STRUCTURAL DESIGN OF THE SUPERBUS

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Abstract

The present paper presents the structural design of the Superbus.

First the overall requirements are defined and analyzed, which have been divided in load (static and dynamic), stiffness and functional requirements. In order to fulfil those requirements two different solutions are defined and analyzed in the preliminary design. From those, the best option in terms of lightness and easiness of production (which influences the cost and time) is chosen. Finally a detailed analysis is carried out on the final design to verify the stiffness and strength of the structure during the most common driving conditions and some solutions for the production of the different parts are presented.

1 Introduction

The Superbus (Fig. 1) is a new concept for innovative collective transport under development at TU Delft [1].

Fig. 1 Rendering of the Superbus.

The *Superbus* is sustainable, it runs at competitive speeds with respect to current high speed transports, it is lightweight and aerodynamically efficient, it is safe, innovative, comfortable, appealing and provides flexible transportation on request for people and goods.

Operations

At cruising speed (250 km/h) the *Superbus* runs on its dedicated and relatively cheap infrastructure, and at lower speed it leaves the dedicated high speed track and runs in city centres and on highways at conventional speeds [2]. Through such operations, the height of the vehicle from the ground varies (from 60mm to 400mm) by the use of a lifting adjustable system, which varies the height depending on presence of obstacles on the road, passengers' accessibility, aerodynamic performance.

Flexibility

The *Superbus* provides flexible transportation on demand. There is not a prefixed time table for the *Superbus*. This means that a passenger books a journey by the use of a phone message or through internet where specifies desired departure time and location and destination. The central control elaborates the best journey based on all requests and operation of all available vehicles and communicates it to passenger.

The *Superbus* is also flexible with regard to the use of infrastructures. The vehicle travels at 250km/h on its dedicated infrastructure and has the ability to use any existing road, unlike trains, to reach any destination.

Infrastructure

One of the strengths of this new type on transport consists in the economic dedicated roads, when compared to the cost of infrastructures for high speed trains and magnetic levitation trains – as it comprise concrete roads and few sensors only. Also, the fact that the dedicated infrastructure will solely be used by *Superbuses* allows it to be cheaper due to the relatively light weights of the vehicles that it is made for. Similar argument holds for durability of the infrastructure.

Safety

One of the main characteristics of the *Superbus* is its safety – both passive and active. The *Superbus* is designed to be structurally very safe and uses a navigation and control system unique to land vehicles. For that, aerospace navigation instrumentations are implemented together with automotive state of the art safety systems. In addition to that, a number of active safety systems are implemented such as airbags, seatbelts, rear parachute and lateral morphing structures for emergency braking.

Sustainability

The *Superbus* is sustainable. This does not only refer to the fact that it does not produce CO2 and NOx emissions – for which it uses 4 electric motors powered by a battery pack. Indeed, the vehicle is sustainable throughout: it thus uses low power per passengers, uses a number of recyclable materials, has a low impact in the use of infrastructures and requires less energy for the production of its dedicated infrastructure, does not waste energy in operation of empty vehicles as there is not a fixed timetable, does not impact as much on the environments with respect to the required areas for the dedicated roads, etc.

Superbus Programme

The *Superbus* Programme is sponsored by the Dutch Ministry of Transport and Water Management for the realisation of a DEMONSTRATOR for evaluation of the feasibility of the system within the "three-stage-rocket" plan. The latter consists in three subsequent phases for the realisation of respectively the demonstrator, the prototype & market readiness and the production type. This is expected to take place in a time frame that spans from 2006 to 2020 and that sees industry to take the lead on the design and manufacturing of the third phase with TU Delft providing one part of the R&D.

The design and manufacturing of the *Superbus* is managed, coordinated and integrated by a dedicated team at TU Delft, which works with a number of other Universities, Institutions and Companies.

Structural Design

For the above, the structure, bodywork and glazing of the Superbus Demonstrator are designed to be as light as possible, within the requirements constraint, to enhance efficiency. As a result, the *Superbus* has a composite chassis, thermoplastic reinforced bodywork panels and polycarbonate glazing, which design and manufacturing is described in this paper.

2 Preliminary Design Phase

2.1 List of Requirements

The list of requirements (LOR) of the structural design for the whole vehicle is very wide and it is summarized, divided and highlighted in this paper into the various areas predominantly impacted. With regard to this it should be stressed that the requirements evolve, within the timeframe of realization, when designing such a complicated and new product. The requirements are, at this stage, only applicable to the demonstrator. The main requirements for what concerns the structure can be summarized in the following:

- **Manoeuvrability**: As the vehicle will drive at a cruising speed of 250 km/h, it has to be able to be easily manoeuvrable, and therefore a minimum torsion stiffness of 30 kNm/° is required.
- **Driving conditions:** Most of the dynamic driving conditions are translated into static loads. These conditions include a vertical bump, cornering, abrupt stopping, roll over and frontal impact.
- **Weight:** The total weight of the vehicle, including payload is set to 8.5 T. The share of the structural weight is set to a maximum of 3.5 T, including payload.
- **Payload:** The vehicle will carry 24 passengers plus driver. Per passenger a weight of 110 kg is considered, including luggage.
- **Exterior shape:** The exterior shape is illustrated in fig 1. Given a total number of 24 passengers, 8 rows of three passengers are envisioned, with each row having its own door, thus 8 doors per side are wished.
- **Safety:** The vehicle must be safe for the occupants during all driving conditions and also in case of roll over. Though a lot of effort is made with active restraining systems, in the case of the demonstrator, given the tight time frame and its scope, also a number of passive safety requirements are considered within the structural design.
- **Crash:** Crash requirements are considered for the safety of the pilot in case of frontal impact, by reinforcing the frontal area, and of the

passengers in case of a side impact including frames which can reduce the severity of the impact on the passengers. In the case of the demonstrator, neither crash analysis nor tests are considered, but it is planned for the second stage of the project.

2.2 Design Options

One important requirement, leading the first design choice, is the torsion stiffness requirement, which should not be less than 30 kNm/degree. This requirement, combined with the wish of having as many doors as possible, ideally one per passenger, leads to the first design choices [2].

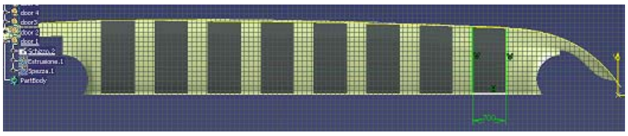

Fig. 2 Rectangular doors.

With a standard shape of doors, as shown in Fig. 2, the torsion stiffness would come mainly from the floor, considering a floor made of a stiff torsion box. This implies a high floor, with a loss of space for the interiors, being the external shape a given starting point.

The second option is to make the entire body work partially as a torsion box. The principle is shown in Fig. 3, where stiffeners are placed at an angle in order to obtain certain stiffness, regardless the cut-outs created by the doors.

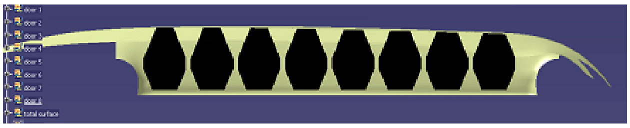

Fig. 3 Diamond shape doors.

These two concepts have been analysed by means of a finite element analysis up to the point when the torsion stiffness requirement is fulfilled. Then the preliminary weight of the two structures is compared and pro's and con's evaluated.

The first option consists of a standard layout with straight frames and therefore rectangular doors, whereas the second layout consists of inclined frames and octagonal doors. The second option is definitely the best option with respect to torsion stiffness and therefore weight reduction, especially when the frames are close to the ideal +/-45° orientation. Due to the amount of doors with respect to the overall chassis dimensions, the implementation of the second option allows only an inclination of about +/-20°.

The advantages of the first configuration are its accessibility - as in the second option the top and bottom part of the door are smaller - the absence of cross-connections which make the production easier and a constant width of the doors which makes production easier. However, the second option offers the freedom to explore more appealing design options and has the potential of being more structurally efficient, which, in turn, allows a lighter structure.

2.3 Evaluation of the results

In order to asses the torsion stiffness of the structure and to make a comparison between the two concepts a number of analyses were carried out, with particular attention to the influence of the single elements. The analyses considered:

- an identical floor box for the two models, 120 mm high, 3 mm thick, with six internal stiffeners;
- a framework made of hollow beams 100 x 100 mm cross section, 3 mm thick;
- a 3 mm thick skin

Carbon fibre reinforced plastic material is used, quasi isotropic, whose material characteristics are defined in Table 1:

Table 1. Material properties, based on T700 type.

	Carbon				
Fibre orientation.	V_f	E_x [GPa]	E_y [GPa]	G_{xy} [GPa]	v_{xy}
Quasi Isotropic	0.5	44.9	44.9	17.1	0.31

The results of the preliminary calculations are shown in Table 2:

Table 2. Preliminary results.

Stiffness [kNm/deg] (Target 30kN/deg)	Octagonal doors	Rectangular doors
Floor only	6.3	6.2
Floor and Framework only	29.8	7.2
Floor, Framework and skin	59.2	28.3

The octagonal door solution is clearly superior to the rectangular door solution. The weight of the respective models differs only little (i.e. 10% of the weight of floor and framework only) prior to optimisation of the material. Indeed, the combination of the cross beam frames with the floor and roof beams reaches the torsion stiffness target without the addition of the exterior panels (bold).

In order to determine the potential weight of the whole structure a number of configurations have been tested so to verify the difference in weight of the two structural options when complying with the target torsion stiffness (30kNm/°). In both cases a minimum thickness in the structure is needed to avoid unwanted vibrations and obtain the desired strength of all components.

2.4 Manufacturing considerations

The *Superbus* structure will be built in several elements and subassemblies. The design driver for such choice is due to the fact that for the demonstrator phase the various subsystems will not be completed simultaneously. This will allow the freedom for late changes and for the improvement of the integration of the whole structural parts.

As for the tooling, they should be affordable; therefore repetitive elements shall be used where possible.

As for the interiors, in order to enable various seating configurations, one uninterrupted interior living space without separations and equidistant spaced seat rails is implemented. Furthermore, the interior structural elements facing the inside are designed to be tooling side. This will result in a relatively clean interior appearance.

For what concerns production and assembly, the following choices have been made for the demonstrator:

- Vacuum infusion (large) structural elements (floor, beams, frames, large curved exterior panels)
- Wet fibre laminate local elements (frame intersection internal structure)
- Hot moulded (rubber pressed) thermoplastic composite for repetitive elements of limited size (transverse shear webs in floor, bath-tub fittings)
- ‘Dry’ mechanical assembly (bolted structure) until all subsystem integration has been achieved
- Final adhesive bonded assembly

3 Final Design

The final design is a compromise between the two designs analysed in the preliminary phase.

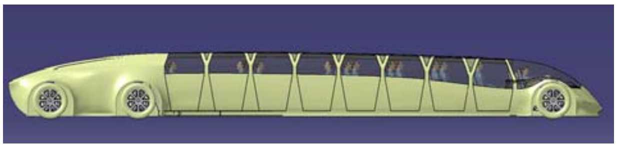

Fig. 4 Final design of the *Superbus.*

As mentioned, the structural efficiency of the design with octagonal doors is penalised with respect to with straight door only by the better accessibility. To compensate for that, the design has been optimised, as shown in Fig. 4, to enhance accessibility comfort whilst maintaining the appealing design and partially its structural advantage.

3.1 Load Cases

For the final design, optimisation analyses have been carried out so to achieve the torsion stiffness target and required structural strength when the vehicle is subjected to ultimate load cases. A list of load cases that covers all the possible driving conditions, typical to this type of vehicle, has been formulated and is shown in Table 3. The type of analysis depends on the desired output. The first load cases refer to overall characteristics of strength and stiffness (load cases 1 to 8), while others are aimed at verifying the strength of some elements locally (load case 9 and 10). The remaining ones are meant to verify the strength of some elements to achieve a safe bus in terms of crashworthiness requirements.

Table 3. Load cases for demonstrator substantiation.

		Nx (g)	Ny (g)	Nz (g)	Criteria
Stiffness requirements					
1	Torsion between axle units	load at front ground contacts			30000Nm/deg
-	Bending between axle units, (calculated with No 2)				5 mm/g
X	Vibration	all masses involved			range of 20-30 Hz
Load cases reacted on wheels / ground contact points					

2	Reference case 1g static	0		1	none
3	Bump, front axle 3g			matching	strength
4	Bump, rear axle 3g			matching	strength
5	Asymmetric inclined road representing 3g case per wheel on one set of diagonal opposing wheels			1.5	strength
6	Breaking	-1		1	strength
7	Cornering		1	1	strength
8	Side crash on bumper, side load reacted on one side wheels		4	1	strength on wheel unit attachments
LOCAL ANALYSED Load cases reacted on wheels / ground contact points					
9	Abrupt stopping 4g	-4		1	strength on wheel unit attachments
10	Windshield/Aero force	Aero load 3000/8000			Windshield stresses
Load cases reacted on structural elements					
11	Head on crash	-10		1	strength of seat rail and floor structure
12	Side crash in seat rail, side load reacted on floor		4	1	strength of seat rail and floor structure
13	Roll over 90 deg situation			-1	strength of frames
14	Roll over 180 deg situation		-1		strength of frames

3.2 Production Techniques and Materials

The floor is made of longitudinal and cross stiffeners, plus bathtub fittings to connect the seat rails with the floor structure without interfering with the longitudinal stiffeners (Fig. 5). The whole floor will be joined using mechanical fasteners to allow for maximum flexibility during the final assembly.

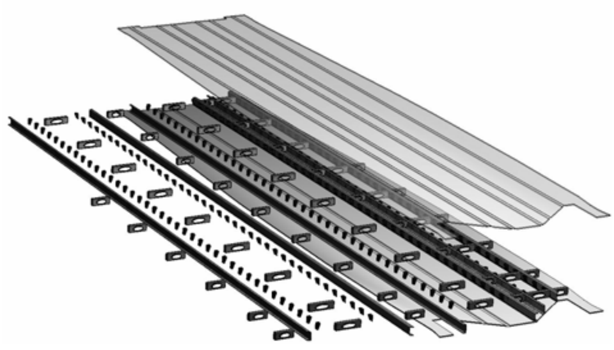

Fig. 5. Floor structure.

The floor structure consists of two sandwich plates forming the top and bottom of the floor which are produced by vacuum infusion [4] on a flat mould. In the bottom plate, access hatches will be present. The hatches are infused separately on the flat mould, cured, trimmed and replaced on the mould cover by Teflon release film. In a subsequent step, the actual bottom plate is infused over the hatches resulting in a flush outer surface. In the floor, the top and bottom plates are separated by longitudinal and transversal beams.

The longitudinal beams are also made by vacuum infusion in a simple U-shaped sheet metal mould. To ensure a proper mould filling and to avoid fibre bridging in the negative mould radii, a patented pre-forming step [4] will be performed in a separate tool.

The transversal beams, due to their amount and dimensions, are produced by rubber pressing in a thermoplastic material using a milled metal positive tool and a silicone rubber negative tool. Holes in the webs of these elements allow for the installation of systems like cables and air-conditioning in the floor structure.

The side panels and the structural beams of the central part are shown in Fig. 6. The internal frame structure is made by vacuum infusion, using one large left and right mould of the whole vehicle to produce the different parts. The moulds used for these frames will be milled by a low-cost direct tooling route. The rough shape of the mould will be milled with a 5 cm offset in polystyrene foam. A tooling paste is then applied over the complete surface which, after curing, will be milled to the final contour. The left and right frames are joined at the top by eight repetitive roof beam elements which are also made by vacuum infusion. The structural parts are all made by CFRP via vacuum injection, while the side panels are low cost GFRP (HPPC) with transparencies made of polycarbonate. The side panels are considered in the analysis as, though non structural parts, they have to be stiff enough to carry aerodynamic loads. As doors are only partially linked to the overall structure, they are not considered in the structural analysis.

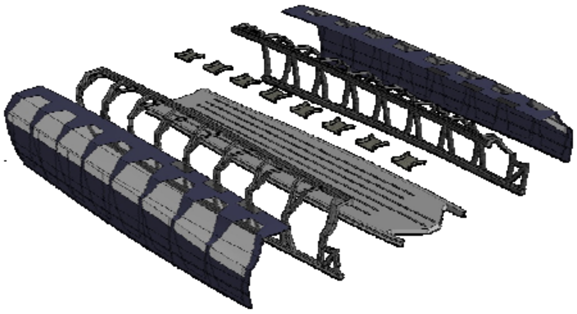

Fig. 6. Side panels.

The door panels will be made of a CFRP frame made via vacuum infusion, supporting PC transparencies in the top part and HPPC panel underneath.

The frames supporting the suspensions will also be CFRP sandwich panels made via vacuum injection.

3.3 Finite Element Model

The FE-model used to carry out the analysis of the final design is much more detailed than the one considered in the preliminary analysis and considers the actual design of suspensions, as shown in Fig. 7, though the suspension design has been schematised via stiff beams for the analysis.

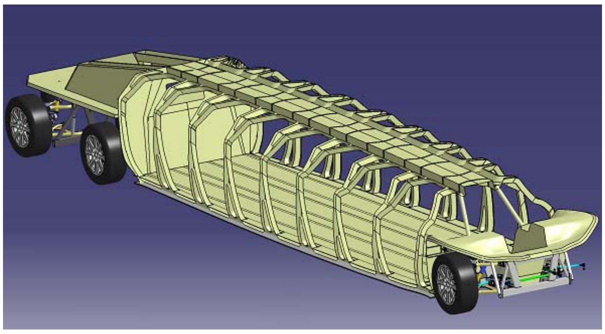

Fig. 7. Load carrying structure of the final design.

All material properties as defined during manufacturing are considered in the model, paying attention to describe in a consistent way all the lay-ups and overlaps of different parts to verify the stiffness in the regions were connections are present, thus in the weakest areas. An example of lay-up definition and different material properties is shown in Fig. 8:

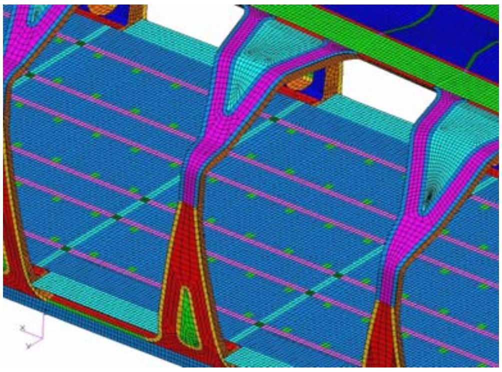

Fig. 8. FE-model refinement and material properties definition.

Here the side beams are shown together with the transparencies of the side panels and the HPPC panels on the bottom. All overlaps are also defined as a different material to verify the stress distribution in the connection.

Also the floor has been divided into different areas, the floor panel itself plus the connection between floor facing and longitudinal and/or transversal beams as well as the bathtub fittings.

In this way, a verification of the design, according to the load cases previously defined has been possible, as well as an optimisation loop to keep the weight as low as possible and still fulfil the requirements.

4. Production Aspects

An interesting and challenging detail of the framework is the cross-beam frame, shown in Fig. 9.

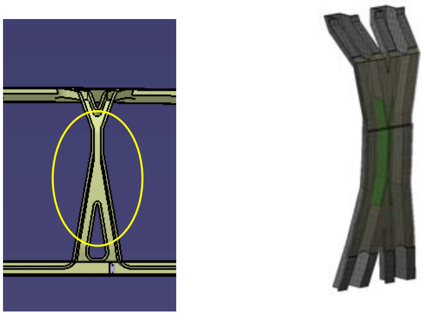

Fig. 9. Side cross-beam

This crossbeam is the consequence of the conceptual trade-off between the octagonal and rectangular door solution. Two beams join to form one beam and split into two beams again. In the central area, an internal element is needed to ensure the overall structural performance of the frame. Since this crossbeam region is one of the more complicated design details with respect production, a simplified section was manufactured to investigate the producability aspects. Fig. 10 shows the realisation of the production of this complicated section. The test resulted in some recommendations for modifications to the original design with respect to internal radii and release angles.

Fig. 10. Cross-beam demonstrator produced by vacuum infusion.

For the exterior body panels, moulds are milled for the complete left and right outer surface. Some of the exterior panels are made from a thermoplastic glass fibre reinforced sandwich laminate. These panels will be produced in smaller sections, due to the processing requirements. For this, moulds with a high temperature resistance are needed. These moulds will be laminated with a high temperature resistant resin from templates produced in the low temperature outer mould. The more complicated body panels with respect to double curvature and thickness steps, and the load carrying closing panels, will be produced directly in the outer mould with vacuum infusion in carbon fibre epoxy.

Each glazing is formed from polycarbonate sheet. This is a challenging operation as the parts are double curved and present sharp edges and combination of concave and convex curvature. To ensure proper weathering properties and UV protection, a plasma coating will be applied to the formed glazing in a subsequent step.

The body panels and glazing are adhesively bonded to the internal frame structure using the outer negative moulds as assembly tools to ensure an aerodynamic smooth surface. The assembled side panels are joined with the floor structure and roof beam elements to form the central part of the body work. Dedicated tooling is used to produce the elements for the driver compartment (including the driver roll-over protection elements) and motor and battery compartment.

5. Final Remarks

The *Superbus* does not fit in any category of existing vehicles. Due to this, the categorization rules and the required crash tests are being evaluated in collaboration with the Dutch Road Authority (RDW).

Therefore, in this phase of the programme, design and manufacturing of the structure of the vehicle are aimed at achieving the performance requirements with consideration of all foreseeable driving and crash conditions. However, the crash tests will be performed during the subsequent prototype phase.

The *Superbus* Demonstrator will be launched at the Beijing Olympics in August 2008. The planning before that date is very tight and includes detail design, production and assembly of all parts alongside testing of the various subsystems. Then, several tests will be carried out to verify both performances and structural integrity.

Acknowledgments

We wish to thank all our partners and suppliers in the definition and realization of this new vehicle.

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