deformation in gravity: 3.2 mm** (*Required: < 2 mm*).
- **Door deformation with 385 N on door lock, parallel to door hinge axis** *(complete system, close):* **16 mm** (*Required: < 20 mm*).

	Hinge arm 1	***Hinge arm 2 (modified)***
Torsional stiffness	294.1 Nm/deg	332 Nm/deg
Total deformation in gravity	6.6 mm	3.2 mm
Total deformation with 385 N on door lock	60.1 mm	16 mm

Table 5: Hinge arm structural comparison

As it is shown in *Table 5*, there is a net improvement on the door stiffness (maintaining the attachment structures with tubular chassis) in terms of displacements, but not enough to satisfy the requirements specified.
Unlikely, we evaluated a torsional stiffness which is higher than the previous hinge arm, but not satisfying enough to fulfil the structural required target of the unconventional doors.

A solution to increase the torsional stiffness of the system and to occupy less volume, can be the realization of **exotic shapes** for the hinge assembly (Figure 73).

- **Advantages:** This hypothesis allows to maintain the initial fasteners (increase the mechanical properties by means of a higher static stiffness). But the main advantage is a reduce occupation of the available volume, maintaining a stiff structure. This allows to have less problems for what concerns interferences with adjacent components.

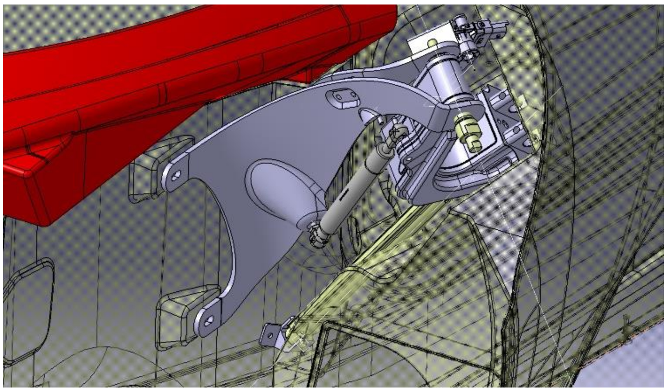


Figure 73: Exotic shape of the door hinge assembly

- **Disadvantages:** Difficulties in design and realization, being the geometric shapes extremely complex.

Another solution can be adopting a door hinge system made up of a **single large compact structure**, welded in steel and milled as the one shown in Figure 74. Unlikely this configuration cannot be easily mounted on our vehicle, since the volume and the overall structure rotation are completely unconventional, therefore it has a difficult application.

- **Advantages:** limited number of components, which allows the structure to be characterized by greater simplicity and a more compact geometry (consequent increase in stiffness).
- **Disadvantages:** Difficulties in realization, being the geometric shapes extremely complex. All these considerations would lead to a complete distortion of the initial project.

Figure 74: Single compact structure milled in steel

5) Lateral windows

The window assembly (including glass, windows lifts, guides, etc.) constitutes a problem for 004S, as there is little space to ensure a complete descent of the window by means of the various types of regulators.

In fact, in order to make the structure stiffer (by inserting large intrusion bars), it was sacrificed the space dedicated to the guides of the window regulator. Therefore, it is not possible to consider the requirements adopted by general door lateral windows (Figure 75).

Figure 75: General door lateral window

In the current project there is not the possibility to rise or descend the glass window, since there is no space for the windows regulators. Therefore, this is something that had to be analyzed and take in consideration during the design phases of the door system, even to the detriment of the overall system stiffness.

The biggest observed problem is that there is no space to ensure a complete descent of the window, due to the presence of door inserts or intrusion bars.

Therefore, to satisfy the customer it is requested to let the window be lowered of at least 20 cm, by mounting special guides inside the door. This is only possible if there are no structural elements to prevent the proper work of the regulators (Figure 76).

Figure 76: Example of windows regulator

4. Case study: Design project of the door hinge assembly of SCG 004S

During this phase of the thesis I had to perform the structural analysis on the door system of the SCG 004S, analysed before in the "lessons learned" chapter. In fact, this door assembly was already analysed in Podium, but it showed many problems related to the structural part, since it did not respect the normative regulation values, and for that reason it shows high values of stresses.

My job was to find new solutions for this system, in order to fulfil the pre-established targets (for design simplicity I had analysed only the "closed door" case). In the Table 6 I will show just a quick reminder of the doors normative 3 main requirements, related to unconventional hinged doors. In fact the SCG 004S has a butterfly door, this means that it is made up of just one hinge and therefore it has less narrow requirements (requirements for conventional doors will be presented in the proposal normative in the next chapter of the thesis).

Load identity number	Load type description	Door position	Reference target
1	Door total deformation on gravity	Closed	< 2 mm
2	Door deformation when a load of 385 N is applied to the door latch/lock, Parallel to hinge axis	Closed	< 20 mm
3	Static torsional stiffness (applying a torque of 10000 Nmm on the door latch)	Closed, door hinge locked	> 450 Nm/deg

Table 6: Unconventional hinged door requirements

In order to analyse the structure, in the Hypermesh software I applied the three loadcases:

1. Gravity load applied to all nodes downwards.
2. Lock Load: A load of 385 N applied to the door latch and parallel to the hinge axis (Figure 77).
3. A moment of 10000 Nmm around x-axis, on the door latch (Figure 78).

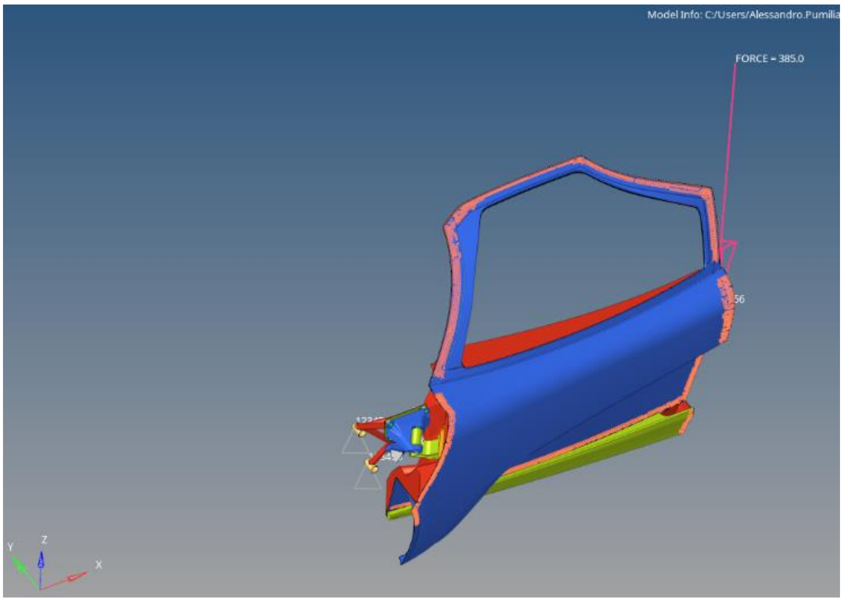


Figure 77: Lock load

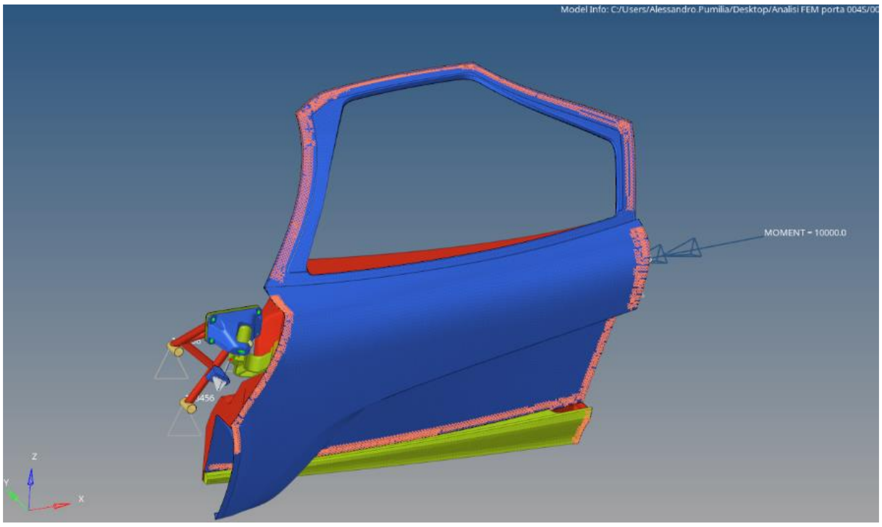


Figure 78: 10000 Nmm torque application to evaluate the torsional stiffness

It is important to fully constrained the three attachment points to the frame, since they cannot rotate and move in the three directions: this almost represent a cantilever beam, with the applied load on the opposite side with respect to the constraints.

Something that has to be fully constrained is the actuator beam as well, which is attached on one side to the door reinforcement on the tubular chassis, while on the other side to the door hinge arm (that has a gooseneck shape). During the model pre-processing in Hypermesh, I decided to adopt a base size of 4 mm for the mesh of the assembly, in order to be the most precise as possible.

Once having applied the loads, considering the gravity load to all the displayed nodes as well, I had to evaluate the displacements and the rotations in order to compare them with the required targets. The displacement and the rotations are computed on the door latch/lock, in order to make the comparisons on that node element. The only deformation that was evaluated as a maximum value was the displacement due to gravity load, since our objective is to compute the total deformation and not the one resulted on the door latch.

The static torsional stiffness (K) is easily computed, since it is inversely proportional to the rotation evaluated at the door latch:

$$\boldsymbol{K} = \frac{\boldsymbol{M}}{\boldsymbol{\theta}}$$

Where **K** represents the torsional stiffness, **M** is the applied torque (10000 Nmm) and **ϑ** is the rotation angle evaluated at the door latch.

In the following paragraphs I will analyse all my design project ideas for the door assembly of the SCG 004S, showing new solutions and design considerations to increase the structural resistance of the system.

4.1 Configuration 001 – Baseline

At first I implemented on the software "Altair Hypermesh" the analysis already performed on the baseline configuration of the door, as already explained in the "lessons learned" chapter (Figure 79). The results obtained are not satisfying from a structural point of view since the door shows low torsional stiffness and too much displacement when the load is applied on the door lock (Figure 80). Therefore, we cannot reach the requirements and targets for automotive side doors, as specified on the norms.

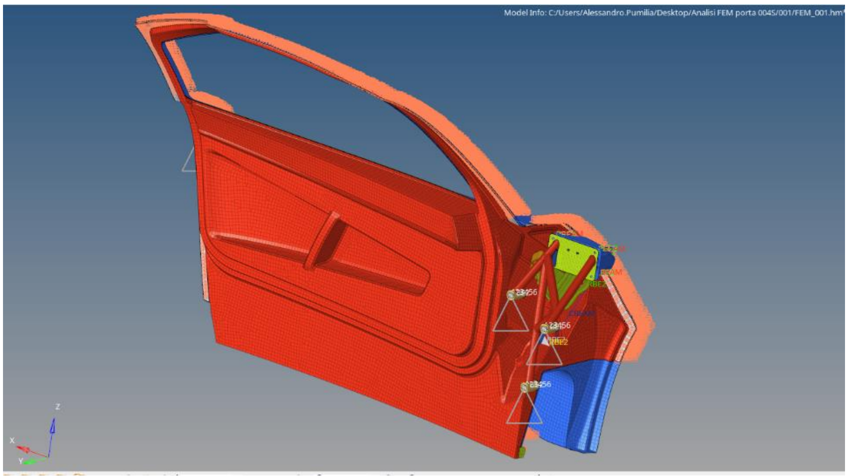


Figure 79: Baseline door assembly with tubular chassis attached to the frame (001)

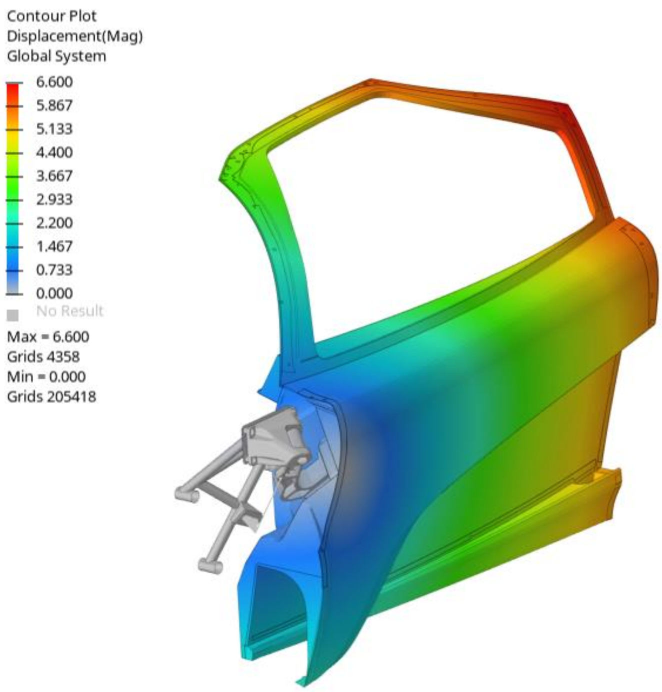


Figure 80: Displacements representation due to gravity load (001)

Model	Loadcase	Target	Result	Unit
001: Baseline configuration (Steel Attachment + Aluminium gooseneck)	**Door total deformation in gravity**	< 2 mm	**6.6**	**mm**
	Door deformation when 385 N applied on door lock (Lockload)	< 20 mm	**60.1**	**mm**
	Torsional stiffness	> 450 Nm/deg	**294.1**	**Nm/deg**

Table 7: 001 structural results

In the Table 7 are defined the results computed on this configuration, as it can be evaluated the target requirements are not been satisfied. The baseline configuration is characterized by a tubular chassis in steel attached to the frame, while the hinge arm has a gooseneck shape (Figure 81), and it is in aluminium. For information and production purposes I should specify that the total mass of the door assembly is 24.85 kg. This 001 system is that which is implemented in the current vehicle, that is now released to the market.

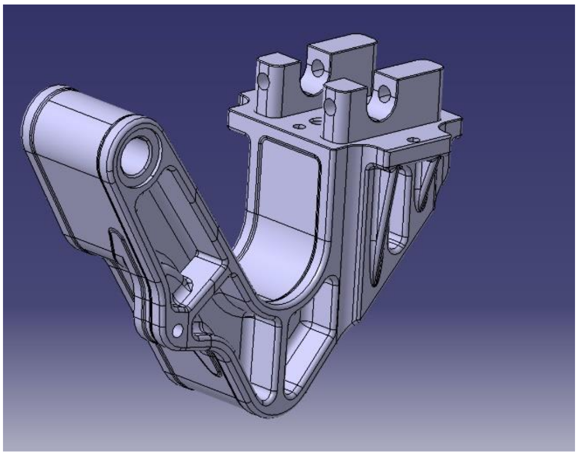


Figure 81: Gooseneck hinge arm (001)

4.2 Configuration 002

The first new solution that I have hypothesized is to insert an additional steel tube of 25 mm of diameter (2 mm thick) on the framework, in order to let the structure be stiffer (Figure 82). Keeping the previous framework system is necessary in order to take as reference the three attachment points to the frame, which allow to reduce costs and design stages. I decided to put this new tube on the tubular chassis because there was an empty space in the bottom part of the door hinge plate, therefore a linkage between this latter component and one of the attachments to the chassis can be inserted. The total mass of the door assembly is 25.23 kg, just 0.38 kg more than 001 configuration. A comparison between the two solutions is illustrated in Figure 84 and Figure 83:

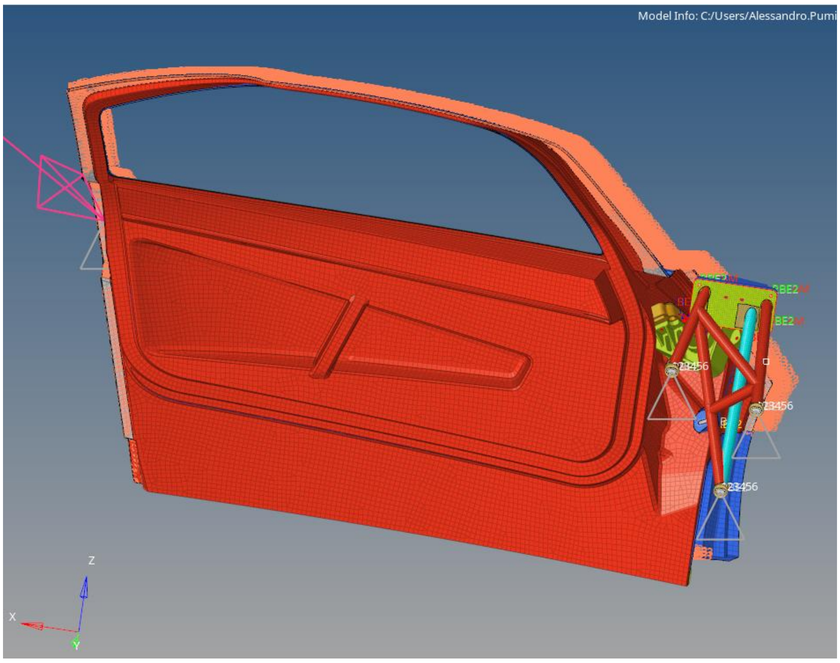


Figure 82: Door assembly (002) with additional tube in light blue

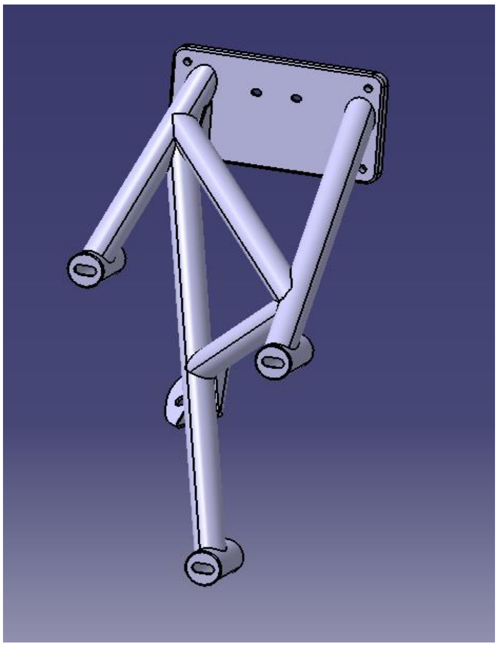


Figure 84: Baseline tubular chassis (001)

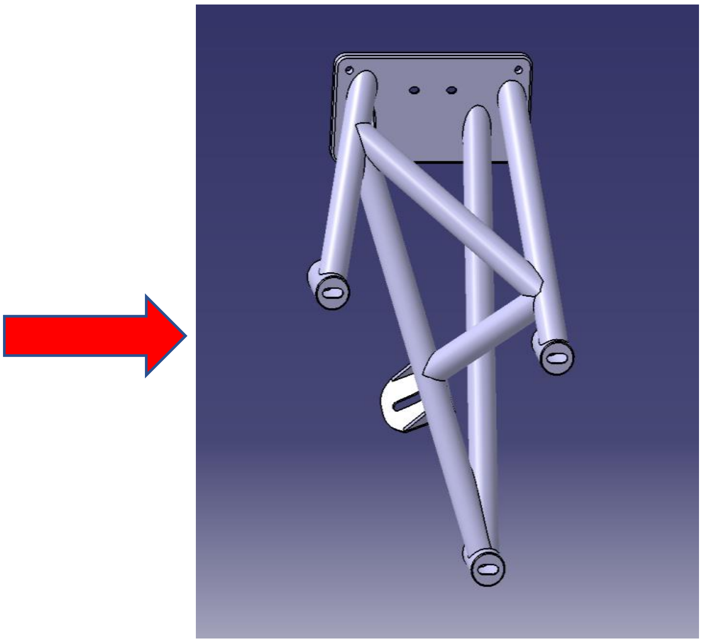


Figure 83: Tubular chassis with additional tube (002)

Applying all the loads previously defined, the following displacements and rotations representations are reached.

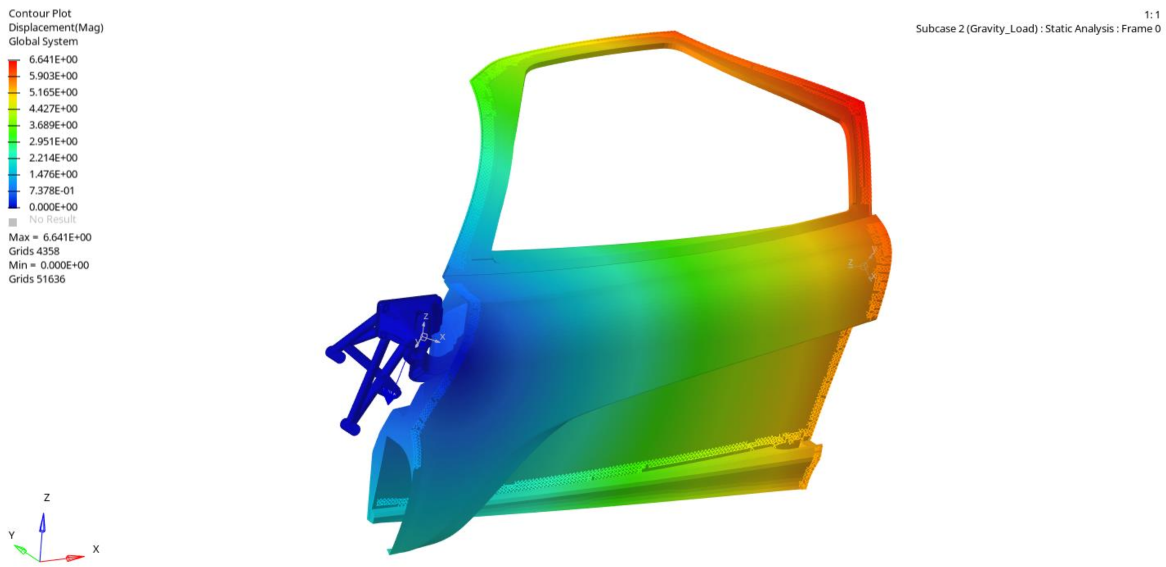


Figure 85: Displacements representation due to gravity load (002)

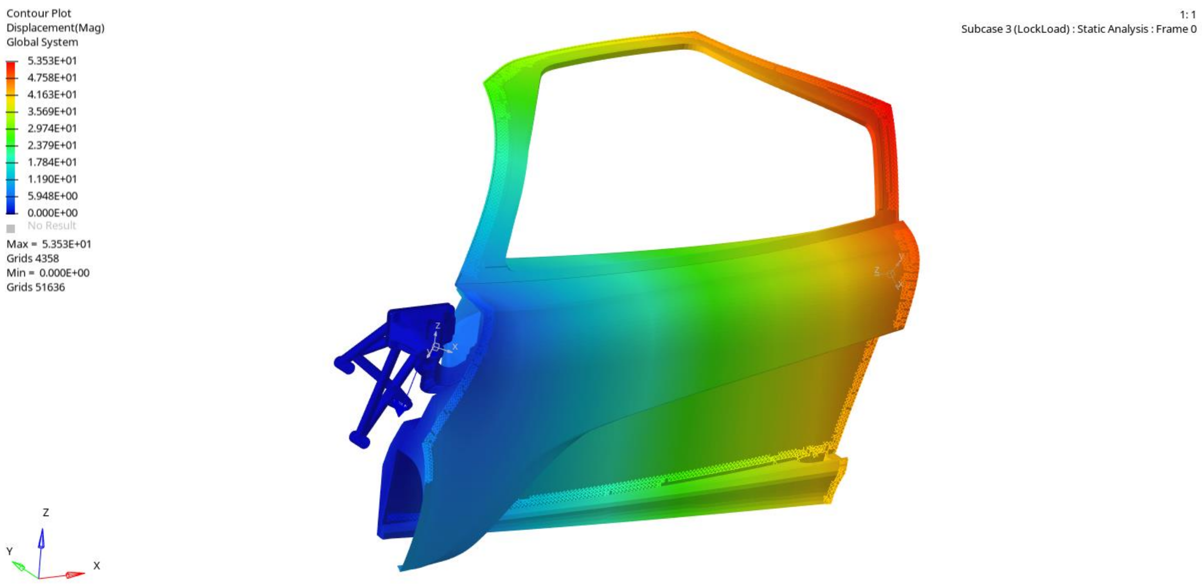


Figure 86: Displacements representation due to lock load (002)

As it can be seen from Figure 85 and Figure 86, the displacements values are little reduced with respect to the baseline configuration: the red zones (highest values) are narrower in the lock load case, while for what concerns the gravity load the displacements remain almost the same.

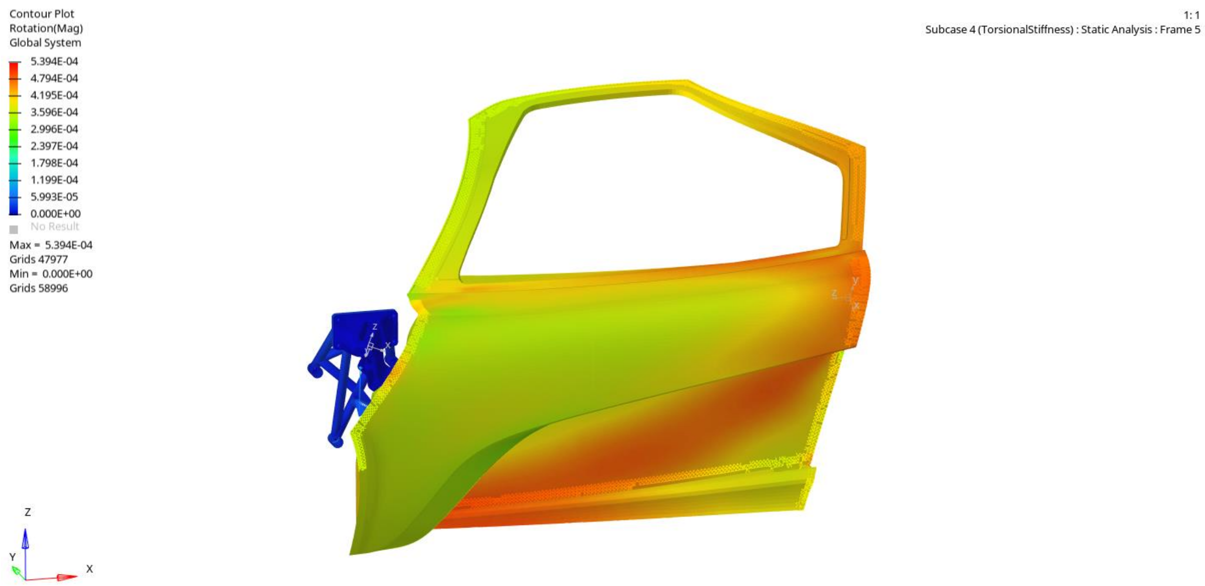


Figure 87: Rotation angles representation due to torque application (002)

In Figure 87 are shown the rotation angles in radians due to the application of a torque of 10000 Nmm around the x-axis on the door latch. After having evaluated the angle $\vartheta = 5.2 * 10^{-4}\,rad$, and converted the radians in degrees, we can compute the torsional stiffness by the inverse equation.

In *Table 8*, the reached values are defined and compared to the previous model (baseline). As it can be seen we have an improvement of the structural stiffness of the system (from 294.1 Nm/deg to 335.83 Nm/deg), and this leads to lower values of displacements (except the gravity one, which remains the same).

However, we still have not fulfil the pre-defined targets, and for that reason other solutions have to be thought in order to increase the overall strength.

Model	Loadcase	Target	Result	Unit
001: Baseline configuration (Steel Attachment + Aluminium gooseneck)	**Door total deformation in gravity**	< 2 mm	**6.6**	**mm**
	Door deformation when 385 N applied on door lock (Lockload)	< 20 mm	**60.1**	**mm**
	Torsional stiffness	> 450 Nm/deg	**294.1**	**Nm/deg**
002: Tube chassis configuration (baseline) + 1 additional tube	**Door total deformation in gravity**	< 2 mm	**6.6**	**mm**
	Door deformation when 385 N applied on door lock (Lockload)	< 20 mm	**46.94**	**mm**
	Torsional stiffness	> 450 Nm/deg	**335.83**	**Nm/deg**

Table 8: 002 structural results comparison with 001 configuration

4.3 Configuration 003

In this configuration it was taken as reference the 002 model while two additional steel connections had been attached to the tubular chassis structure to increase the strength of the overall system (Figure 88). A big concern is that it increases the mass of the vehicle, and therefore we cannot reach big structural improvement, as it will be seen from the torsional stiffness, which is even worse than the previous configuration. For information and production purposes I should specify that the total mass of the door assembly is 25.77 kg, just 0.5 kg higher than the previous configuration. A comparison between the 002 and 003 configurations is done in Figure 89 and Figure 90, in order to underline the main design differences.

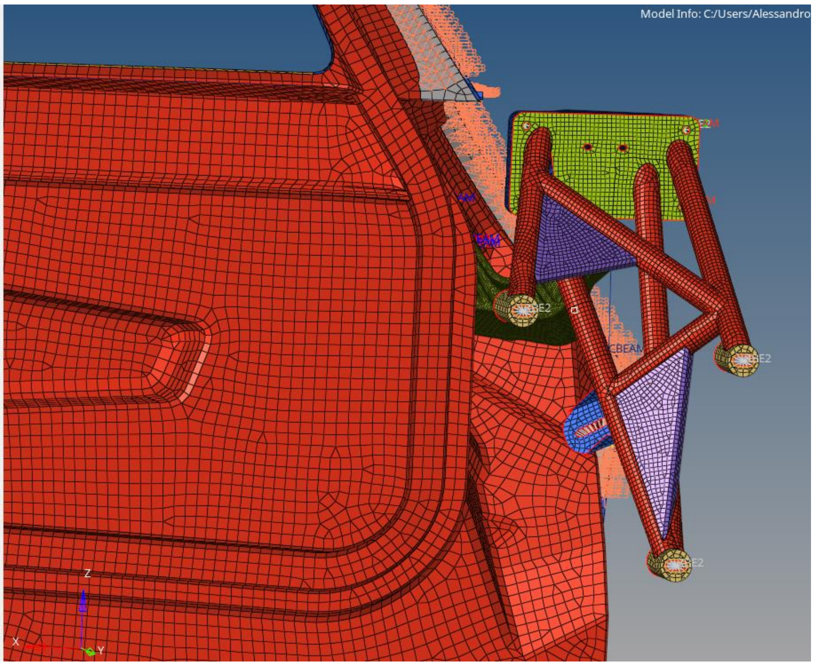


Figure 88: Door assembly (003)

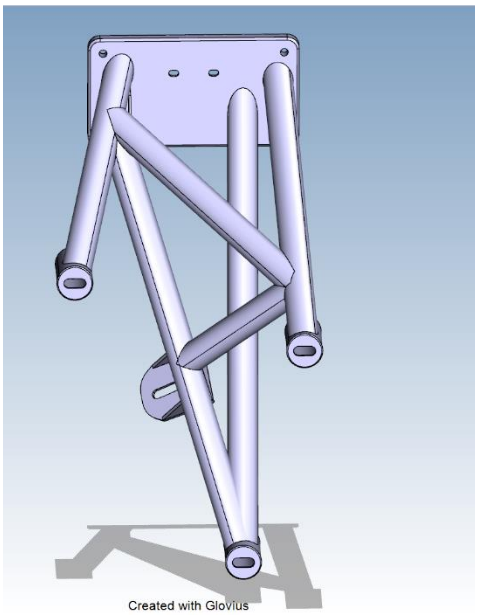


Figure 89: 002 configuration

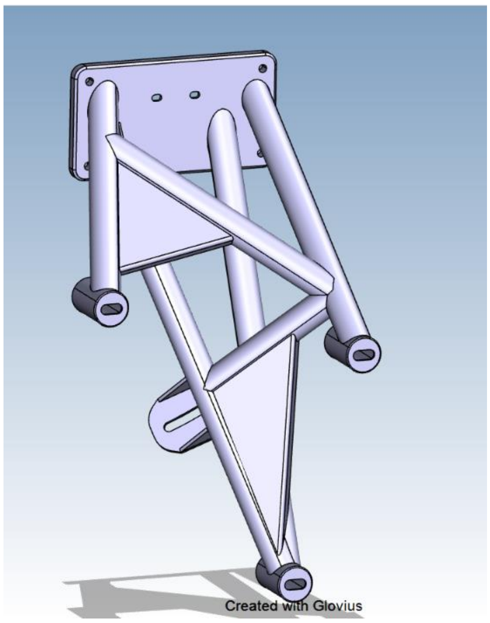


Figure 90: 003 configuration

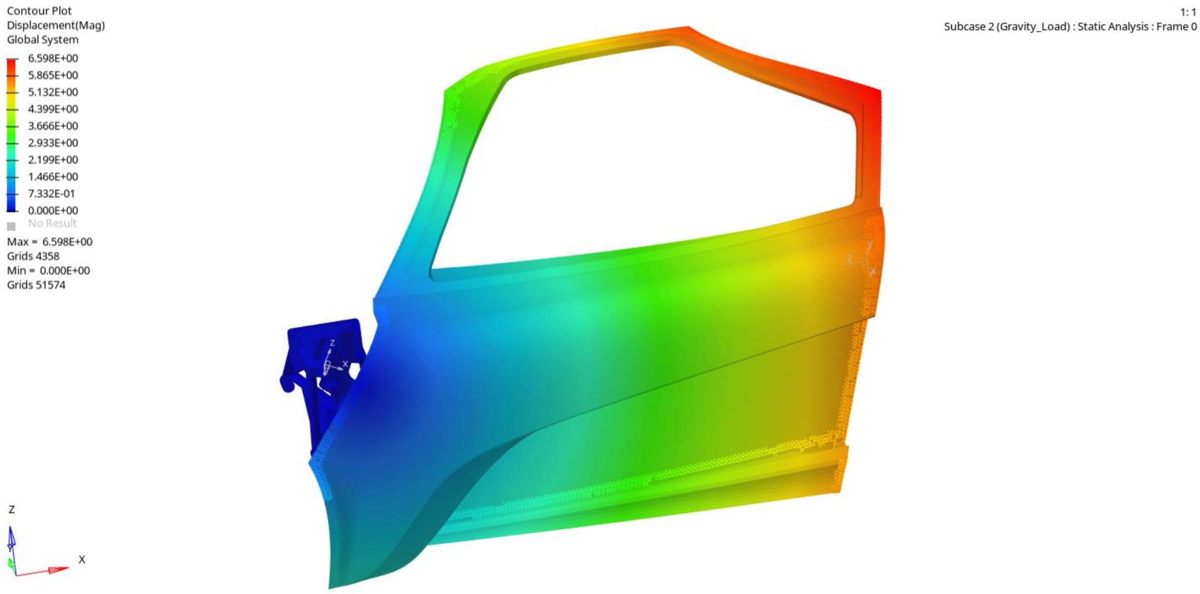


Figure 91: Displacements representation due to gravity load (003)

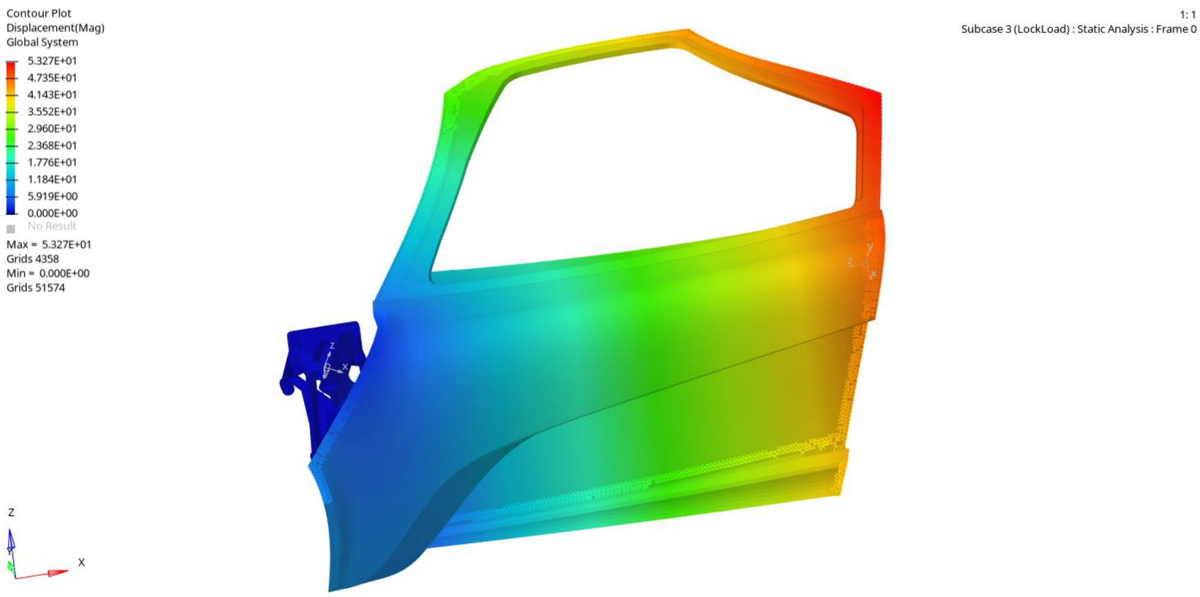


Figure 92: Displacements representation due to lock load (003)

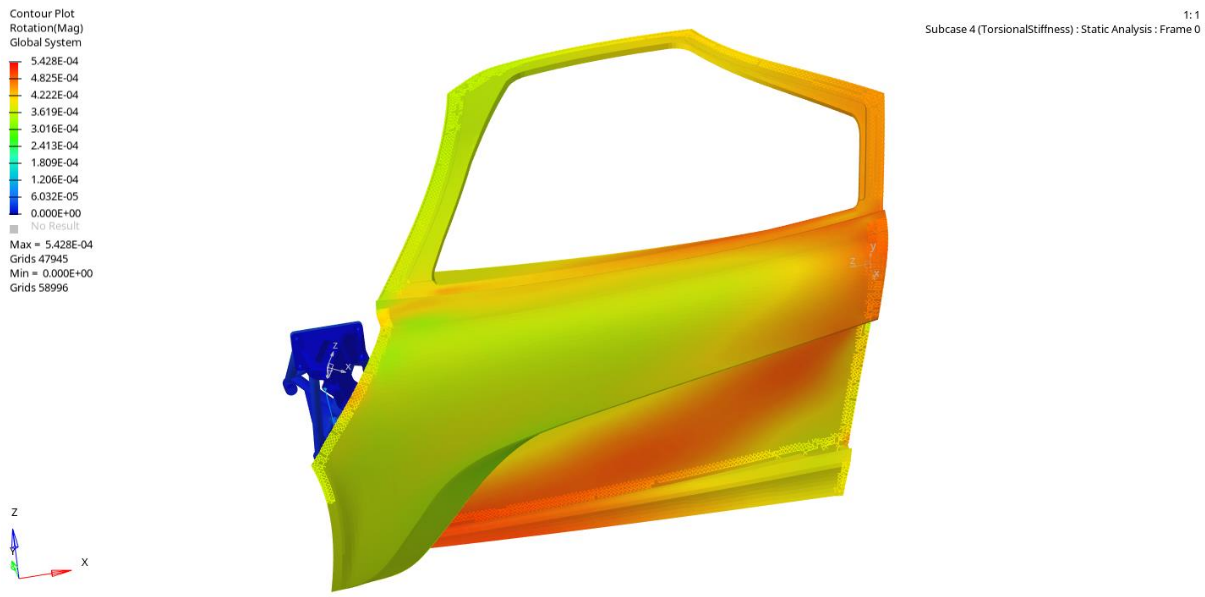


Figure 93: Rotation angles representation due to torque application (003)

The structural analyses representations are shown in Figure 91, Figure 92 and Figure 93. In the *Table 9* are displayed the results evaluated from the structural analysis of this configuration, as it can be seen I reported a comparison between this latter system and the previous version.

Looking carefully the table we can notice that inserting the two connections did not change too much the values of the displacements, in fact we have a small improvement: for example applying a 385 N load on the door lock (parallel to door hinge inclination) we can evaluate a reduced value from 46.94 mm on 002 model, to 46.68 mm in this current configuration. Since the target values are not fulfilled (< 20 mm) I had to think to another model in order to get narrower to the requirements previously pre-established.

Model	Loadcase	Target	Result	Unit
002: Tube chassis configuration (baseline) + 1 additional tube	**Door total deformation in gravity**	< 2 mm	**6.6**	**mm**
	Door deformation when 385 N applied on door lock (Lockload)	< 20 mm	**46.94**	**mm**
	Torsional stiffness	> 450 Nm/deg	**335.8**	**Nm/deg**
003: 002 + 2 connections	**Door total deformation in gravity**	< 2 mm	**6.6**	**mm**
	Door deformation when 385 N applied on door lock (Lockload)	< 20 mm	**46.68**	**mm**
	Torsional stiffness	> 450 Nm/deg	**332.06**	**Nm/deg**

Table 9: 003 structural results comparison with 002 configuration

4.4 Configuration 004

In this configuration I decided to keep the model studied in 003 and at the same time I changed the design of the door hinge arm (keeping the gooseneck shape), since the tubular structure has little contribution improvements in the structural strength of the overall door system. For that reason, looking carefully the movement of the door due to load applications in Hypermesh (an high torsion displacement around x-axis), it is necessary to reinforce the door hinge structure with two additional bars on the sides (increasing the thickness from 55 to 99 mm) and a linkage in the central position between the "elbow" with two reinforcements transversely (Figure 94). This hypothesis was done since I have seen that the door rotates excessively, and I had to think something that allows to reduce that movement.

Unlikely, the insertion of this hinge arm increases the overall mass of the system (total mass of the door assembly: 26.93 kg, which is 1.16 kg higher than 003 version), leading to a worse performance for what concerns the resistance to the gravity load application, getting far away from the target requirement of 2 mm of displacement in a closed position. A comparison between the previous hinge arm and the current configuration is shown in Figure 95 and Figure 96.

In order to let the mass be the smallest we have decided to choose an aluminium material for the gooseneck hinge arm, which it has strength values that can be compared with steel materials as well.

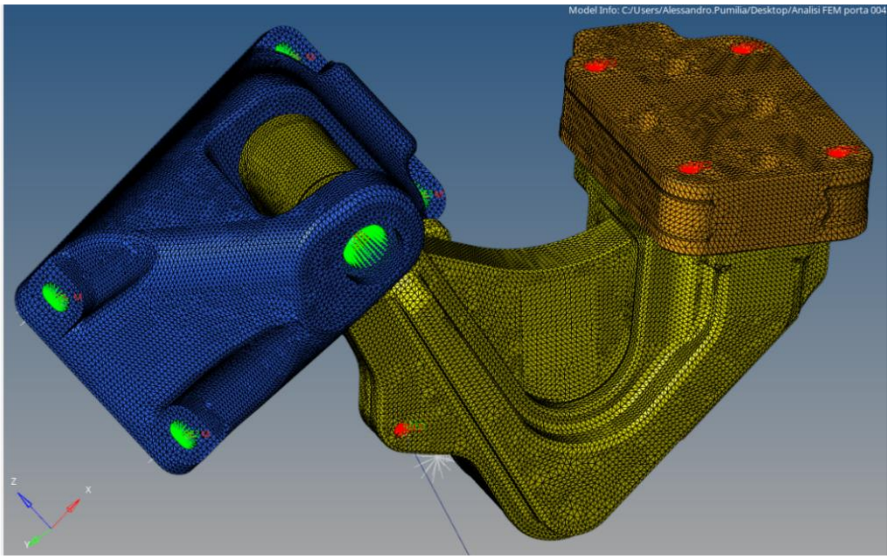


Figure 94: Door hinge arm modified (004)

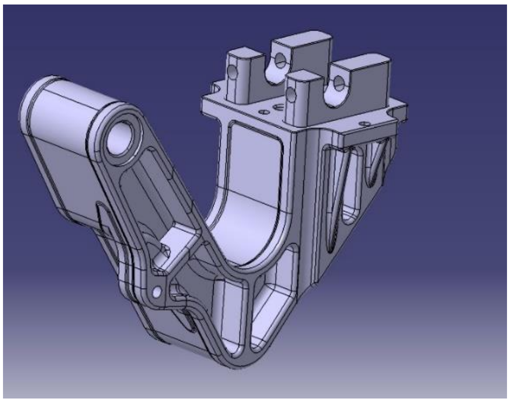


Figure 95: Baseline gooseneck hinge arm (001)

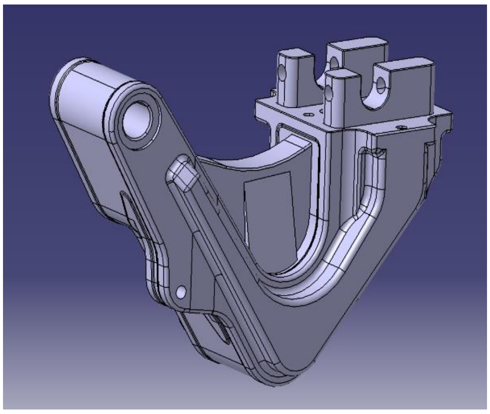


Figure 96: 004 configuration hinge arm

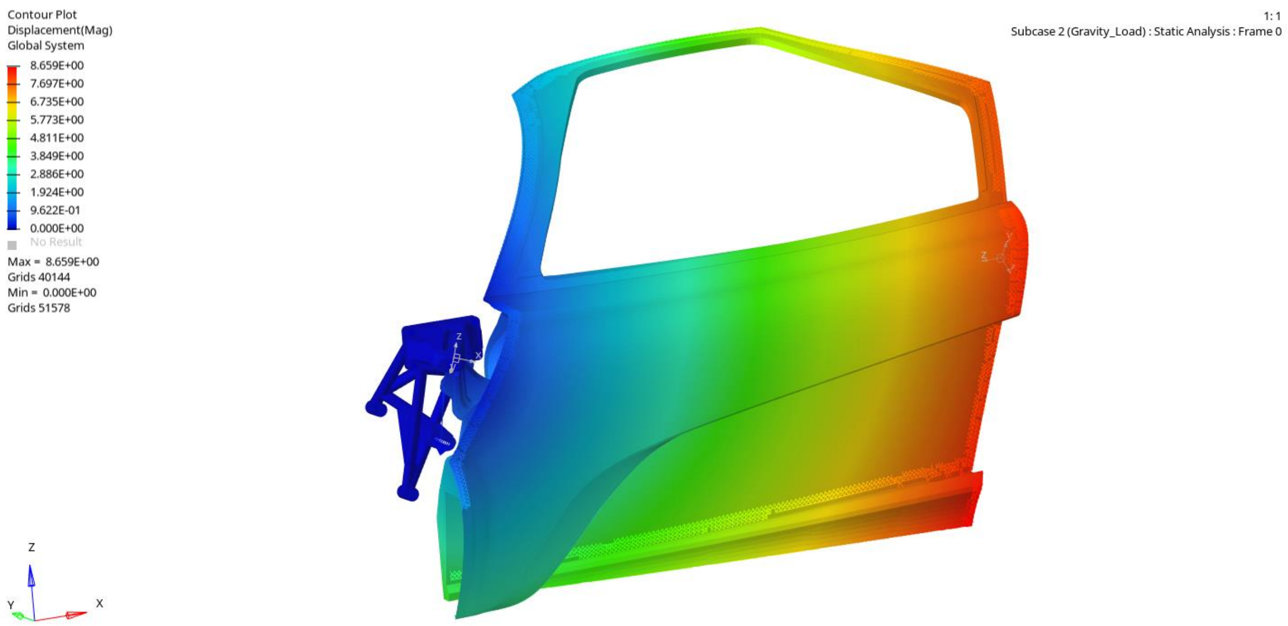


Figure 97: Displacements representation due to gravity load (004)

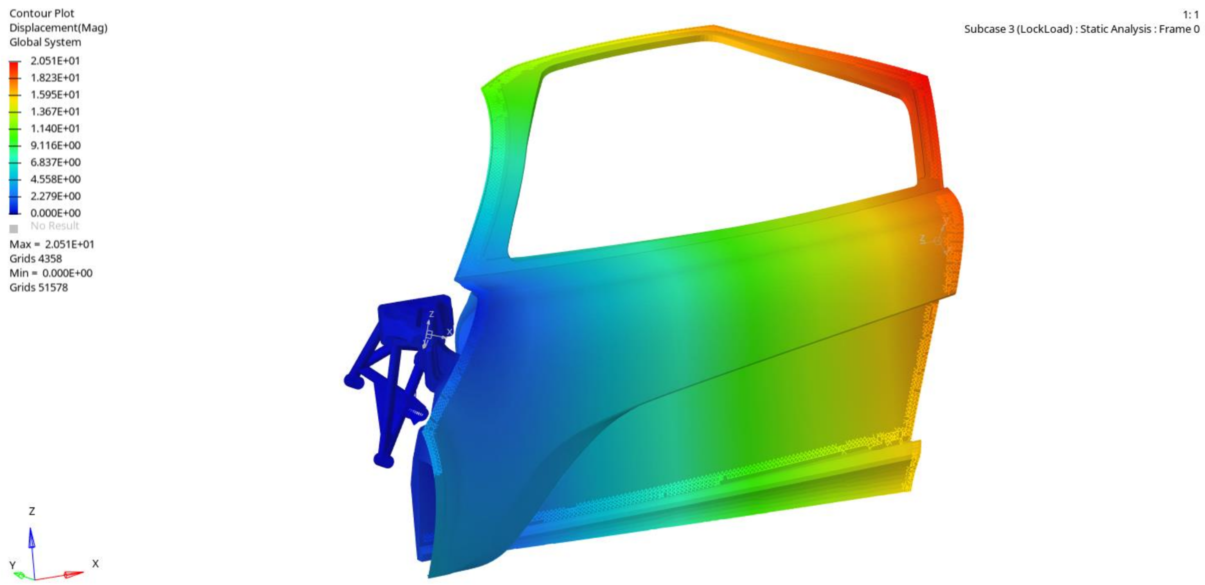


Figure 98: Displacements representation due to lock load (004)

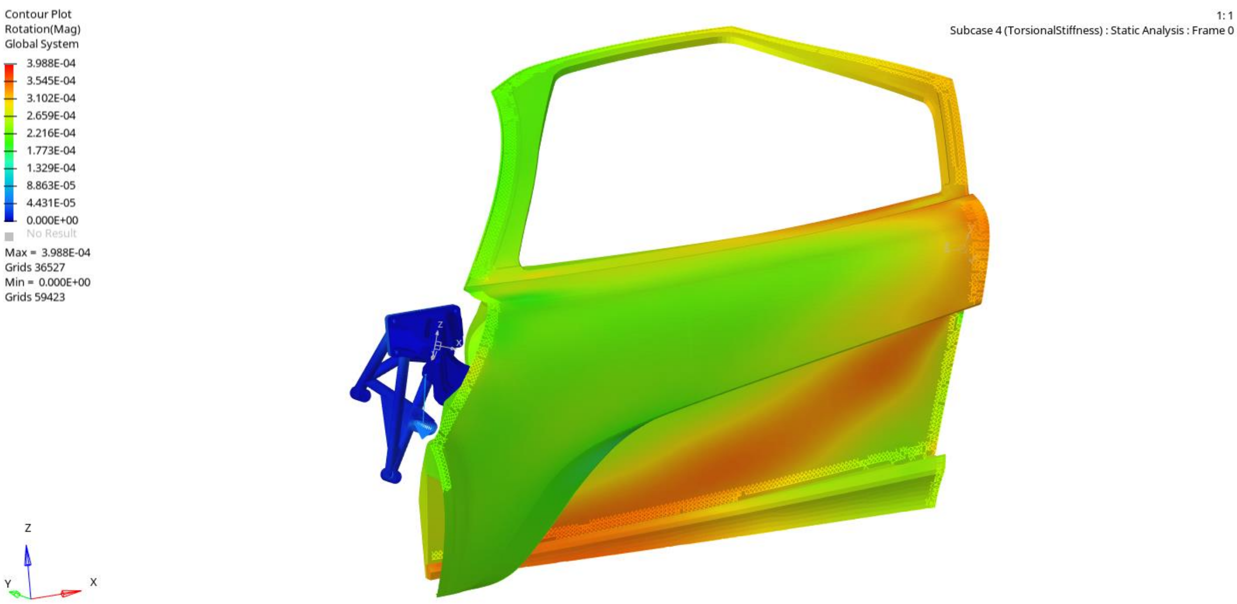


Figure 99: Rotation angles representation due to moment application (004)

Model	Loadcase	Target	Result	Unit
003: 002 + 2 connections	**Door total deformation in gravity**	< 2 mm	**6.6**	**mm**
	Door deformation when 385 N applied on door lock (Lockload)	< 20 mm	**46.68**	**mm**
	Torsional stiffness	> 450 Nm/deg	**332.06**	**Nm/deg**
004: 003 + modified gooseneck shape (aluminium)	**Door total deformation in gravity**	< 2 mm	**8.6**	**mm**
	Door deformation when 385 N applied on door lock (Lockload)	< 20 mm	**17.77**	**mm**
	Torsional stiffness	> 450 Nm/deg	**456.41**	**Nm/deg**

Table 10: 004 structural results comparison with 003 configuration

Hypermesh structural analyses results in terms of displacements and rotations (due to torsional torque) are presented in Figure 97, Figure 98 and Figure 99.

In *Table 10* I have compared the last two models: as it can be clearly seen we have a huge increase in the torsional stiffness of the system, reaching the required target of at least 450 Nm/deg when a torque of 10000 Nmm is applied on the door latch.For what concerns the other two loadcases, I have substantially reduced the displacement when a 385 N is applied on the door latch, passing from 46.68 mm to 17.77 mm, and finally reaching the door structural target of maximum 20 mm.

The only drawback of this model, as described above, is the increasing mass of the system (1.2 kg more than 003 configuration) that leads to a worse performance of the door total deformation in gravity, which reaches almost 9 mm (8.6 mm) which is more than 4 times the value to chase. Therefore, the system can be considered still satisfying from the structural and design point of view.

In order to underline the net improvement of the structural results of the 004 configuration with respect to the previous ones, we can evaluate the stress values around the hinge arm, as shown in Figure 100 and Figure 101. The switch from a narrower hinge arm to a thicker one leads to have a big increase in the static torsional stiffness, with the reduction of the stresses.

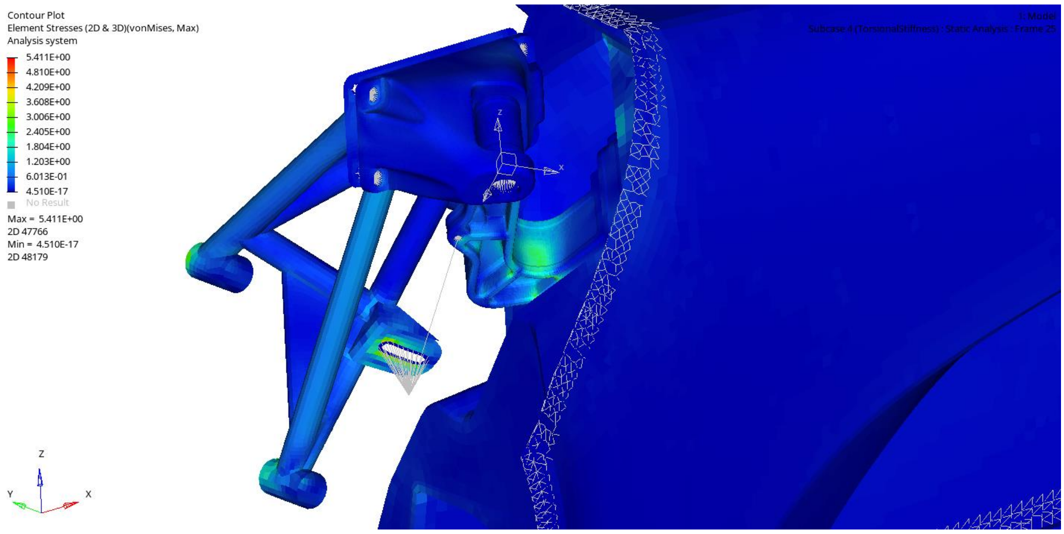


Figure 100: Stresses representation due to torsional load (003 configuration)

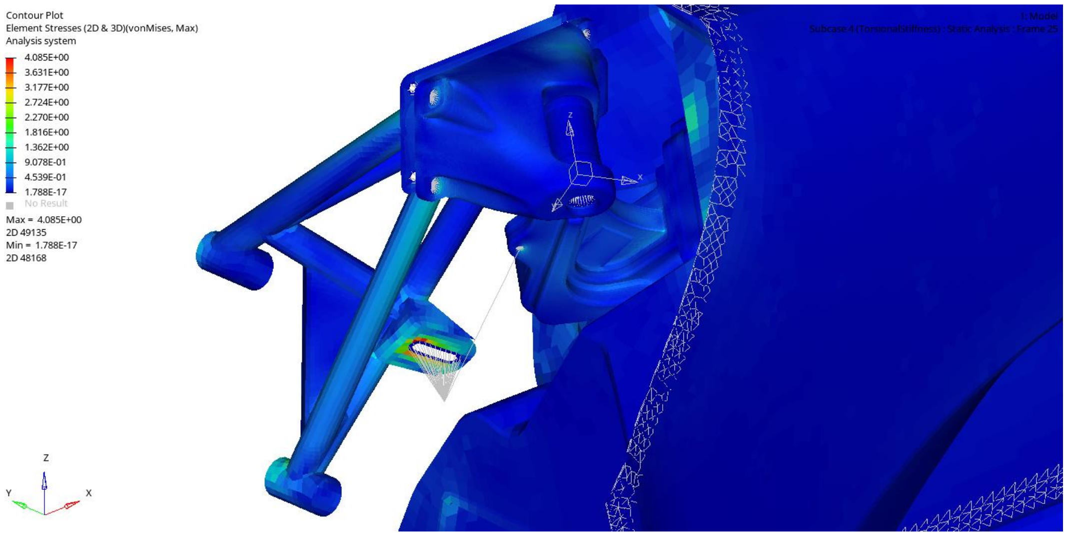


Figure 101: Stresses representation due to torsional load (004 configuration)

In Figure 100 there is the representation of the stresses distribution in the hinge area of the 003 version, as it can be evaluated we have a value of almost 4 MPa in that zone. While a lower value (1.4 MPa maximum) is computed in Figure 101, where the 004 configuration is analysed.

4.5 Configuration 005

This model is completely equal to the one just studied (004) with the modified gooseneck shape, with the only difference of a change in material. I decided to switch from aluminium to generic steel (Young Modulus: E = $2{,}1*10^5$ MPa), since it has a higher yield strength and could increase the stiffness of the system. The only problem is that having a component in steel material increases the overall mass of the assembly (5.4 kg more than 004 configuration), and therefore it could impact on the total deformation due to gravity load.

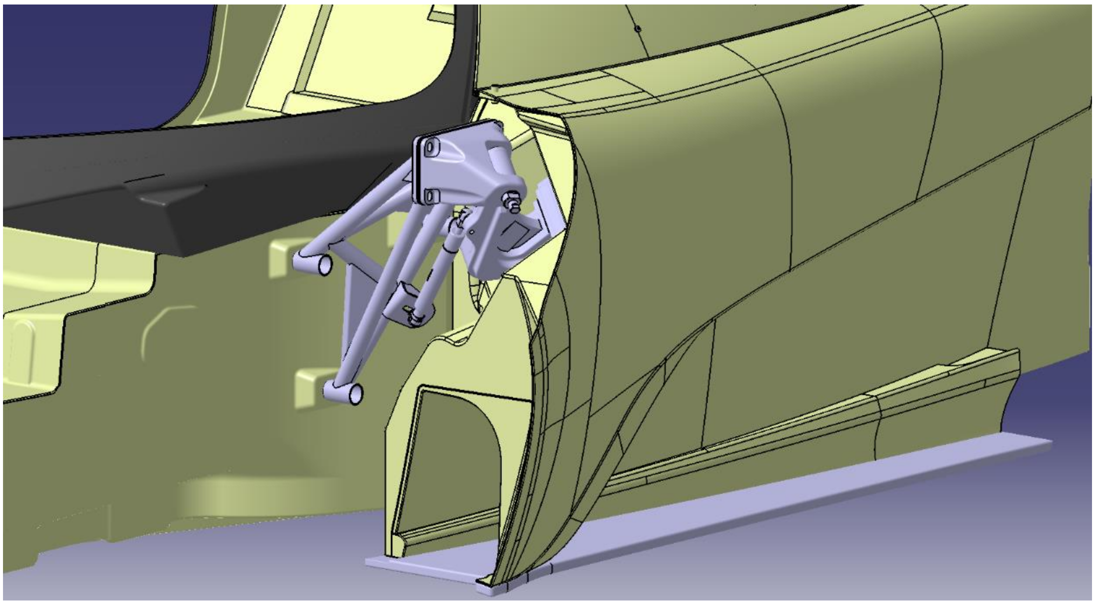


Figure 102: Door hinge assembly (Modified gooseneck) on Catia

As it can be seen on Figure 102, the new shape of the gooseneck hinge arm does not generate interferences with adjacent components.

Interferences can represent the worst-case during design phases, since whenever an already existing component is modified, adding new reinforcements or little inserts, it is necessary to keep in mind the volume occupied by the new shape not to obstruct the components.

Hypermesh structural analyses results in terms of displacements and rotations (due to torsional torque) will be presented in Figure 103, Figure 104 and Figure 105.

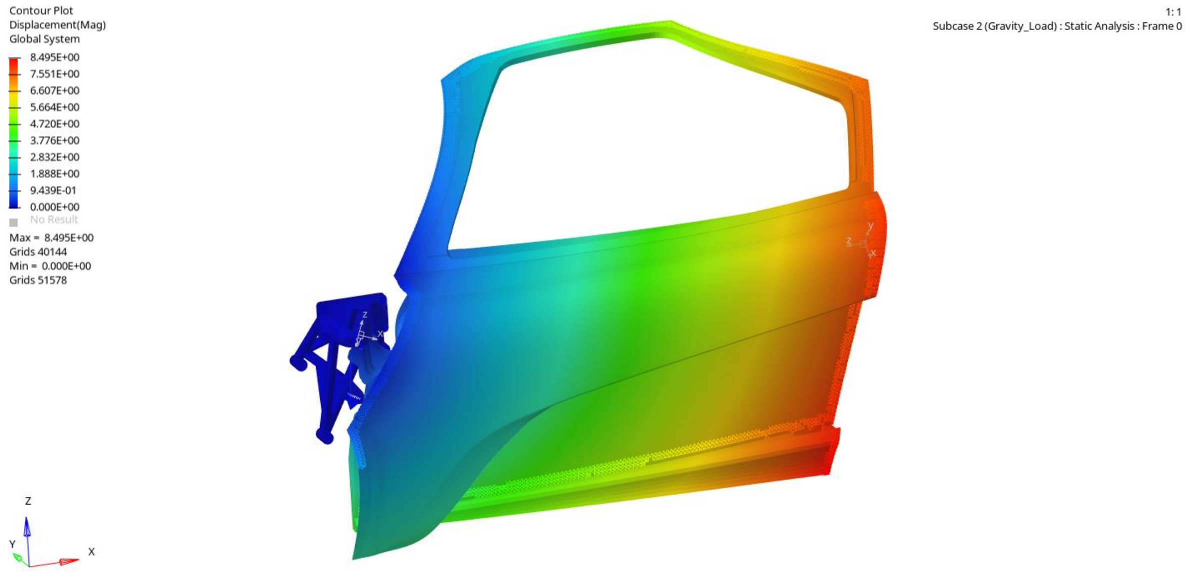


Figure 103: Displacements representation due to gravity load (005)

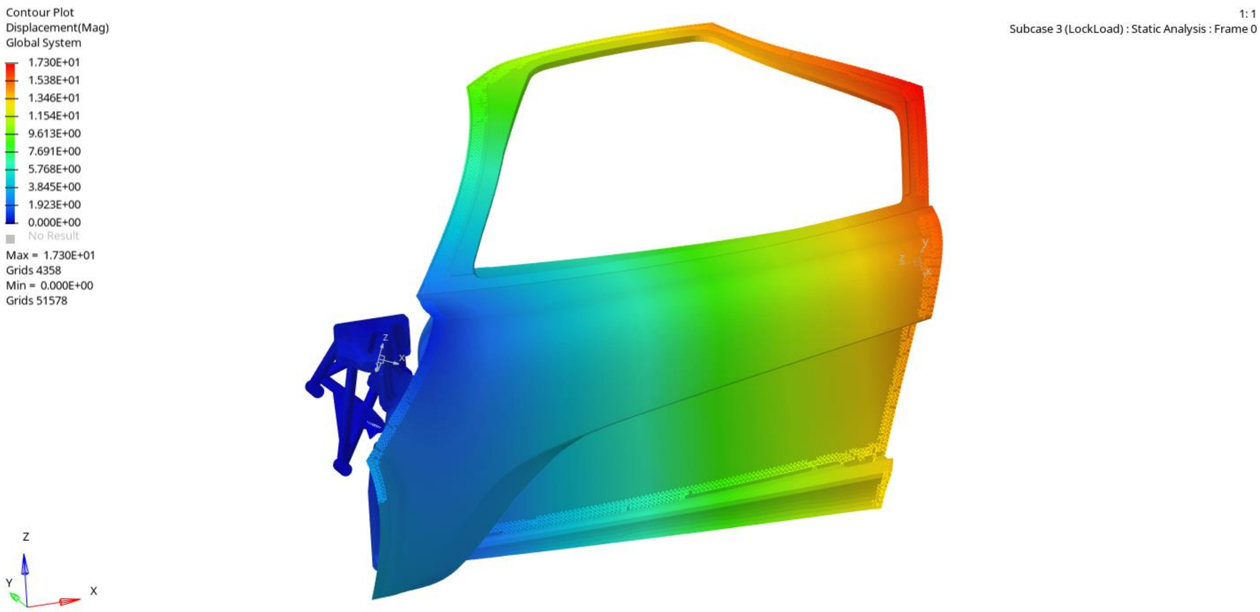


Figure 104: Displacements representation due to lock load (005)

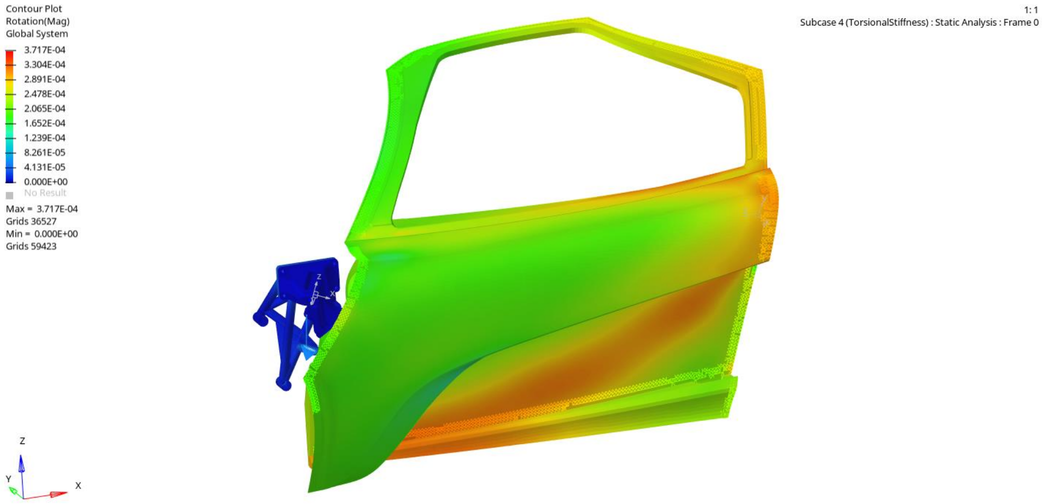


Figure 105: Rotation angles representation due to moment application (005)

Model	Loadcase	Target	Result	Unit
004: 003 + modified gooseneck shape (in aluminium)	**Door total deformation in gravity**	< 2 mm	**8.6**	**mm**
	Door deformation when 385 N applied on door lock (Lockload)	< 20 mm	**17.77**	**mm**
	Torsional stiffness	> 450 Nm/deg	**456.41**	**Nm/deg**
005: 003 + modified gooseneck shape (in steel)	**Door total deformation in gravity**	< 2 mm	**8.5**	**mm**
	Door deformation when 385 N applied on door lock (Lockload)	< 20 mm	**14.94**	**mm**
	Torsional stiffness	> 450 Nm/deg	**494.001**	**Nm/deg**

Table 11: 005 structural results comparison with 004 configuration

In the Table 11 we can see the improvement in each field of interest, with a huge increase in torsional stiffness, which is our main goal.

For what concerns the two deformations analyses, we can evaluate how the displacement due to lock load is clearly reduced, while on the other side that due to gravity is just 0.1 mm less with respect to the previous configuration.

The big problem is that the target of the door total deformation in gravity is not reached yet (< 2 mm) but the results are still satisfactory, therefore we can consider this model as the best among all the ones studies in terms of trade-offs between torsional stiffnesses and deformations.

The big problem in this case is the total mass of the component, due to its material properties (steel); therefore 004 configuration can be still considered as a better choice for production and weight purposes.

5. Definition of normative design proposal of side doors for Podium Advanced Technologies

The engineering design phase that we follow has a linear procedure, in order to define all the design steps that must be performed. The V model shape allows me and my colleagues to set the systems development lifecycle in an order way, by means of validations and verifications stages.

5.1 V-Model shape

The V-Model is a graphical representation of a systems development lifecycle (Figure 106), it is used to produce rigorous development lifecycle models and project management models. The V-Model is the model used by almost every engineering company (Podium Advanced Technologies included) in order to follow defined process steps, minimizing mistakes during the design and validation development of the project.
The V-model falls into three broad categories: the German V-Modell, a general testing model and the US government standard.

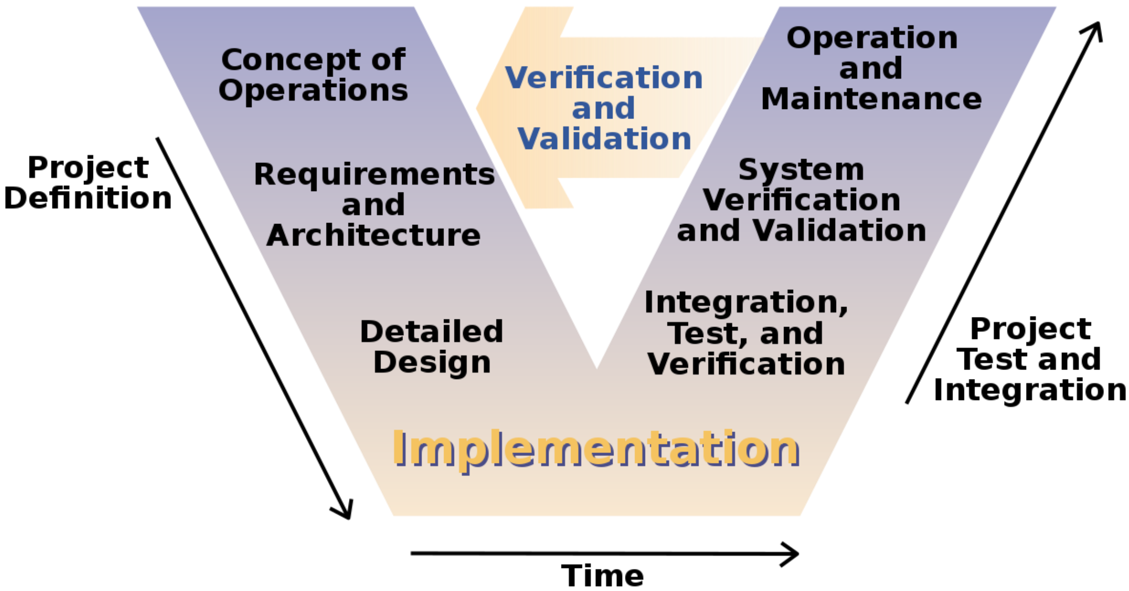


Figure 106: V-model shape scheme

The V-Model summarizes the main steps to be taken in conjunction with the corresponding deliverables within computerized system validation framework, or project life cycle development. It describes the activities to be performed and the results that have to be produced during product development.

- **Left side of the "V":** represents the decomposition of requirements and the creation of system specifications.
- **Right side of the "V":** represents integration of parts and their validation. The validation is done at first on each single component, during their development, and then on the total assembly (in this case on the whole vehicle, to perform physical testing).

However, requirements need to be validated first against the higher-level requirements or user needs. Furthermore, there is also something as validation of system models, such as FEM analysis (structural analysis), which can partially be done at the left side also. To claim that validation only occurs at the right side may not be correct, the easiest way is to say that verification is always against the requirements and validation always against the real world or the user needs.

Validation can be expressed by the query "Are you designing the right thing?" and *verification* by "Are you building it right?".
In engineering terms these two words can be described as follows:

- **Validation**: the assurance that a product, service, or system meets the need of the customer and other identified stakeholders by means of software and then physical testing. It often involves acceptance and suitability with external customers.
- **Verification**: the evaluation of whether a product, service, or system complies with a regulation, requirement, specification, or imposed condition. It is often an internal process.

The V-Model provides guidance for the planning and realization of projects. The following objectives are intended to be achieved by a project execution:

- <u>Minimization of project risks</u>: the V-Model permits an early recognition of planning deviations and risks and improves process management in order to reduce the project risk.
- <u>Improvement and guarantee of quality</u>: as a standardized process model, the V-Model ensures that the results to be provided are complete and have the desired quality. Defined interim results can be checked at an early stage.
- <u>Reduction of total cost over the entire project and system life cycle</u>: the effort for the development, production, operation, and maintenance of a system can be calculated, estimated and controlled in a transparent manner by applying a standardized process model.

Advantages:

1. It suits perfectly for restricted projects, due to the stringent nature of the V-Model and its linear design, implementation and testing phases. In situations where the project length and scope are well-defined, the technology is stable, and the documentation and design specifications are clear, the V-model can represent a perfect method.
2. It is ideal for time management, since this method is well-suited for projects that must maintain a strict deadline and meet key milestone dates throughout the process.

Disadvantages:

1. The most problematic aspect to the V-Model is its lack of adaptability to any necessary changes during the development life cycle.
2. The V-Model is completely linear and thus the project cannot be easily altered once the development is completed. The model is therefore poorly suited to handle long-term projects that may require many versions or constant updates.
3. It encourages the "design-by-committee" development since its nature tends to emphasize a development cycle befitting managers and users, rather than developers and designers. It can be all too easy for project managers or others to overlook the vast complexities of software development in favour of trying to meet deadlines based just on what stage in the life cycle is actively being developed.

5.2 Mission of the vehicle

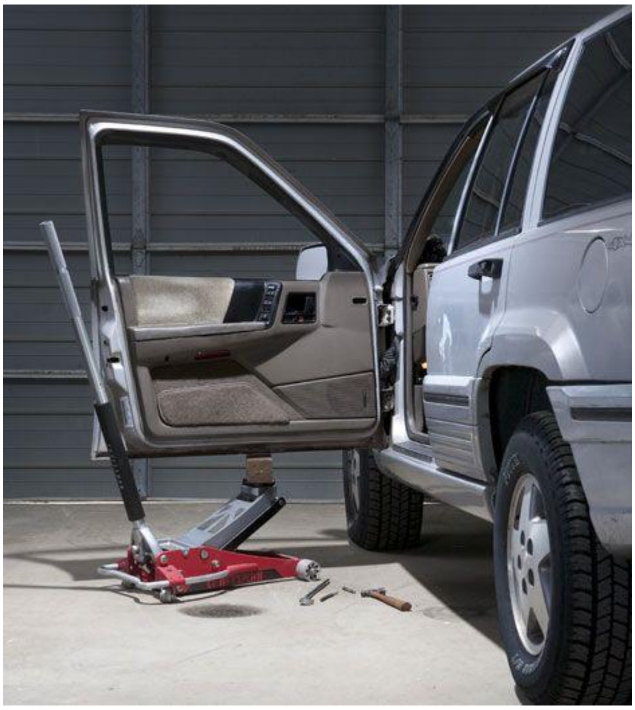
The design norms of the vehicle's side doors assemblies differ for each type of side doors: conventional hinged doors, sliding doors and not conventional hinged doors (scissors, butterfly, gullwing, canopy, etc…).

Therefore, it is necessary at the beginning of each design normative to define the type of door to which the regulations belong. Taking in considerations such sentences, I am going to create and define a new design norm of the side doors for the company Podium Advanced Technologies, considering each type of door and its specifics in terms of supported loads and sealings.

This differentiation was defined since it is important to underlined that usually conventional doors are mounted on mass production vehicles, while the unconventional types belongs to small series vehicles. For that reason the norms described below must underline the differences between the two types of vehicles: since on one hand mass production vehicles should be more resistant and durable (day life vehicles), while on the other side small series vehicles undergoes smaller kilometres annually, therefore they have different requirements.

It could happen as well that one-off vehicles mount conventional doors, therefore it is important at the beginning of the design phase to have in mind the target/mission of the vehicle, for instance about its lifecycle:

- **Mass production vehicles**: lifecycle of almost 240000 km.
- **Small series vehicles**: lifecycles of 60000-100000 km (we have to consider the effective use of the specific customer).



5.3 How to design a car door?

The design process of automotive doors is driven by several constraints and restrictions. Requirements concerning crashworthiness, ergonomics, tightness and others have to be fulfilled considering weight, costs, legislative regulations and quality. To achieve all these objectives in an efficient, time reduced development process, it is necessary to implement virtual engineering methods. The focus lies on the design of the hinge axis, which has a main impact on the door gap characteristics, and on the design requirements of the doors, such as sealings reactions and panel thicknesses. Furthermore, the opening and closing forces are affected by the orientation of the axis. Beside these boundary conditions, a collision between the body and the opening door has to be avoided under all circumstances. With the applied method these requirements can be fulfilled, and an optimised solution can be computed. The applied method is based on a CAD platform and combines structural simulations with parametric designs. This leads to a high level of flexibility and simple handling. Later on, the main design choices on the door system are defined in general (consideration about material have already been performed before), and only after each specific case will be taken into account (conventional doors or not).

5.3.1 Side doors hinges

For conventional doors the most common hinges for (almost) vertical axis side doors usually are made up of two half hinges, articulated using a cylindrical pin. The movable half hinge is screwed or welded to the door whereas the fixed half hinge is usually screwed or welded to a body side pillar. The cylindrical pin connecting both half hinges and leaving one freedom degree only, is kept in its seat by a removable screw.

Three types of conventional hinges are most used in current vehicles doors [2]:

a) **Type A:** Type A includes two steel forged half hinges (Figure 107): blade 1 is inserted in a slot inside the body side pillar, until the rectangular flange stays close to the body surface. The outer half hinge 2 can be screwed or welded to the door pillar reinforcement. As can be observed, the end 4 of half hinge 2 has a tooth shape in order to provide a stop to the complete door rotation that can damage the body panel.

Figure 107: Type A door hinges

b) **Type B:** Type B is always drawn from steel sheet; it is welded to the door and screwed to the body side outer, to which is matched. Door to body alignment is performed, in this case, by a chosen number of selected spacers positioned between half hinge 1 and the body side before screwing (Figure 108).

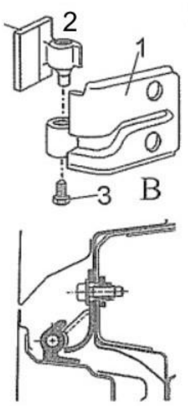


Figure 108: Type B door hinges

c) **Type C:** Type C is made of extruded aluminium or steel profile, screwed to door and to body side; even in this case, alignment between door and body side is fixed by insertion of spacers between the fixed hinge and body side (Figure 109).

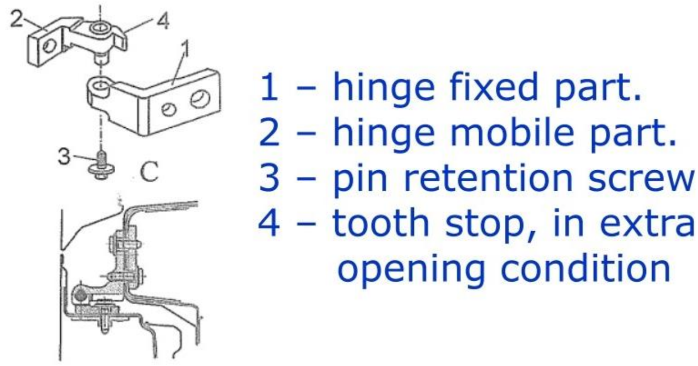


Figure 109: Type C door hinges

Other hinge configurations are on the market with similar technology and behaviour, although the shapes can be different. A hinge family, that is distinguished by its specific features, is that which includes an elastic door brake device (Figure 110).

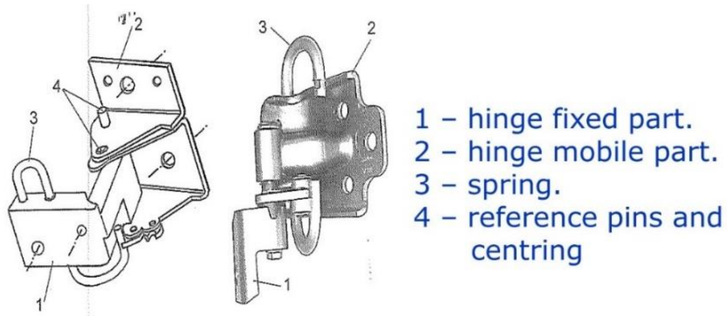


Figure 110: Hinge with elastic brake device

Unconventional door hinges have different shapes in order to allow performing not simple rotations, for that reason they do not have a specific normative to follow (as we have seen in the case of the SCG 004S the hinge arm is not conventional, therefore it can cover any shape). The most common unconventional hinge is that of Lamborghini (Figure 111), that allows a small side rotation followed by at least 90° rotation upwards; and they have a gooseneck shape [8].

Figure 111: Lamborghini side door hinges

5.3.2 Door brakes

Apart from brakes integrated into the door hinges, independent brakes are also in production, usually located between the hinges. The main advantage of such independent brakes is a better sharing of stop stresses between the different devices connecting the door and the body side. Of course, the disadvantage is a higher overall cost.
Two types of door brakes are mostly adopted on current vehicles doors [2]:

a) **Type A:** Type A uses a shaped plate rod sliding between two plastic rollers, one of them being pushed by a spring pivoted on a cage screwed to the door while the other slides over an uneven profile. In this type of door brake, the end position is determined by the contact of the roller with the hook shaped link (Figure 112).

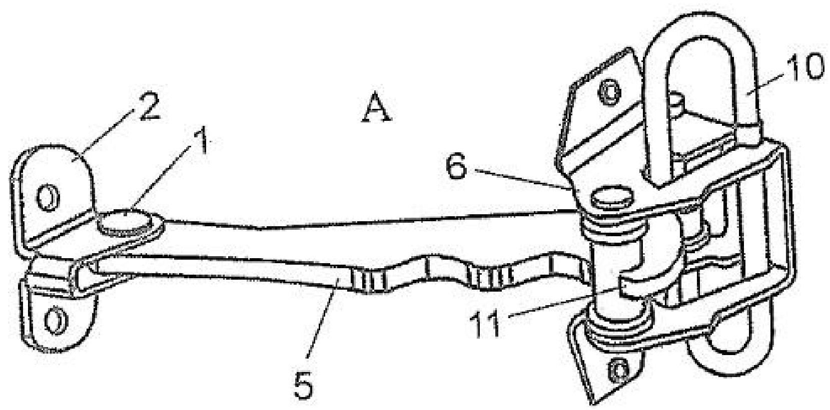


Figure 112: Type A door brakes

b) **Type B:** In type B, the link has a shaped thickness and slides between two plastic rollers, pressed against the link by two elastomeric devices, inserted in a cage screwed to the door. In type B the end position is determined by the end bumper contact with the cage (Figure 113).

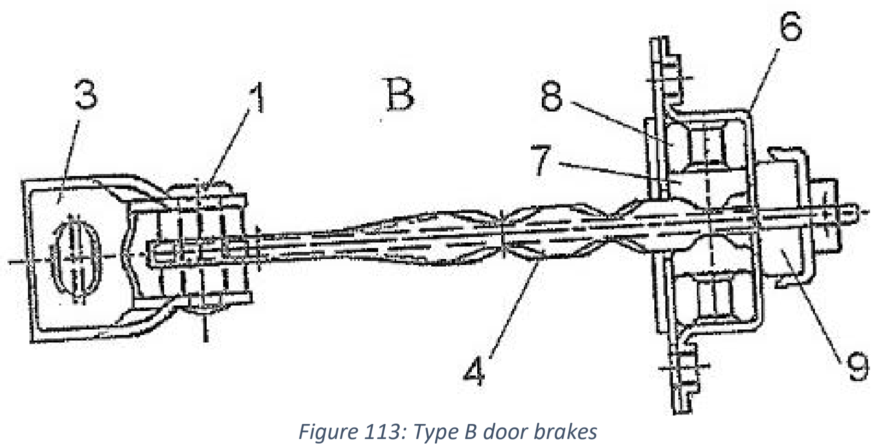


Figure 113: Type B door brakes

5.3.3 Distances between the hinges

In order to design a stiff door for the vehicles, it is useful to locate the upper and lower hinges on predefined distances among them, on conventional side doors (Figure 114). Conventional doors have always 2 hinges, one upper and one lower; while unconventional hinges have usually just one hinge per door in order to have a better functionality and stylish look (but a worse structural strength).

- Distance between the 2 hinges (upper and lower): > 350 mm.
- Distance between hinges and the flange/doorsill: < 150 mm.
- The door brake is placed above the middle between the 2 hinges.

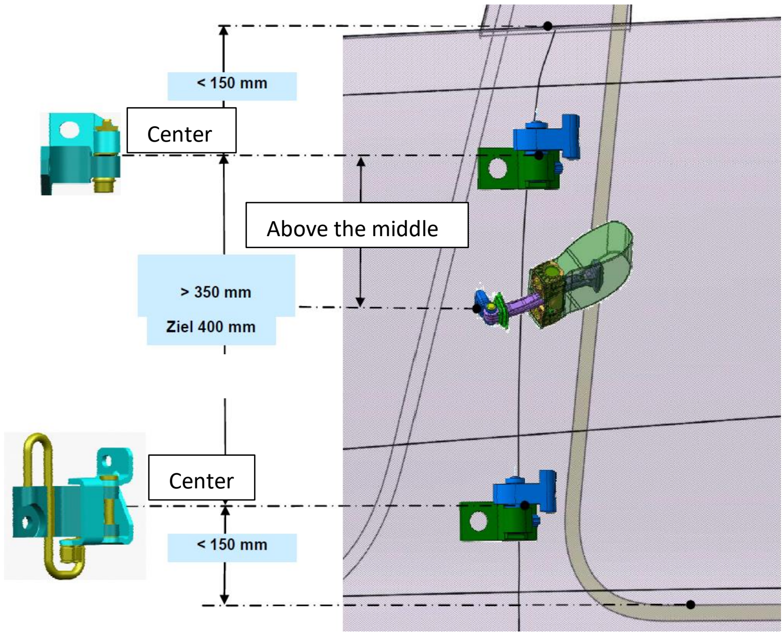


Figure 114: Door hinges distances (upper and lower)

5.3.4 Hinge axis inclination

The centerline shall be selected in such a way as to provide an appropriate entrance and exit, a lift of the door and must support the closure efforts. When the door is closed, the lower edge of the door must not rise more than 25 mm and less than 0 mm. The slope of the hinge causes the center of gravity to drop when the door is closed. The optimal slope is between 1.5° and 4° (forward and inward of the car): it is preferred to adopt a range between 1° and 3° inwards (α), and between 1.5° and 2.5° forward (β).

The setting of the hinge axis is a consequence of hinge positioning, close to outer door surface, and of door perimeter cutting so as to allow complete door rotation without any interference with adjacent components. The main constraints affecting that setting, in addition to style model, are the allowable spans between hinges and the self-closing criterion selected.

Self-closing criterion: if the hinge axis is perfectly vertical, when opening the door of a climbing car the door tends to close whilst, while in a descending car it tends to complete opening. Instead, if the hinge axis is sloped, a self-closing effect can be increased or reduced, of course with an opposite effect on self-opening.

Being β the forward angle, it can be computed in degrees by means of the setting of the hinges positions with this equation:

$$\beta = \arctan\frac{X_1 - X_2}{Z_1 - Z_2} * \frac{360}{2\pi}$$

Where X_1 and Z_1 are the longitudinal and vertical coordinates of the upper hinge, while X_2 and Z_2 are the longitudinal and vertical coordinates of the lower hinge.
Being α the inward angle, it can be computed in degrees as well by means of the setting of the hinges positions:

$$\alpha = \arctan\frac{Y_1 - Y_2}{Z_1 - Z_2} * \frac{360}{2\pi}$$

Where Y_1 and Z_1 are the lateral and vertical coordinates of the upper hinge, while Y_2 and Z_2 are the lateral and vertical coordinates of the lower hinge.

In order to evaluate the self-closing effort, in terms of energy consumed [8], we have to take in consideration the total force applied during the closing action due to the hinge inclination, and the distance travelled where the force is applied (outer door handle location).

The total self-closing force due to hinge axis inclination, when the door is opened, is given by the sum of 3 contributes:

$$F_t = F_{hf} + F_f + F_i$$

Where F_{hf} is the hinge friction force, F_f is the force due to forward inclination of the hinge axis and F_i is the force due to inward hinge axis. All of these loads can be evaluated as it follows:

$$F_{hf} = \frac{T_{sd}}{d} * 2$$

Where d is the distance from outer handle from the hinge, and T_{sd} is the static to dynamic frictional torque on each hinge (that is 80% of the hinge torque, which is specified during design stage).

$$F_f = \frac{L_g}{L_d} mg * sin\,\theta * \sin(180° + \beta)$$

$$F_i = \frac{L_g}{L_d} mg * sin\,\theta * \sin(180° + \alpha)$$

Where ϑ is the door opening angle, while α and β are the inward and forward hinge axis inclination angles respectively. L_g is the distance from the door center of gravity to the hinge axis, and L_d is the distance from center of gravity to outer door handle.

Finally, we can compute the energy due to self-closing force, which is given by the following equation:

$$E_{scf} = F_t * l$$

Where l is the distance travelled by the door at outer door handle location.

If E_{scf} has a negative sign, it indicates that the behavior of the door is self-closing, while the positive sign indicates that the door needs additional energy for closing.

5.3.5 Door frame pre-load

The deflection of the door frame must not exceed **2 mm** due to the reactions of the seals with the door (weatherstrips and door in nominal positions).

The door frame is designed to compensate for this deflection by moving the frame of this amount inwards, so that it is in a nominal frame position when received by the customer. This inward movement is determined by CAE analysis. If the deviation evaluated exceeds 2 mm, the stiffness of the door frame should be increased, while the seal forces reduced.

5.3.6 Outside door corner radius

A minimum radius of 10 mm should be guaranteed on the lower corners of the doors, for what concerns the outside surfaces, as it is illustrated in Figure 115.

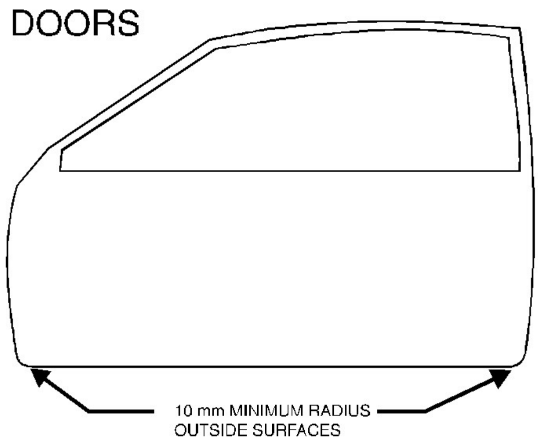


Figure 115: Outside doors corner radius

5.3.7 Clearances to prevent seal damage

Sheet metal, interior trim, exterior trim, hardware, and electrical components must not unintentionally wipe or rub against the weatherstrips during the opening-closing operation under all build variations. The following clearances are recommended:

- ***Lock striker*** > 9.0 mm.
- ***Front fender*** > 3.5 mm.
- ***All other components*** > 8.0 mm

These requirements are intended to prevent weatherstrips tearing, abrasion or other damage along their positions (Figure 116); and at the same time, they do not prohibit intentional sealing contact and the required clearances should be based on a program specific tolerance study.

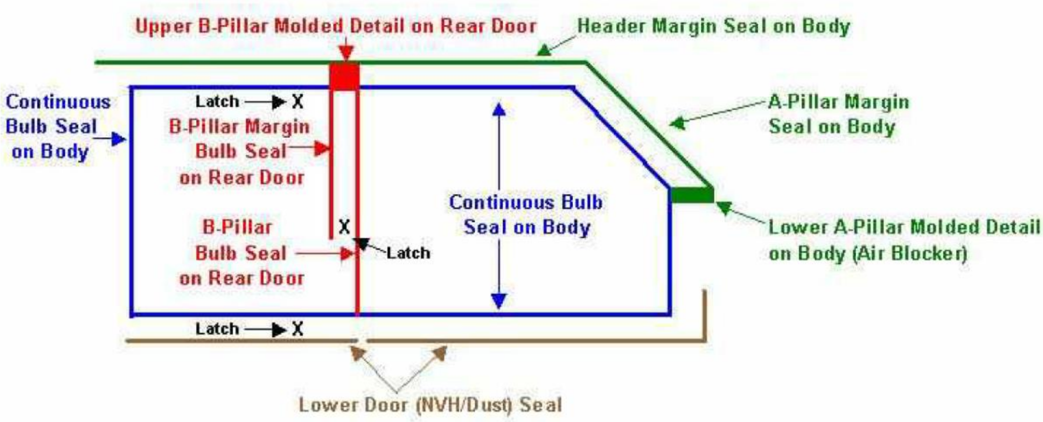


Figure 116: Sealings positions and their clearances

5.3.8 Outer panel thickness

In order to prevent adhesive induced bond read-through it is recommended that thickness of the outer panel in composite material (which are the body panels that are visible to the customer: Class "A" surfaces) should be design at a minimum of 3.0 mm in all bonded areas (Figure 117).

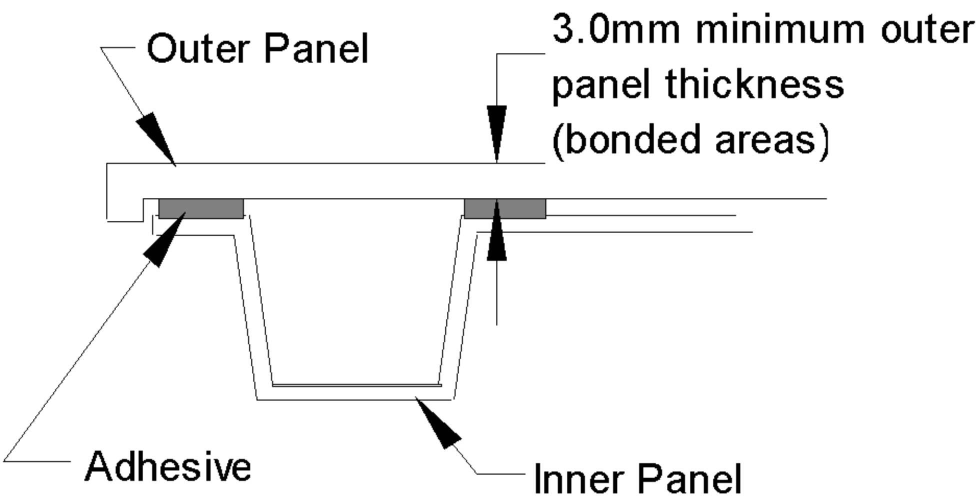


Figure 117: Outer panel thickness section

5.3.9 Hinge free play variability

Free play is a measure of the vertical and radical free play in the hinge assembly. The vertical free play may be measured by holding the body half of the hinge fixed, and moving the door half completely to one side along the pin axis and measuring the gap between the body half and the door half. Radial free play may be measured in a similar way except that the movement of the hinge halves would be normal to the pin axis.

The target of this design phase is to minimize the variability in the door setting due to free play in hinges (vertical or pin to bushings) as it is shown in Figure 118.

- *Maximum vertical free play*: 0.5 mm.
- *Maximum radial free play*: 0.1 mm.

Hinge bushings which are coated with Teflon are tolerant of interference and may help reduce or eliminate free play in the hinges. Where free play in the hinges exists, the hinge to door and door to body mounting fixtures shall means to account/compensate for the free play.

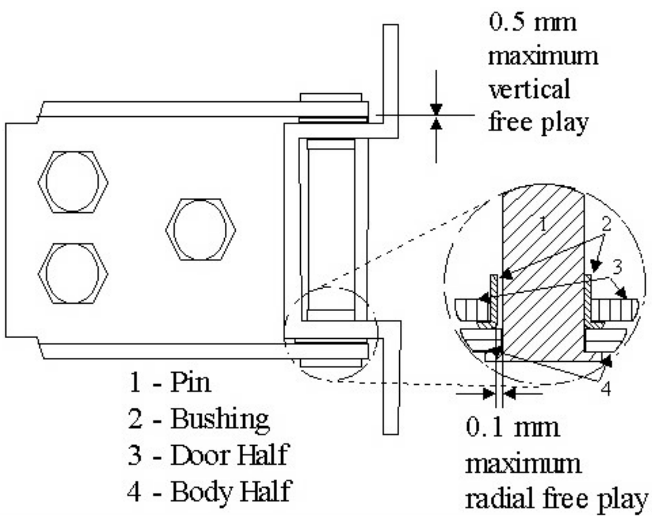


Figure 118: Hinge free play variability

5.3.10 Sliding doors design

Sliding doors have nearly rectilinear rails, in which trolleys with one or more rollers slide. The rails can be on the roof or sills or on the body side or on the door. In order to establish a statically determined overall constraint condition, three connecting, non-aligned devices should be designed which can be located on three or two independent rails (three rails at different heights: low/sill, middle/belt line and up/roof).

Usually a car body side has very different curvatures at different heights: for that reason only two rails are frequently used, one at the belt line level and one at the sill level. The third trolley is located inside one of the two rails, in such a position so as to avoid door rotation around the axis determined by other two trolleys.

Some factors in favour of the upper rail vertical reaction:

1) Lower mud risk.
2) Easier alignment of the door with upper body side.
3) Lower distance between the upper trolley and the door, therefore lower stress on the body and door frames.
4) Lower crush risk in the case of side impact.
5) Lower risk of trolley wedging.

The main advantage of vertical reaction on the lower rail relates to the higher strength and stiffness of rocker panel, compared with the roof frame.

Regarding two comparison with three rails, it can be seen that the horizontal reactions are much higher in the case of two rails, due to the lower lever distance. For instance, in the case of two rails, the horizontal reaction is inversely proportional to the distance between the rails. Trolleys have one horizontal roller when they provide a horizontal constraint, while two horizontal rollers are required to control the direction of the vertical reaction roller.

In Figure 119 it is shown a schematic example of the location of door attitude control devices which are used to drive a precise latch matching at closing run end and support the door, while reducing the load on the trolleys. In the transverse direction, some rubber pads are located for vibration damping.

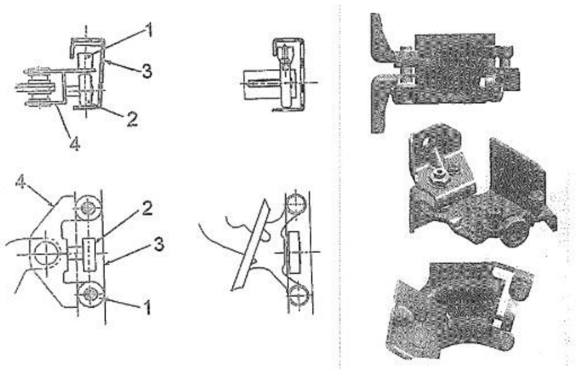


Figure 119: Sliding door control devices mechanism

It is important to note that side sliding doors never feature self-closing while the vehicle is stationary on up to a 20° slope: this legal requirement can cause a closing start-up force between 120 and 180 N, depending on the door mass and device type.

Even the door slam testing speed on a horizontal road is specified: the maximum allowed value is < 1 m/s, while the recommended value is about 0.5 m/s. Moreover, if the door is opened on a slope, it must engage a brake, capable of absorbing the whole kinetic energy of the door, without permanent yield of frames and rubber dampers.

5.4 Door performances to be fulfilled

Many requirements have to be satisfied at the end of the design stage for automotive doors. In this chapter of the thesis I have focused mainly on creating a design normative to be followed by the Podium company whenever a door structure will be studied. For that reason, I divided the normative in three main design areas:

1. Conventional hinged doors.
2. Sliding doors.
3. Not conventional hinged doors.

Sliding doors are unconventional doors considered separated from the other two solutions since they are characterised by rails and trolleys, and not hinge. Therefore, they should be differentiated for what concerns the performances to achieve during the design stages.

5.4.1 Conventional hinged doors

The main performances and design choices to fulfil and to follow during the project phases of conventional doors are:

- *Door system durability*
- *Side door performance in complete vehicle durability*
- *Door total deformation in gravity*
- *Door frame lateral strength*
- *Door torsional rigidity*
- *Door frame deflections due to seal forces*
- *4 post shaker simulation*
- *Side door slam-open durability*
- *Door opening/closing sound*
- *General requirements for side doors safety*
- *Door opening and closure effort*
- *Door rotational inertia*
- *Commodity retention – dynamic event*
- *Hinge axis inclination – hinge centerline*
- *Ease of ingress/egress*
- *Extraction of air*
- *Door hinge strength requirements*
- *Door check efforts*
- *Dynamic sealing*
- *Clearance to prevent seal damage*
- *Water protection*
- *Side door corrosion resistance*
- *Paint protection from door slam damage*

After having made a list, I will analyse in detail each specific requirement to fulfil during or at the end of the design processes.
Obviously, whenever it is not possible to achieve all the specifics underlined, a trade-off between them is necessary to be done, in order to have a reliable and stiff structure to deliver to the customer.

- ***Door system durability***

  The door system must have a life cycle that differs from what type of vehicle is taken into consideration: mass production vehicles or one-off/small series vehicles.

  - *Mass production vehicles*: at least 10 years/240000 km for 90% of the customers.
  - *Small series vehicles*: 10 years/60000-100000 km (the real usage is attributed to each specific customer).

  These considerations are demonstrated by going to carry out the key life test of the door. The key life test is an accelerated life design test to detect the door component failure mode, involving repeated 6 d.o.f. vibration and rapid temperature changes.

  Once the test is completed, the door must still pass the fit and finish requirements, the opening effort requirement, the closing effort requirement, the squeak and rattle requirement and the door closing sound quality requirement.

  Comments:
  This is the ultimate test for the door assembly as it considers all interactions in the system. However, it has negative aspects, such as cost and duration, which are not always low.

- ***Side door performance in complete vehicle durability***

  The door system must withstand the full durability test (84,000 opening/closing cycles) without having structural damage or loss of door-related functions.

  Once the test is completed, the door must still pass the fit and finish requirements, the opening effort requirement, the closing effort requirement, the squeak and rattle requirement and the door closing sound quality requirement.

- ***Door total deformation in gravity***

  The door is installed on the body in a closed position supported by the inner panel along the center of gravity. When the door is released (in closing conditions), it must not fall more than 1 mm below its weight (the additional weight of the hardware/trim must result in a deviation of no more than 1 mm total → **total deformation in gravity: 2 mm**).

- ***Door frame lateral strength***

The door frame strength is evaluated considering 3 main cases:

- **Doors with frame**: the maximum deviation of the door frame must not exceed 3 mm under a load of 180 N along the middle of the door belt opening (as shown in Figure 120).
  Permanent deformations must not exceed 1.5 mm under a load of 360 N.

- **Frameless doors**: The opening of the door belt should not deflect for more than 3 mm with a compression or expansion force of 180 N applied along the middle of the door belt opening. Permanent deformations must not exceed 0.5 mm under a load of 360 N.

- **Door with window frame and single-arm or lift-arm windows regulators**: The opening of the belt line should not deflect for more than 5 mm with a compression or extension force of 180 N applied along the middle of the door belt opening.

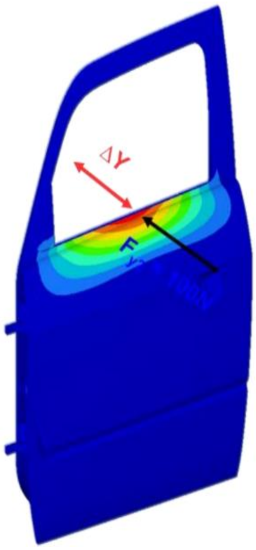


Figure 120: General door loadcases application

These tests must be carried out on a fully trimmed door mounted on the vehicle, including all seals and overslam bumpers (Figure 121) . On the front framed doors, the load is initially applied on top of the B pillar, then on top of the A pillar (which corresponds to the upper corner of the windshield). Then on the rear framed doors, the load is applied first on top of the B pillar and then on top of the C pillar (which corresponds to the upper corner of the rear light).

Figure 121:Overslam bumpers

If a load of 385 N is applied to the door lock, along the direction parallel to the hinge axis, the maximum displacement on that point must be:

- < 10 mm if the door is in *an open position.*
- < 10 mm if the door is in *a closed position*.

- ***Door torsional rigidity***

  A torque of 275 Nm must be supported by the door without deflecting for more than 4 mm at the top of the belt line and the lower corner of the latch side of the door.

  The door system must have a torsional stiffness of at least 600 Nm/deg when a torque (around x-axis) of 10000 Nmm is applied on the door latch.

- ***Door frame deflection due to seal forces***

  The deviation of the **door frame** must not exceed **2 mm** due to the reactions of the seals with the door (weatherstrips and door in nominal positions).

  The door frame is designed to compensate for this deflection by moving the frame of this amount inwards, so that it is in a nominal frame position when received by the customer. This inward movement is determined by CAE analysis. If the deviation evaluated exceeds 2 mm, the stiffness of the door frame should be increased, while the seal forces reduced.

- ***4 post shaker simulation***

  The door system must withstand a 4 post-shaker/vibrations simulation (just for conventional or sliding doors) of the complete vehicle, without loss of its functions or exterior appearance. The 4 post shaker test consists of four servo hydraulic actuators which are coordinated to simulate the motion of the vehicle on the ground.

  Once the test is completed, the door must still pass the fit and finish requirements, the opening effort requirement, the closing effort requirement, the squeak and rattle requirement and the door closing sound quality requirement.

- ***Side door slam-open durability***

  No failure should be provided structurally or functionally during the door's strong opening and closing cycles:

  1. Conventional front and rear side doors: 84000 slam open cycles when the door is fully opened.
  2. Access panels without an intermediate hardstop: 42000 slam open cycles when the door is fully opened.
  3. Access panels with an intermediate hardstop: 42000 slam open cycles against door brake and 21000 open slam cycles when the door is fully opened (access panels are equivalent to 40% of the doors).

  The door must be tested in completely trimmed conditions with all the interiors, hardware components, windows regulators, weatherstrips, mirrors, ornaments, etc. fully installed. The front doors of vehicles with access panels must be tested with and without the access panel option.

  Once the test is completed, the door must still pass the fit and finish requirements, the opening effort requirement, the closing effort requirement, the squeak and rattle requirement.

- ***Door opening/closing sound***

The closing and opening of the door must not produce any noise, including, but not limited to chirps, clicks and rattles.

➢ *Non-luxury vehicles:*

The closing sound of the door on a fully assembled car should not exceed a loudness peak of 40 sones, and an intensity that should not exceed 3.5 acum when tested at the minimum closing speed (the value of 1 acum is attributed to a narrow-band noise at 1 kHz).

Noise must not exceed a maximum of 48 sones and the intensity should not exceed 4 acum at 1.3 times the minimum closing speed.

➢ *Luxury vehicles:*

The closing sound of the door on a fully assembled car should not exceed a loudness peak of 35 sones, and an intensity that should not exceed 3.3 acum when tested at the minimum closing speed.

Noise should not exceed 42 sones and the intensity should not exceed 3.8 acum at 1.3 times the minimum closing speed.

➢ *All vehicles:*

The closing noise of the doors must be evaluated subjectively with all the option levels, with the windows in various positions, with energetic closures at 25 J in order to check special causes: slam of the side windows, contacts between components, etc...

NB: the value of 1 sone corresponds to 28 dB, while 8 sones corresponds to 58 dB.

- ***General requirements for side door safety***

All side door systems (conventional hinges, suicide, sliding doors, butterfly doors) must comply with safety requirements.
Rules related to the structure of the door include:

➢ Door locking and maintenance.
➢ External projections.
➢ Internal fittings.
➢ Flammability (for seals and composite door structures).
➢ General Requirements for Structural Integrity - Impacts.
➢ Side impact of side door strength.
➢ Frontal impact.
➢ Passenger protection at impacts.
➢ Post-opening impact of door.
➢ Forward Visibility.

- ***Door opening and closure effort***

  - The door **dynamic *closing*** effort must not exceed the 8 J of energy that corresponds to a spring force of 86.7 N, tested on a fully trimmed door of a vehicle in environmental conditions.
    The closing effort must not exceed a maximum of 12 J of energy (or 104.5 N of spring strength) at a temperature of -29 °C.

  - ***Opening*** the door (measured on the centerline of the inner handle):
    a) Maximum effort of 22 N if the weight of the door: ≤ 30 kg.
    b) Maximum effort of 36 N if the weight of the door: > 30 kg.

Maximum opening angle of the door: 80° - 90° maximum.

No oscillations/shakes should be guaranteed during the opening action of the door.

- ***Door rotational inertia***

The polar moment of inertia of the door around its hinge axis must not exceed 35 kgm^2, otherwise the customer may perceive the door as too complex to move.

Note: This value can be reduced by making the door lighter or by moving heavier components near the hinge axis.

- ***Commodity retention – dynamic event***

The structure of the vehicle to which the doors, seats, seatbelts and spare wheels are attached must retain these elements in case the vehicle is subjected to a frontal barrier impact test at 56 km/h.

A deformation is allowed in the structure of the vehicle, while cuts and separations are not allowed.

The side door must remain restrained by its hinges and attachments and must remain closed and tight during the fixed barrier collision at 48 km/h.

- ***Hinge axis inclination – hinge centerline***

  The centerline shall be selected in such a way as to provide an appropriate entrance and exit, a lift of the door and must support the closure efforts. When the door is closed, the lower edge of the door must not rise more than 25 mm and less than 0 mm. The slope of the hinge causes the center of gravity to drop when the door is closed. The optimal slope is between 1.5° and 4° (forward and inward of the car): it is preferred to adopt an α angle range between 1° and 3° inwards (Figure 122), and between 1.5° and 2.5° forward (angle β, Figure 123).

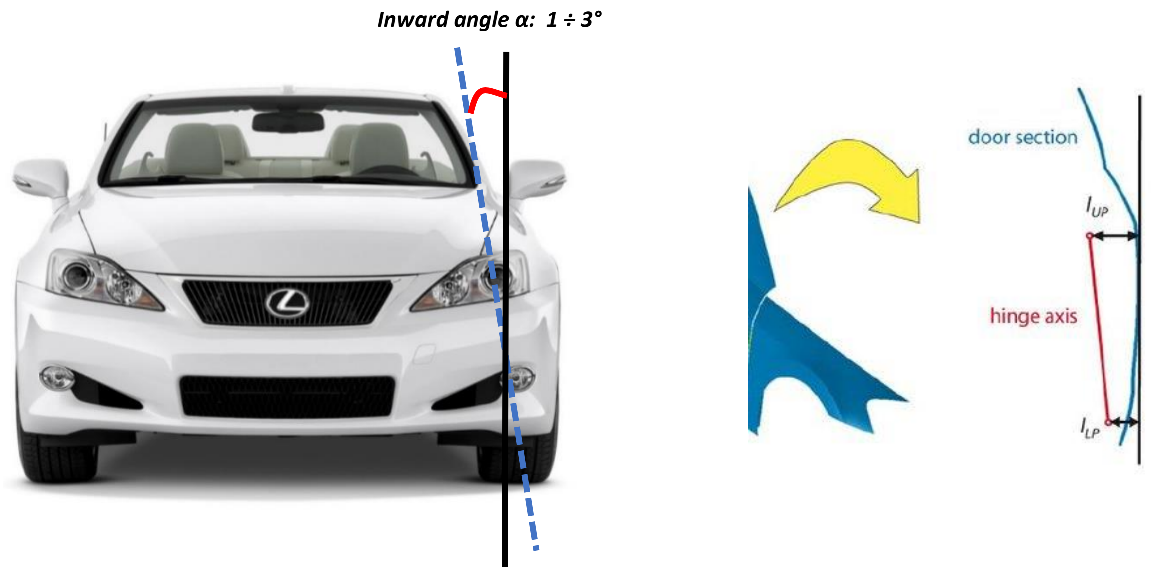


Figure 122: Hinge inclination axis (inward of the car)

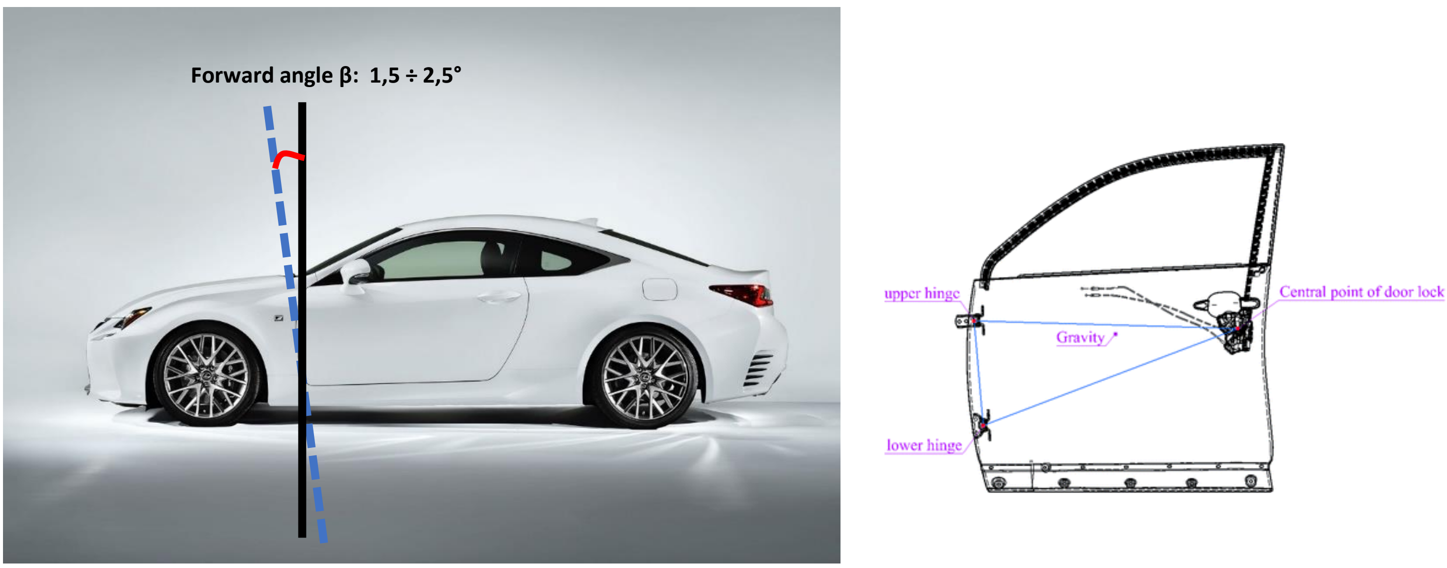


Figure 123: Hinge inclination axis (forward of the car)

- ***Ease of ingress/egress***

  The door system must ensure a space to enter and exit the vehicle even when it is parked at 600 mm from adjacent vehicles.

  Objects that should be considered during evaluation, for hinged doors:

  - Head/shoulder space to enter/exit the vehicle in restricted spaces. This is mainly influenced by the slope of the hinge axis that influences the tip of the door around the Y axis as it opens and the profile of the door cutline in the side view.
  - Space for your feet to enter/exit the vehicle in restricted spaces. This is mainly influenced by the door and the trim panels thickness at the front and rear edges of the door.
  - Hip space to enter/exit the vehicle in restricted spaces. This is mainly influenced by the front/rear position of the B pillar relative to the seat position.

  Design considerations:

  Reduce the size and thickness of the door: the result is a decrease in weight, a decrease in requirements on the rigidity of the structure, and a reduction in noise (squeaks, ...).

- ***Extraction of air***

  There must be two air extractors that must be placed externally in a symmetric way on opposite sides of the vehicle, in order to facilitate the closing of the side doors: such that the customer should not apply too much effort in the closing action.

  Extractors must be placed in areas of negative pressure coefficient between 0.20 and 0.25, so that air can exit the vehicle from the back. The location of the extractors must prevent water and dust from entering the vehicle's cockpit.

  Extractors must have a minimum tolerance of 25 mm from other objects on both sides (internally and externally).

- ***Door hinge strength requirements***

  The door hinges, when tested, should not separate when a transversal load of 16 kN or a longitudinal load of 20 kN are applied to them.

- ***Door check efforts***

  The front and rear check force must be sufficient to keep the door in a stable position in case the vehicle is parked on a road with 15% slope on a windless day. The force required to release the door from this stable position should not exceed 100 N, as measured along the central line of the door's inner handle. The force to release the door from this stable position cannot vary for more than 40 N between doors on the same vehicle.

- ***Dynamic sealing***

  Door weatherstrips should be:

  - Continuous bulb seal on body.
  - A-pillar/header margin seal on body.
  - Lower A pillar air blocker seal.
  - Lower door NVH seal.
  - B pillar primary bulb seal on leading edge of rear door (full-length).
  - B pillar margin bulb seal on upper rear door.

  The cavity around the upper latch must be sealed to prevent noise, dust, and water intrusion into the cabin. It is requested a rear door to quarter panel margin seal, and a door to door margin seal below belt as well.

- ***Clearance to prevent seal damage***

  Sheet metal, interior trim, exterior trim, hardware, and electrical components must not unintentionally wipe or rub against the weatherstrips during the opening-closing operation under all build variations. The following clearances are recommended:

  - ***Lock striker*** > 9.0 mm.
  - ***Front fender*** > 3.5 mm.
  - ***All other components*** > 8.0 mm.

  These requirements are intended to prevent weatherstrips tearing, abrasion or other damage. These requirements do not prohibit intentional sealing contact and the required clearances should be based on a program specific tolerance study.

- ***Water protection***

  The door weatherstrips should only be made with materials that do not emit bad odors during the assembly of the car or during the life cycle of the car in weather conditions between -29 °C up to +52 °C (including thermal loads due to the sun and 90% humidity relative to a temperature of 45 °C).

- ***Side door corrosion resistance***

  The door structure and hinges must comply with the functional demands of corrosion resistance: subjecting the component to an exposure for 96 hours of saline spray and subsequently verifying that no iron corrosion points are forming.

- ***Paint protection from door slam damage***

  There must be no paint defects when the customer is using the vehicle, even when there are very energetic closures. The door must not come into contact with the body during any closure until 25 J of energy.

  The body and door must be provided with tolerances to counter the conditions of energetic closure. The seals and lock of the door typically behave like the first components that prevent the door from impacting the body.

5.4.2 Sliding doors

Sliding doors are a type of unconventional doors which differs completely from every kind of door typology. This is due to the fact that they are characterized by rails and trolleys that allow the door to slide longitudinally, instead of being supported by side hinges mounted on the pillars. For that reason, they have different requirements to satisfy during the design processes, while those of unconventional doors will be evaluated afterwards.

The main performances and design choices to fulfil and to follow during the project phases of sliding doors are:

- *Door system durability*
- *Side door performance in complete vehicle durability*
- *Sliding door stability*
- *Door total deformation in gravity*
- *Sliding door strength requirements*
- *Sliding door torsional rigidity*
- *Window frame lateral rigidity*
- *Door frame deflections due to seal forces*
- *Commodity retention – dynamic event*
- *4 post shaker simulation*
- *Door slam testing speed*
- *Power sliding door cycle time requirement*
- *Power sliding door operating temperature range*
- *General requirements for side doors safety*
- *Sliding door minimum closing energy*
- *Sliding door body contact (static)*
- *Retain the door open (static and dynamic)*
- *Ease of ingress/egress*
- *Water protection*
- *Sliding door corrosion resistance*
- *Seal gaps*

After having made a list, I will analyse in detail each specific requirement to fulfil during or at the end of the design processes.
Obviously, whenever it is not possible to achieve all the specifics underlined, a trade-off between them is necessary to be done, in order to have a reliable and stiff structure to deliver to the customer.

- ***Door system durability***

  The door system must have a life cycle that differs from what type of vehicle is taken into consideration: mass production vehicles or one-off/small series vehicles.

  - *Mass production vehicles*: at least 10 years/240000 km for 90% of the customers.
  - *Small series vehicles*: 10 years/60000-100000 km (the real usage is attributed to each specific customer).

  These considerations are demonstrated by going to carry out the key life test of the door. The key life test is an accelerated life design test to detect the door component failure mode, involving repeated 6 d.o.f. vibration and rapid temperature changes.

  Once the test is completed, the door must still pass the fit and finish requirements, the opening effort requirement, the closing effort requirement, the squeak and rattle requirement and the door closing sound quality requirement.

  Comments:
  This is the ultimate test for the door assembly as it considers all interactions in the system. However, it has negative aspects, such as cost and duration, which are not always low.

- ***Side door performance in complete vehicle durability***

  The door system must withstand the full durability test (84,000 opening/closing cycles) without having structural damage or loss of door-related functions.

  Once the test is completed, the door must still pass the fit and finish requirements, the opening effort requirement, the closing effort requirement, the squeak and rattle requirement and the door closing sound quality requirement.

- ***Sliding door stability***

  The movement of the sliding door relative to the body structure under dynamic loading (vehicle motion) conditions must not be more than ± 2 mm in the x, y and z directions measured at the four corners of the door and at the latch/striker locations.

- ***Door total deformation in gravity***

  The door is installed to the body shell in the closed position supported from the inner panel at the center of gravity. When the door is released, it must not drop off more than 1.0 mm under its own weight.

  The additional weight of the hardware/trim components shall result in an additional deflection of no more than 1.0 mm **(2 mm of total door deformation due to gravity).**

- ***Sliding door strength requirements***

  - With the sliding door opened to the full open position (engaged in the check or hold open latch) on the track, the track/hinge/rollers shall withstand a static 1500 N transverse load, applied at the front and at the rear of the sliding door in the outboard direction only. The door shall not disengage from the tracks and when the load is removed, the door must remain functional.
  - With the sliding door at 50 mm from full close, the sliding door's hinge/rollers system and track(s) shall withstand a static load of 1000 N for car and car based vehicles and 1500 N for truck based vehicles applied on the door at the centerline of the outside door handle in the upward and downwards directions. When the load is removed, the door must remain functional.
  - With the sliding door at full open, the sliding door's hinge/rollers system and track shall withstand a static load of 1000 N for car and car based vehicles and 1500 for Truck based vehicles applied on the door at the centerline of the outside door handle in the upward and downward directions. When the load is removed, the door must remain functional.
  - With the sliding door at full open, the sliding door's hinge/rollers system and track shall withstand a static load of 1000 N for car based vehicles and 1500 N for Truck based vehicles applied on the door at the inside grab handle in the downward direction. When the load is removed, the door must remain functional. This sub-requirement is not applicable to sliding doors without an inside grab handle.
  - The sliding door must not disengage when a static 17800 N transverse load is applied in the outboard direction with the door in the closed position.
  - With the sliding door opened to the weakest position on the track, the track/hinge/rollers shall withstand a static 1500 N transverse load, applied at the front and at the rear of the sliding door in the inboard and outboard directions. The door shall not disengage from the tracks and when the load is removed, the door must remain functional.
  - The power or manual sliding door shall not disengage from the tracks or supporting structure when a 670 N cyclic load is applied at the outside or inside handle in the opening or closing direction for 20 cycles with the door in a seized condition in the tracks at any open position along the travel path. After the load is applied, the door shall remain functional and meet the sliding door operating efforts requirement and minimum closing energy requirement.

- ***Sliding door torsional rigidity***

  The door must withstand a torque of 300 Nm without deflecting more than 4 mm at the top of the belt and the lower corner on the latch side of the door.

- ***Window frame lateral rigidity***

  For doors with frames: the maximum deflection of the door frame shall not exceed 5.0 mm under a 180 N load. Permanent set shall not exceed 1.5 mm after the application of a 360 N load.

  For doors without frames: the maximum deflection of the top of the mirror sail shall not exceed 2.0 mm under a 180 N load. Permanent set shall not exceed 0.5 mm after the application of a 360 N load.

- ***Door frame deflection due to seal forces***

  The door frame deflection shall not exceed 2.0 mm due to the seal loads with the door and weatherstrips in the design nominal conditions. This is verified by measuring the flushness of the door before and after the weatherstrips are installed.

- ***Commodity retention - dynamic event***

  The vehicle structure to which doors, seats, seat belts, spare wheel and jack stowage are attached must retain those commodities during a 56 km/h full frontal barrier impact test. Deformation in the body structure/sheet metal is acceptable however tearing or separation are not.

  The side doors shall be retained by their hinges and attachments and they shall remain closed and latched during a 48 km/h fixed barrier collision test.

- ***4 post shaker simulation***

  The door system must withstand a 4 post-shaker/vibrations simulation of the complete vehicle, without loss of its functions or exterior appearance. The 4 post shaker test consists of four servo hydraulic actuators which are coordinated to simulate the motion of the vehicle on the ground.

  Once the test is completed, the door must still pass the fit and finish requirements, the opening effort requirement, the closing effort requirement, the squeak and rattle requirement and the door closing sound quality requirement.

- ***Door slam testing speed***

  On a flat road the maximum allowed value of the door slam speed is < 1 m/s, while the recommended value is about 0.5 m/s. Moreover, if the door is opened on a slope, it must engage a brake, capable of absorbing the whole kinetic energy of the door, without permanent yield of frames and rubber dumpers.

- ***Power sliding door cycle time requirement***

  The sliding door power closure mechanism shall be capable of fully opening the sliding door in 2-5 seconds and fully closing the sliding door in 3-6 seconds with the engine off, at ambient temperature and on a level grade.

  This mechanism must also be capable of fully opening or fully closing the sliding door within 2-10 seconds under any combination of temperature, battery voltage and grade.

- ***Power sliding door operating temperature range***

  The sliding door's power closure mechanism shall meet all door system requirements within the temperature range of -40°C to 82°C.

- ***General requirements for side door safety***

  All side door systems (conventional hinges, suicide, sliding doors, butterfly doors) must comply with safety requirements.
  Rules related to the structure of the door include:
  - Door locking and maintenance.
  - External projections.
  - Internal fittings.
  - Flammability (for seals and composite door structures).
  - General Requirements for Structural Integrity - Impacts.
  - Side impact of side door strength.
  - Frontal impact.
  - Passenger protection at impacts.
  - Post-opening impact of door.
  - Forward Visibility.

- ***Sliding door minimum closing energy***

  The sliding door system must completely latch close (primary latching position) by imparting a maximum 15 J of work. The point of application of the force is at the center of the exterior door handle and the direction of force is parallel to sliding door travel in the closing direction (towards the front of the vehicle).

  The sliding door must be in a completely assembled and fully trimmed conditions (including weatherstrips, glass, door hardware, door handles, door trim, etc.).

- ***Sliding door body contact (static)***

  The roller and track system shall provide 12 mm of minimum clearance between the sliding door and the rear quarter panel, weatherstrips and any part of the body sheet metal, when a load of 300 N is applied in the inboard y-direction. This requirement applies for the entire length of the sliding door travel from full open to 50 mm from fully closed.

- ***Retain the door open (static and dynamic)***

  - *Static condition*: the sliding door's hold open mechanism shall hold the door in the open position while vehicle is parked on a 20% grade downhill.
  - *Dynamic condition*: the sliding door hold open mechanism shall retain the door open with the door in fully open position and the vehicle accelerating from 0 to 40 km/h max on a 18% grade downhill, with sudden application of brakes, bringing the vehicle to a complete stop.

- ***Ease of ingress/egress***

The door system must ensure a space to enter and exit the vehicle even when it is parked at 600 mm from adjacent vehicles.

Objects that should be considered during evaluation, for hinged doors:

- The relationship of the forward/backward position of the outer handle relative to the forward/backward position of the top corner of the B pillar and its rotation axis during the opening.
- Head/shoulder space to enter/exit the vehicle in restricted conditions. This is mainly influenced by the slope of the hinge axis that influences the end of the door around the Y axis as it opens and the profile of the door cutting line in the side view.
- Space for your feet to enter/exit the vehicle in restricted conditions. This is mainly influenced by the door and trim thickness of the front and rear edges of the door.
- Hip space to enter/exit the vehicle in restricted conditions. This is mainly influenced by the front/back position of the B pillar relative to the seat position.

- ***Water protection***

Door watershields shall contain only such materials that will not give off objectionable odors during assembly, or customer usage due to environmental conditions ranging from -29 °C to +52 °C ambient conditions including sun loads, and 90% relative humidity at a temperature of 45 °C.

- ***Sliding door corrosion resistance***

The sliding door system when subjected to the 90^{th} percentile corrosive operating environment must be functional after 10 years of exposure, be serviceable after 6 years of exposure and not exhibit visible red rust on first class surfaces after 5 years of exposure in high corrosion areas.

- ***Seal gaps***

The seal gap must provide an environment that minimizes the sealing systems sensitivity to the closure panels build variability. The main requirements that it has to follow are:

- The seal gap must maintain a constant dimension along the length of each extrusion.
- Single piece body opening panels are preferred to provide a datum surface for a constant seal gap.
- The build tolerance of the seal gap must be ≤ ± 3 mm in pre-delivery.

5.4.3 Not conventional hinged doors

Many requirements have to be satisfied at the end of the design stage for not conventional hinged doors (such as scissor, gullwing, butterfly, etc..). Sliding doors are not included in this paragraph since they do not have side hinges to support the structure, but rails and trolleys. The main performances and design choices to fulfil and to follow during the project phases of not conventional doors are:

- *Door system durability*
- *Side door performance in complete vehicle durability*
- *Door total deformation in gravity*
- *Door frame lateral strength*
- *Door torsional rigidity*
- *Door frame deflections due to seal forces*
- *4 post shaker simulation*
- *Side door slam-open durability*
- *Door opening/closing sound*
- *General requirements for side doors safety*
- *Door opening and closure effort*
- *Door rotational inertia*
- *Commodity retention – dynamic event*
- *Ease of ingress/egress*
- *Ergonomic and reachability*
- *Extraction of air*
- *Door hinge strength requirements*
- *Door check efforts*
- *Dynamic sealing*
- *Clearance to prevent seal damage*
- *Water protection*
- *Side door corrosion resistance*
- *Paint protection from door slam damage*

After having made a list, I will analyse in detail each specific requirement to fulfil during or at the end of the design processes. It is important to keep in mind that unconventional doors have less stringent requirements than the conventional types. Therefore, they can be characterized by less stiffness specifics.
Obviously, whenever it is not possible to achieve all the specifics underlined, a trade-off between them is necessary to be done, in order to have a reliable and stiff structure to deliver to the customer.

- ***Door system durability***

  The door system must have a life cycle that differs from what type of vehicle is taken into consideration: mass production vehicles or one-off/small series vehicles.

  - *Mass production vehicles*: at least 10 years/240000 km for 90% of the customers.
  - *Small series vehicles*: 10 years/60000-100000 km (the real usage is attributed to each specific customer).

  These considerations are demonstrated by going to carry out the key life test of the door. The key life test is an accelerated life design test to detect the door component failure mode, involving repeated 6 degrees of freedom vibration and rapid temperature changes. Once the test is completed, the door must still pass the fit and finish requirements, the opening effort requirement, the closing effort requirement, the squeak and rattle requirement and the door closing sound quality requirement.

  Comments:
  This is the ultimate test for the door assembly as it considers all interactions in the system. However, it has negative aspects, such as cost and duration, which are not always low.

- ***Side door performance in complete vehicle durability***

  The door system must withstand the full durability test (30,000 opening/closing cycles, instead of 840000 cycles for conventional doors) without having structural damage or loss of door-related functions.

  Once the test is completed, the door must still pass the fit and finish requirements, the opening effort requirement, the closing effort requirement, the squeak and rattle requirement and the door closing sound quality requirement.

- ***Door total deformation in gravity***

  The door is installed on the body in a closed position supported by the inner panel along the center of gravity. When the door is released (in closing conditions), it must not fall more than 1 mm below its weight (the additional weight of the hardware/trim must result in a deviation of no more than 1 mm total → **total deformation in gravity: 2 mm**).

- ***Door frame lateral strength***

The door frame strength is evaluated considering 3 main cases:

- **Doors with frame**: the maximum deviation of the door frame must not exceed 3 mm under a load of 180 N along the middle of the door belt opening (as shown in Figure 124).
  Permanent deformations must not exceed 1.5 mm under a load of 360 N.

- **Frameless doors**: The opening of the door belt should not deflect for more than 3 mm with a compression or expansion force of 180 N applied along the middle of the door belt opening. Permanent deformations must not exceed 0.5 mm under a load of 360 N.

- **Door with window frame and single-arm or lift-arm windows regulators**: The opening of the belt line should not deflect for more than 5 mm with a compression or extension force of 180 N applied along the middle of the door belt opening.

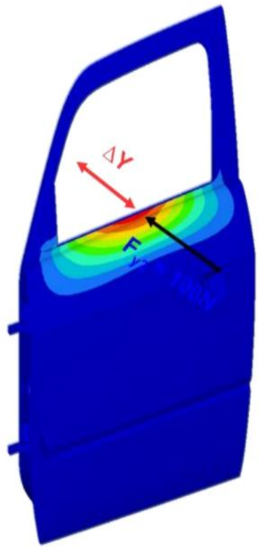


Figure 124: General door loadcases application

These tests must be carried out on a fully trimmed door mounted on the vehicle, including all seals and overslam bumpers. On the front framed doors, the load is initially applied on top of the B pillar, then on top of the A pillar (which corresponds to the upper corner of the windshield). Then on the rear framed doors, the load is applied first on top of the B pillar and then on top of the C pillar (which corresponds to the upper corner of the rear light).

If a load of 385 N is applied to the door lock, along the direction parallel to the hinge axis, the maximum displacement on that point must be:

- < 20 mm if the door is in *an open position (10 mm more than conventional doors).*
- < 20 mm if the door is in *a closed position (10 mm more than conventional doors)*.

These larger values with respect to conventional doors are due to the different shapes and numbers of the unconventional hinges. In fact, unconventional doors have usually just one hinge for design style, nut the drawback is that it leads to a worse structural stiffness of the door assembly.

- ***Door torsional rigidity***

  A torque of 250 Nm (instead of 275 Nm for conventional doors) must be supported by the door without deflecting for more than 4 mm at the top of the belt line and the lower corner of the latch side of the door.

  The door system must have a torsional stiffness of at least 450 Nm/deg when a torque (around x-axis) of 10000 Nmm is applied on the door latch.

- ***Door frame deflection due to seal forces***

  The deviation of the **door frame** must not exceed **2 mm** due to the reactions of the seals with the door (weatherstrips and door in nominal positions).

  The door frame is designed to compensate for this deflection by moving the frame of this amount inwards, so that it is in a nominal frame position when received by the customer. This inward movement is determined by CAE analysis. If the deviation evaluated exceeds 2 mm, the stiffness of the door frame should be increased, while the seal forces reduced.

- ***4 post shaker simulation***

  The door system for small series vehicles should not withstand a 4 post-shaker/vibrations simulation of the complete vehicle, since it is an expensive procedure and useless if we consider this low production cars. This is because this simulation is performed directly on the road, considering the complete vehicle durability period.

- ***Side door slam-open durability***

  No failure should be provided structurally or functionally during the door's strong opening and closing cycles:

  1. Conventional front and rear side doors: 30000 slam open cycles when the door is fully opened.
  2. Access panels without an intermediate hardstop: 15000 slam open cycles when the door is fully opened.
  3. Access panels with an intermediate hardstop: 15000 slam open cycles against door brake and 10000 open slam cycles when the door is fully opened (access panels are equivalent to 40% of the doors).

  The door must be tested in completely trimmed conditions with all the interiors, hardware components, windows regulators, weatherstrips, mirrors, ornaments, etc. fully installed. The front doors of vehicles with access panels must be tested with and without the access panel option.

  Once the test is completed, the door must still pass the fit and finish requirements, the opening effort requirement, the closing effort requirement, the squeak and rattle requirement.

- ***Door opening/closing sound***

  The closing and opening of the door must not produce any noise, including, but not limited to chirps, clicks and rattles.

  - *Non-luxury vehicles:*

    The closing sound of the door on a fully assembled car should not exceed a loudness peak of 45 sones, and an intensity that should not exceed 3.5 acum when tested at the minimum closing speed (the value of 1 acum is attributed to a narrow-band noise at 1 kHz).

    Noise must not exceed a maximum of 48 sones and the intensity should not exceed 3.6 acum at 1.3 times the minimum closing speed.

  - *Luxury vehicles:*

    The closing sound of the door on a fully assembled car should not exceed a loudness peak of 35 sones, and an intensity that should not exceed 4.0 acum when tested at the minimum closing speed.

    Noise should not exceed 42 sones and the intensity should not exceed 3.4 acum at 1.3 times the minimum closing speed.

  - *All vehicles:*

    The closing noise of the doors must be evaluated subjectively with all the option levels, with the windows in various positions, with energetic closures at 25 J in order to check special causes: slam of the side windows, contacts between components, etc...

NB: the value of 1 sone corresponds to 28 dB, while 8 sones corresponds to 58 dB.

- ***General requirements for side door safety***

  All side door systems (conventional hinges, suicide, sliding doors, butterfly doors) must comply with safety requirements.
  Rules related to the structure of the door include:

  - Door locking and maintenance.
  - External projections.
  - Internal fittings.
  - Flammability (for seals and composite door structures).
  - General Requirements for Structural Integrity - Impacts.
  - Side impact of side door strength.
  - Frontal impact.
  - Passenger protection at impacts.
  - Post-opening impact of door.
  - Forward Visibility.

- ***Door opening and closure effort***

  - The door **dynamic *closing*** effort must not exceed the 8 J of energy that corresponds to a spring force of 86.7N, tested on a fully trimmed door of a vehicle in environmental conditions.
    The closing effort must not exceed a maximum of 12 J of energy (or 104.5 N of spring strength) at a temperature of -29 °C.

  - ***Opening*** the door (measured on the centerline of the inner handle):
    a) Maximum effort of 22 N if the weight of the door: ≤ 30 kg.
    b) Maximum effort of 36 N if the weight of the door: > 30 kg.

Maximum opening angle of the door: 80° - 90° maximum.

No oscillations/shakes should be guaranteed during the opening action of the door.

- ***Door rotational inertia***

The polar moment of inertia of the door around its hinge axis must not exceed 35 kgm^2, otherwise the customer may perceive the door as too complex to move.

Note: This value can be reduced by making the door lighter or by moving heavier components near the hinge axis.

- ***Commodity retention – dynamic event***

The structure of the vehicle to which the doors, seats, seatbelts and spare wheels are attached must retain these elements in case the vehicle is subjected to a frontal barrier impact test at 56 km/h.

A deformation is allowed in the structure of the vehicle, while cuts and separations are not allowed.

The side door must remain restrained by its hinges and attachments and must remain closed and tight during the fixed barrier collision at 48 km/h.

- ***Ease of ingress/egress***

The door system must ensure a space to enter and exit the vehicle even when it is parked at 600 mm from adjacent vehicles.

Objects that should be considered during evaluation, for hinged doors:

- Head/shoulder space to enter/exit the vehicle in restricted spaces. This is mainly influenced by the slope of the hinge axis that influences the tip of the door around the Y axis as it opens and the profile of the door cutline in the side view.
- Space for your feet to enter/exit the vehicle in restricted spaces. This is mainly influenced by the door and the trim panels thickness at the front and rear edges of the door.
- Hip space to enter/exit the vehicle in restricted spaces. This is mainly influenced by the front/rear position of the B pillar relative to the seat position.

Design considerations:

Reduce the size and thickness of the door: the result is a decrease in weight, a decrease in requirements on the rigidity of the structure, and a reduction in noise (squeaks, ...).

- ***Ergonomic and reachability***

Small series vehicles could have different specifics with respect to passengers' cars for what concerns the door system reachability.

Therefore, the door mechanism can be automatic in order to allow the opening and closing action in an automatic way, for style and ergonomic purpose. In fact, different vehicles have the driver seat in the middle position, and it will be impossible to operate the closing of the door manually. The effort performed by the driver has to be minimized during the closing of the door, so the automatization is done by means of electric or electro-hydraulic mechanisms.

For the opening stage it is important to consider that the door handle has to be located on a reachable height by the customer, even if the opening action could be automatized.

- ***Extraction of air***

There must be two air extractors that must be placed externally in a symmetric way on opposite sides of the vehicle, in order to facilitate the closing of the side doors: such that the customer should not apply too much effort in the closing action.

Extractors must be placed in areas of negative pressure coefficient between 0.20 and 0.25, so that air can exit the vehicle from the back. The location of the extractors must prevent water and dust from entering the vehicle's cockpit.

Extractors must have a minimum tolerance of 25 mm from other objects on both sides (internally and externally).

- ***Door hinge strength requirements***

  The door hinges, when tested, should not separate when a transversal load of 16 kN or a longitudinal load of 20 kN are applied to them.

- ***Door check efforts***

  The front and rear check force must be sufficient to keep the door in a stable position in case the vehicle is parked on a road with 15% slope on a windless day. The force required to release the door from this stable position should not exceed 100 N, as measured along the central line of the door's inner handle. The force to release the door from this stable position cannot vary for more than 40 N between doors on the same vehicle.

- ***Dynamic sealing***

  Door weatherstrips should be:

  - Continuous bulb seal on body.
  - A-pillar/header margin seal on body.
  - Lower A pillar air blocker seal.
  - Lower door NVH seal.
  - B pillar primary bulb seal on leading edge of rear door (full-length).
  - B pillar margin bulb seal on upper rear door.

  The cavity around the upper latch must be sealed to prevent noise, dust, and water intrusion into the cabin. It is requested a rear door to quarter panel margin seal, and a door to door margin seal below belt as well.

- ***Clearance to prevent seal damage***

  Sheet metal, interior trim, exterior trim, hardware, and electrical components must not unintentionally wipe or rub against the weatherstrips during the opening-closing operation under all build variations. The following clearances are recommended:

  - ***Lock striker*** > 10.0 mm.
  - ***Front fender*** > 5.0 mm.
  - ***All other components*** > 9.0 mm.

  These requirements are intended to prevent weatherstrips tearing, abrasion or other damage. These requirements do not prohibit intentional sealing contact and the required clearances should be based on a program specific tolerance study.

- ***Water protection***

  The door weatherstrips should only be made with materials that do not emit bad odors during the assembly of the car or during the life cycle of the car in weather conditions between -29 °C up to +52 °C (including thermal loads due to the sun and 90% humidity relative to a temperature of 45 °C).

- ***Side door corrosion resistance***

  The door structure and hinges must comply with the functional demands of corrosion resistance: subjecting the component to an exposure for 96 hours of saline spray and subsequently verifying that no iron corrosion points are forming.

- ***Paint protection from door slam damage***

  There must be no paint defects when the customer is using the vehicle, even when there are very energetic closures. The door must not come into contact with the body during any closure until 25 J of energy.

  The body and door must be provided with tolerances to counter the conditions of energetic closure. The seals and lock of the door typically behave like the first components that prevent the door from impacting the body.

6. Conclusions

The requirements described in the previous paragraphs are the basic targets that the engineer should satisfy during the design phases of a door system. Starting from that, it is important to differentiate whenever we have a conventional door or not, for example during my curricular internships I have worked most of the time on the (almost) race car SCG 004S, which mounted butterfly doors.

For that reason, the design normatives should constitute a guide to follow, but on those particular situations when an unconventional door is taken into account, it is important to think that it is a "custom" assembly: different from any other seen in each type of vehicle.

Therefore, it was not easy to find solutions to adopt to these doors, above all since the goal of my analysis was to overcome the problems related to structural integrity of the door hinge assembly, considering the required target at structural level.

Model	Loadcase	Target	Result	Unit
001: Baseline configuration (Steel Attachment + Aluminium gooseneck)	Door total deformation in gravity	< 2 mm	**6.6**	**mm**
	Deformation due to 385 N applied on door lock (Lockload)	< 20 mm	**60.1**	**mm**
	Torsional stiffness	> 450 Nm/deg	**294.1**	**Nm/deg**
002: Tube chassis configuration (baseline) + 1 additional tube	Door total deformation in gravity	< 2 mm	**6.6**	**mm**
	Deformation due to 385 N applied on door lock (Lockload)	< 20 mm	**46.94**	**mm**
	Torsional stiffness	> 450 Nm/deg	**335.83**	**Nm/deg**
003: 002 + 2 connections	Door total deformation in gravity	< 2 mm	**6.6**	**mm**
	Deformation due to 385 N applied on door lock (Lockload)	< 20 mm	**46.68**	**mm**
	Torsional stiffness	> 450 Nm/deg	**332.06**	**Nm/deg**
004: 003 + modified gooseneck shape (aluminium)	Door total deformation in gravity	< 2 mm	**8.6**	**mm**
	Deformation due to 385 N applied on door lock (Lockload)	< 20 mm	**17.77**	**mm**
	Torsional stiffness	> 450 Nm/deg	**456.41**	**Nm/deg**
005: 003 + modified gooseneck shape (steel)	Door total deformation in gravity	< 2 mm	**8.5**	**mm**
	Deformation due to 385 N applied on door lock (Lockload)	< 20 mm	**14.94**	**mm**
	Torsional stiffness	> 450 Nm/deg	**494.001**	**Nm/deg**
006: 002 + modified gooseneck shape (aluminium)	Door total deformation in gravity	< 2 mm	**8.3**	**mm**
	Deformation due to 385 N applied on door lock (Lockload)	< 20 mm	**18.26**	**mm**
	Torsional stiffness	> 450 Nm/deg	**453.21**	**Nm/deg**

Table 12: SCG 004S final box results

The *Table 12* shows my design phases during the complicated decisions of making the door assembly of the SCG 004S stronger. As it can be seen I started to analyse the biggest component in terms of volume (the framework, composed by tubular chassis), thinking at first that it was the main contributor to the overall stiffness of the door system.

After the first 3 configurations (until 003) I have found that only small amount of improvements is detected, so that something else should have been the main promotor of the "structural change": the hinge arm with a gooseneck shape. Starting from the original hinge arm with 55 mm of thickness, since it was important to improve the torsional stiffness of the system, I increased the thickness up to 99 mm with two additional bars on the side, so that the arm could resist better to the moment application around x axis.

The improvement of the results agreed with my considerations, a part of the 006 configuration which was a try in order to reduce the overall weight of the system keeping the ultimate gooseneck shape. Unlikely, reducing the mass of the hinge assembly did not lead to better results (because of that I did not show the analyses performed on it), therefore for that reason I took as the best choice the 004 configuration, which reaches all the target pre-established, except the displacement due to gravity (but this differs of a small amount , so it should be considered satisfying as well). The 004 configuration is preferred with respect to the 005 since it is lighter, while the structural results are extremely similar and satisfying from the point of view of targets achievement. For that reason, it is the best production choice in terms of trade-off between structural and weight issues.

These considerations lead to underline the main limit of my project, which can be further studied in order to solve the possible problems encountered. In fact, I have reached optimal results in terms of static torsional stiffness, and even the total door deformation due to a load applied on the lock satisfies the pre-defined targets. However, the drawback is that I had to increase the total mass of the door system to chase the requirements, and this brought to have a worse performance for the deformation due to application of gravity. Therefore there are wide margins of improvement to satisfy all the 3 structural requirements, and at the same time to find the best possible design project in terms of weight (without adopting steel hinge arm, which in our case increases the total mass of almost 6 kg).

Finally, we can conclude that all the design choices that I have consider in this project derive from the normative that I have described in the previous chapter. While, for what concerns the performances that each vehicle should fulfil (for example durability or 4 post-shaker simulations for conventional or unconventional doors), we have to wait for the car to be assemble, and only after that we can compare those results with that defined in my proposal normative.

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