A Design Methodology for Hydrogen Fuel Powered City Vehicles in Rear Impact Collisions

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Abstract

With the overwhelming reliance on fossil fuels, alternative fuel vehicles are beginning to emerge in the market. Battery electric vehicles are largely inferior to conventional fuel vehicles, as a result of the poor energy density (storage capacity) of current battery technology. Hydrogen technology may be a stepping-stone to a viable alternative fuel vehicle.

The Microcab vehicle, considered in this study, is based on the hydrogen technology and has been designed using M1 criteria with front and side crash protection in mind. The hydrogen fuel tank is however located in the rear floor area, hence its structural integrity after rear crash needs to be considered despite the lack of relevant legislative requirements.

The research presented proposes a design methodology for hydrogen fuel tanks protection in rear impact accidents using Computer Aided Engineering (CAE) analysis.

A generic rear impact safety load case, involving a rigid 1500kg barrier travelling at 30mph, is proposed to mimic a plausible rear city impact, allowing a structural assessment of the vehicle via explicit crash dynamics simulation and understanding the risks of tank rupture.

The initial CAE studies suggested that the Microcab backup structure needed improvements for the rear impact. Following initial studies a link was established between the stability of the structure and its sequential crush for robustness in the rear impact load case. This discovery was the underpinning for the improvements of the Microcab rear impact structural integrity.

The new design assessment method established the creation of adequate load paths in the structure, support for the envisaged crash loads, and the fulfilment of the hydrogen tank and structural integrity targets. This design process has the potential to be improved in the future by parameterising the dimension and masses of bullet vehicles to reflect a large variety of possible rear end accidents as part of the design process to ensure that hydrogen fuel tanks remain intact.

Keywords: EV, Hydrogen Fuel Cell, crashworthiness, Rear Impact, Optimisation

1 Introduction

The Microcab vehicle is a lightweight city car, for research into hydrogen fuel cell technology. Microcab has been the focus of project work with Coventry University as a joint venture with TSB funding. This paper aims to understand the implications hydrogen technology has in lightweight city cars, in terms of rear impact safety.

Research presented in this paper investigates the performance of the Microcab rear end structure in a city crash scenario and formulates the basis of a design method to consider all vehicle types impacting the Microcab vehicle (Figure 1).

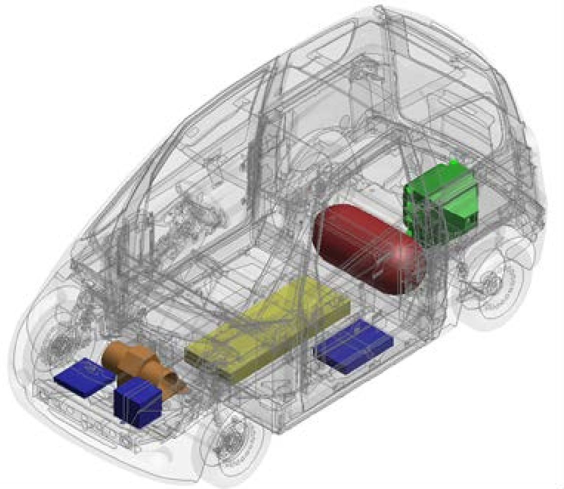


Figure 1 Hydrogen fuel cell propulsion system overview in Microcab.

The Microcab vehicle is based on a fuel cell propulsion system, in which hydrogen fuel tank is located in front of the rear axle and a fuel cell is mounted just behind the bumper system, as depicted in Figure 1. The primary load carrying structure of interest for this investigation is the chassis which provides the primary load path to the vehicle. The construction method employed relies on folded aluminium sheet parts bonded together to form box sections and panels. It can be observed that there are load path discontinuities at the heel board and toe board areas and there is no provision for bolt on/off replaceable structures at the front or back of the car (see Figure 2).

The paper investigates a base design methodology to assess and design the rear structure of the vehicle carrying a high pressure hydrogen fuel cell. As such, the implications of hydrogen as a fuel on vehicle architectures and the design implications for crashworthiness are initially discussed. A robust and numerically stable Microcab vehicle is then developed in order to set the basis for the development of the new design assessment process. This base model stability has been verified against 5 standard impact barriers, including frontal, side and rear scenarios.

Once the Microcab computer model is complete, a new rear impact test method is proposed and applied on the current vehicle. This method provides the bases for fuel cell design target assessments and also a window to the future of parameterising the bullet vehicle to replicate the full fleet of vehicles able to impact the rear of the Microcab.

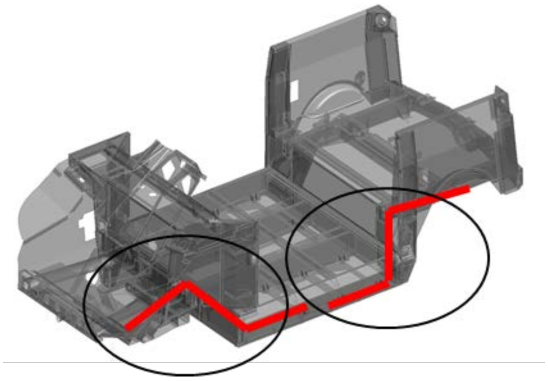


Figure 2 Microcab chassis layout showing discontinuities in structural load path.

2 Hydrogen fuel cell risk in impact situations

Hydrogen is a viable option as an alternative fuel for vehicles when considering greenhouse gases emissions, even if it does not offer the same level of energy density as petroleum fuels (see Figure 3) [1]. The handling of the hydrogen is quite different to current automotive petrol and diesel fuels, being lighter than air, colourless and odourless. It is often considered that hydrogen is a high risk because of its wide flammability range. Nevertheless, being lighter than air, it tends to diffuse quickly, limiting risk. The best method/technology to store hydrogen in a vehicle is still up for debate and is the subject of many current research projects.

The risk of a gaseous hydrogen tank (or other pressure vessel LPG/CNG, etc.) rupturing and causing a major hazard in an impact situation is low. Results of the fire safety evaluation of the hydrogen vehicle indicated that the fire of a vehicle equipped with compressed-hydrogen cylinders is not particularly more dangerous than that of a CNG vehicle or gasoline vehicle, so the level of safety during a single vehicle fire is equal to or superior to that of vehicles currently in use [2]. In order to prevent the fire risk of hydrogen the fuel tank integrity needs to be maintained after the impact event.

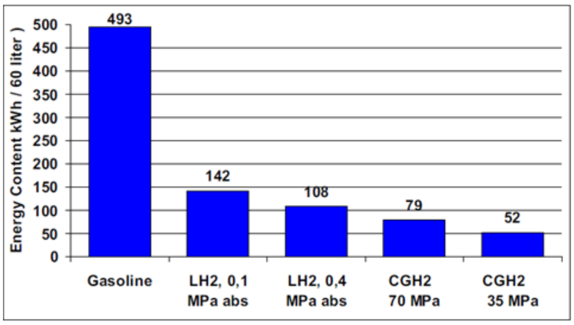


Figure 3 Energy content in 60 litre tank [1]

To investigate the strength of the pressure tank Fell at al. [3] conducted low velocity impact test which replicated the puncture of the fuel tank. For the test purpose, a 25mm diameter impactor was loaded quasi statically into the non-pressurised tank (strain rate effect not considered), as shown in Figure 4 and Figure 5. The results suggest composite tanks working at high pressures can withstand significant levels of load before structural integrity is compromised.

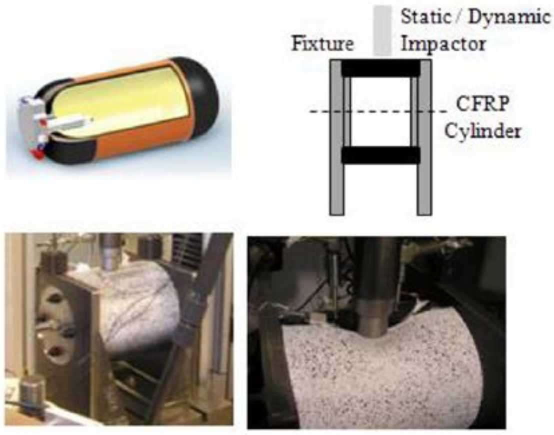


Figure 4 Level 3 CFRP cylindrical test setup [3]

Figure 5 Comparison of experimental load displacement curve with simulation results [3]

Although the pressure tanks are relatively strong and can withstand a considerable impact force without sustaining damage, the pressure levels must adhere to the pressure vessels standards in order to mitigate the risk of rupture and failure [3].

As the Microcab is a lightweight vehicle, it is important to engineer the hydrogen fuel tank with the lowest possible mass, whilst still maintaining a good level of safety. The structure could be designed for no contact to the hydrogen tank, but in reality it would be a very pessimistic approach to design. This would result in an unnecessarily heavy structure which would impact other global attributes of the vehicle i.e. reduced ranged.

Conventional hydrogen vehicle architecture tends to force the position of the hydrogen tank in to less vulnerable areas of the car [4]. It can be seen from the GIDAS crash intrusion data that the current location of the H2 tank in the Microcab has been located in a low vulnerability area of the car, and so should offer a good level of passive safety as a result of the vehicle architecture, as depicted in Figure 6.

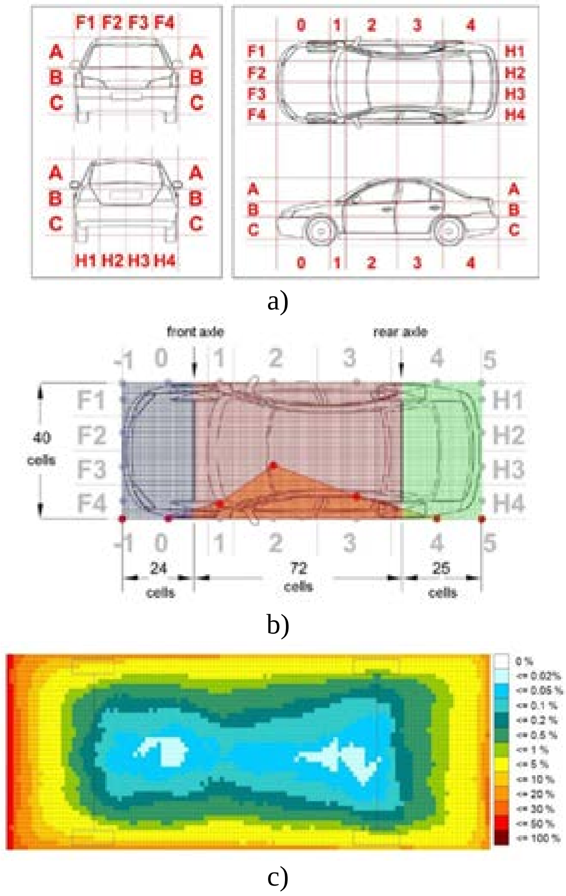


Figure 6 a) GIDAS deformation zones, b) Vehicle independent grid and one deformation matrix, c) Combination of the GIDAS deformation matrix with Cell Frequency Matrix based on the sample of 8600 vehicles.

The GIDAS data shown in Figure 6 and Figure 7 represents the areas of maximum intrusions based on 8600 vehicles. As the Microcab fuel tank is located behind its rear axle, it is expected to have good crash performance in rear impact scenarios [5].

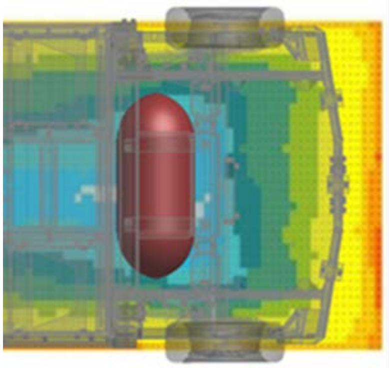


Figure 7: Overlay of scaled GIDAS data vs Microcab Hydrogen fuel tank location.

Although there is no legislatives rear impact tests requirements on these vehicles and the Microcab hydrogen fuel tank is packaged reasonably, it is important to create a design and analysis process to assess its structural performance and ensure that failure / rupture does not happen.

A finite element model of the Microcab was built in order to study the suitability of its rear crash structure.

3 Rear crash load case development

To understand the current performance of the vehicle, a representative load case for a 'typical' rear crash event was developed to reflect the Microcab typical usage, which is in the city. The max speed likely to be encountered in a city is 30mph. With car to car compatibility considered for this test, i.e. 'real world safety', the mass of the impacting car is likely to always be higher than the Microcab vehicle itself, which is 850kg. The mass of the impacting vehicle can be estimated in the region of 1500kg (comprising of an average car mass [6] + average occupant (50^{th}) + luggage = 1383 +80 + 40). In order to simulate this possible event, the proposed rear impact scenario considers a 1500kg rigid trolley moving at 30mph (13.41m/s) (Figure 8).

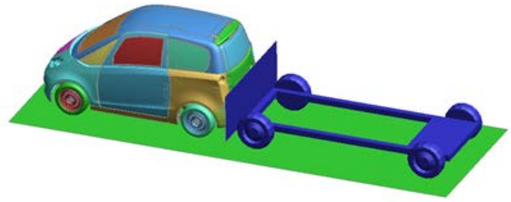


Figure 8 Proposed trolley to assess the Microcab rear impact performance.

The full overlap has been chosen as at low speeds the overlap tends to be greater than at higher speeds. A rigid barrier has been chosen to simulate this event for 2 reasons:

- A rigid impactor computes faster than a deformable one.
- In the future it will be possible to change the profile of the plane to represent the profile of a family of vehicle frontends and study the effect of vehicle profiles.

Comparing the new test proposal with FMVSS 301 [7], which provides requirements for fuel integrity during rear impact and after the event with limits on the amount of fuel that can leak during tests, it can be noticed that the impact velocity is the same but the vehicle mass is different as FMVSS301 relates to truck impacts.

In addition to these fuel integrity legislative tests, with the increasing number of electric vehicles becoming type approved, a test method for the integrity of the electrical system is also required. This has been addressed **in 'FMVSS 305 – Safety requirements for electric vehicles'** [8]**.** These are additional requirements to take into account any possible electric powertrain specific issues in addition to the current test procedures for FMVSS 305 [8].

- 'Max 5 litre electrolyte spillage, no electrolyte leakage in passenger compartment'
- 'All components of the energy storage/conversion to remain anchored to the vehicle'
- 'No battery system located outside of the passenger compartment shall enter passenger compartment'
- 'Electrical isolation greater than 500Ω/V for AC high voltage, 100 Ω/V for DC'

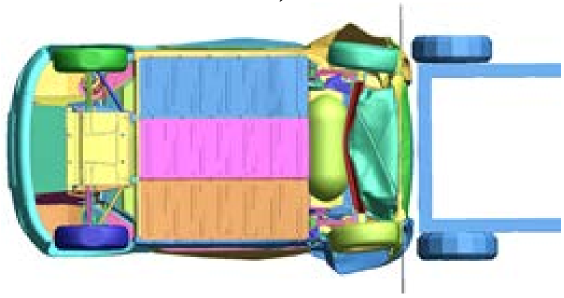
To develop a structure virtually new CAE numerical targets need to be proposed. However, detecting leaks post-test is simply not possible in CAE and requires a more subjective assessment of the structure and contact events/interaction of fuel system in the simulation animations to identify potential risks.

The above requirements are fundamental to determine a sensible, realistic load case for the Microcab rear impact assessment and development as there are no current legislative requirements.

In order to meet fuel system integrity standards, it was decided to monitor the total vehicle rear intrusion, hydrogen tank contact force and contact event and structural plastic strain (structural integrity).

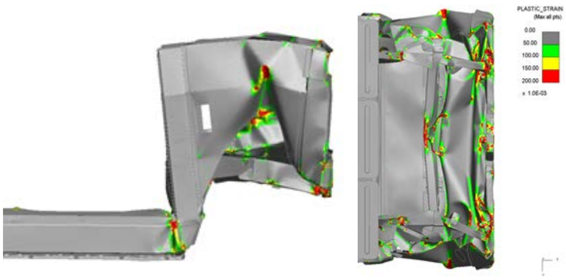
The original Microcab was subjected to the new test and it was observed that the longitudinals were hinging and lozenging, suggesting a lack of lateral support and an unstable base design, as depicted in Figure 9 and Figure 10.

a)



b)

Figure 9 Deformation shape of the Microcab after rigid barrier impact: a) side view, b) bottom view

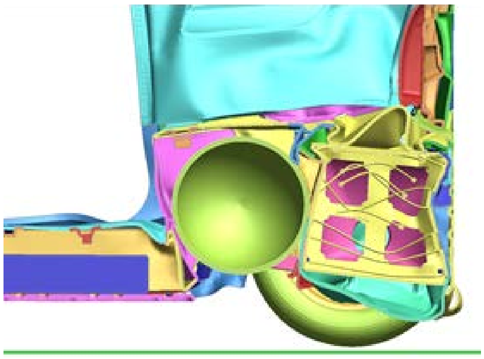


a) b)

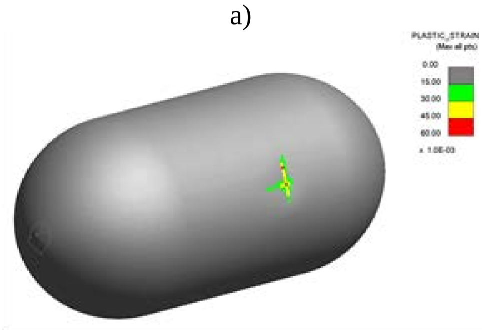
Figure 10 Detail lozenging of chassis under rear impact: a) rear structure side view, b) rear structure bottom view.

It was also noted that the rear structure rotated and contacted the hydrogen fuel tank, indicated by a localised plastic strain concentration of 6% (sharp contact), as depicted in Figure 11.

In body structure development, the start of permanent damage can be seen when the plastic strain reaches numerically 4% [9]. Consequently, this impact outcome would need new design consideration. Nevertheless, the plastic strain concept requires extensive knowledge of the fuel tank material property in the plastic range as well as in the dynamic plastic range, due to strain hardening effect. Alternative method to assess the structural suitability of the fuel cell is to compare its contact force with the rear components. The contact force could be then compared with the fuel tank physical test results presented in Figure 5. In the base case the contact force was estimated to 22.5kN (Table 1) which appears not to be cause for concern, nonetheless the stability of the chassis needs improvements without compromising the fuel tank integrity.



a)



b)

Figure 11 a) Microcab rear structure rotation, b) Contact with fuel tank.

Load path determination.

To understand the baseline performance of the vehicle it was decided to track the force level travelling through the structure.

Initial development studies focused on improving both the local modelling of the car and its global performance, which included:

- Fuel cell orientation (Figure 12)
- H2 tank mounting (Figure 13)
- Conceptual effects of up-gauging the vehicle rear longitudinals and stiffening the backup structure.

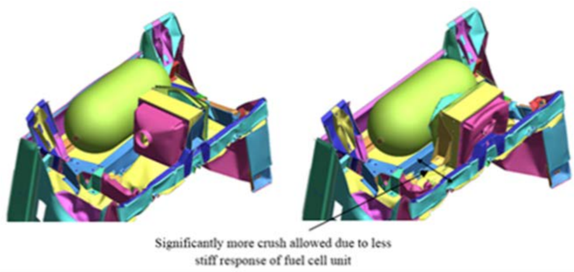


Figure 12 Fuel cell orientation

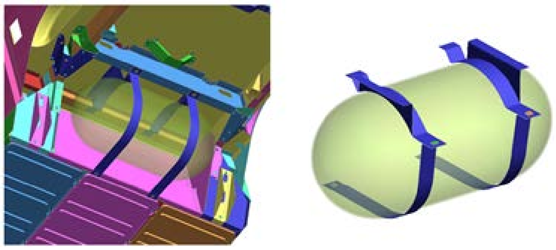


Figure 13 New hydrogen tank mounting strategy

Key Performance drivers

From the initial studies, it was found that the key issues with the structure were a result of its low longitudinal energy absorption, caused by the longitudinal crush mode, and the backup structure not providing enough stiffness to support the progressive longitudinal collapse.

An up-gauge of 2.5mm to the current rear longitudinal section was found to provide both sufficient energy absorption and structural intrusion to allow the hydrogen fuel tank to be protected in this impact event. This change also requires a further increase of the stiffness of the backup structure in order to support increased initiation crush force of rear longitudinal.

The up-gage could not be performed because of manufacturing constraint, hence the need to redesign the backup structure. The current backup structure is a result of the packaging and architecture of the vehicle. Two concepts were developed in order to address the additional support required for the stiffer longitudinals.

The first concept connected the rear of the longitudinal and the floor with a bent sheet of metal to create a gusset, as depicted in Figure 14. The second concept is based on a high strength extruded heelboard using internal ribbing in box sections to support the bending load (Figure 15)

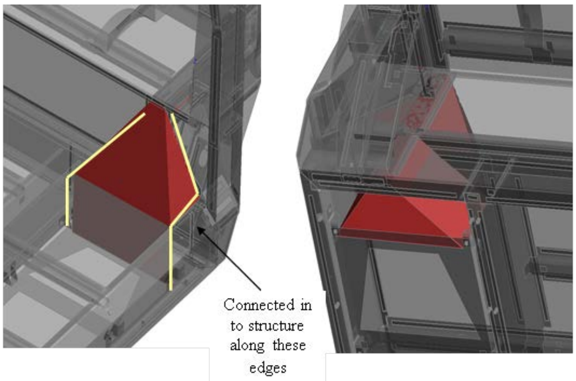


Figure 14 Concept 1 - Gusset reinforcement

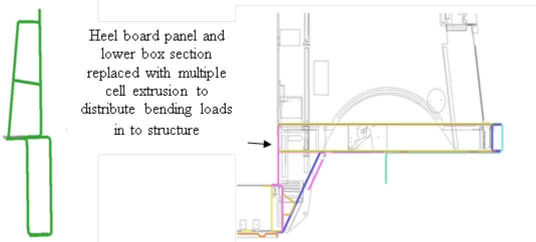


Figure 15 Concept 2 – heelboard concept

Concept performance

Both concepts developed offer significant structural integrity improvements with very similar levels of performance.

Folded longitudinal load spreading with a gusset (concept 1) appears to be the best solution for cost and added mass, based on the results from Table 1. Although, there are still some shortcomings in the design like reduction in rear occupant foot space and a lack of tunability.

Table 1 Results between Concept 1, Concept 2 and baseline

	Baseline	Concept 1 gussets	Concept 2 Extruded heelboard
Chassis structural integrity	High risk	Low risk	Low risk
Front floor X deformation (mm)	15	12	11
Hydrogen tank contact force (kN)	22.3	22.7	30.5
Level of intrusion (mm)	426	368	368
Packaging change	None	Rear pass foot space	Small
Tunability range	Limited	Limited	High
Manufacturing change	None	Low	High
Estimated added mass (kg)	0	11	20
Estimated cost (£)	0	27.6	93.4

Comparison of the hydrogen tank contact force value (see Table 1) with the test result from Figure 5 indicates that there is no risk of fuel tank damage.

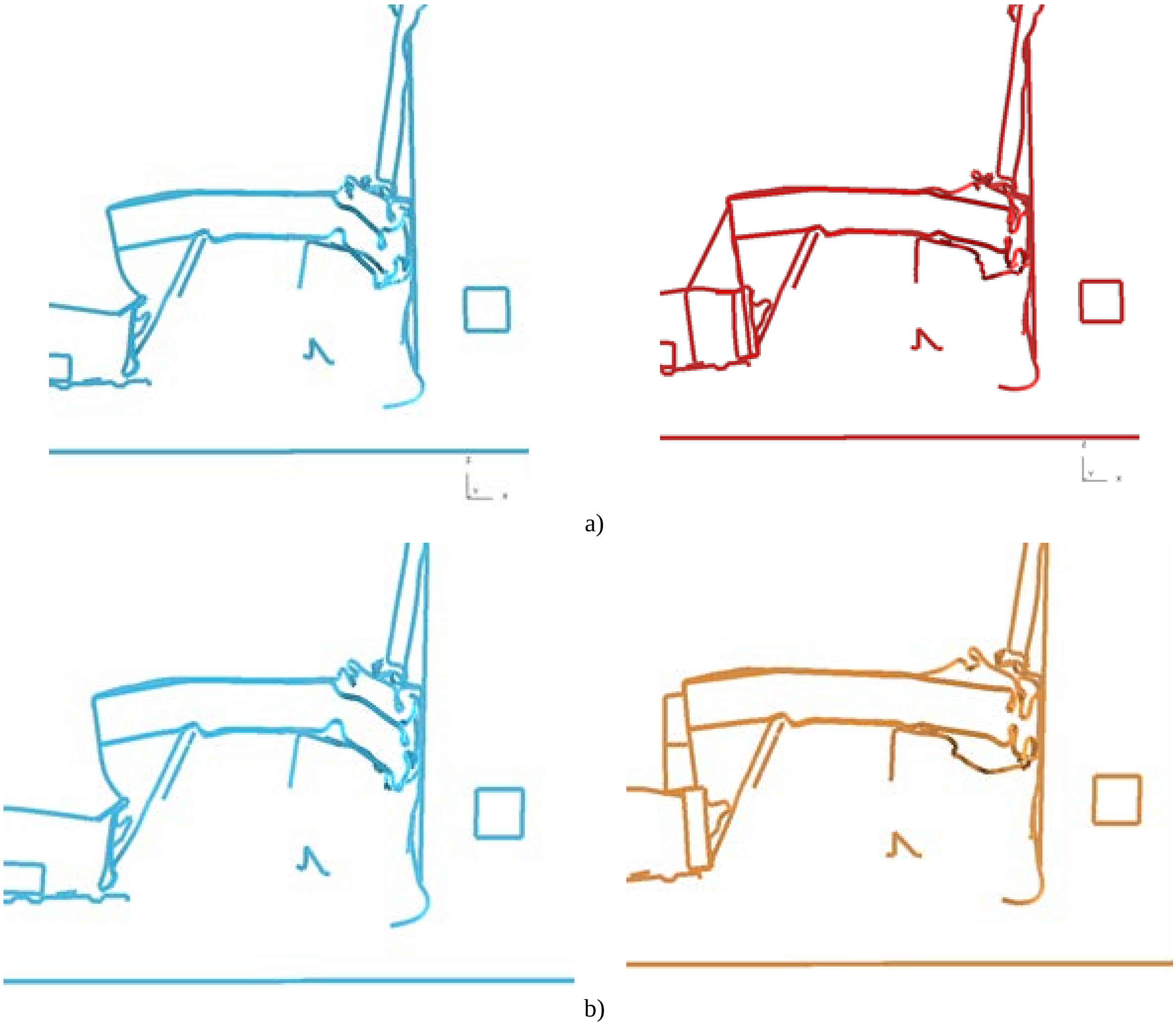


Figure 16 Comparision between the deformed shape of the rear of the Microcab a) Baseline - Concept 1, b) Baseline - Concept 2

From Figure 16, it can be observed that the baseline model folds more than the two proposed concepts, which is consequently generating more intrusions. Concept 1 and 2 output the same deformation, however, it comes with a weight penalty in excess of 10kg.

Extruded heelboard concept ensures good performance on most metrics, however, it comes with a major drawback related to the cost of the extruded solution. Even if the design could be tuned and reduced in mass the cost would still be much higher than the folded solution and with £10-15k additional tooling cost. The construction-assembly method requires some revision as the connections to the extrusion need detailed design work to get the solution production ready. It would probably offer the highest tuning scope of the two concepts. With further optimisation of rib patterns and wall thicknesses, the weight could be significantly reduced.

As with all aspects of design, there is clearly a compromise to be made. Concept 1 provides overall the best solution to meet the newly devised rear impact load case as it offers the max improvement in terms of kg/£ spend for the additional occupant protection.

Tank mounting integrity

Together with improvement of the global vehicle performance, sub system performance was also investigated in this study. This was a result of the FMVSS 305 Safety requirements, to retain electrical fuel cell items in impact event. In order to understand whether the current design could achieve this, bolt forces were extracted to size the fixings and ensure the structure was capable of supporting these loads (Table 2).

Table 2 Bolt forces iin the Microcab rear section (Concept 1)

Bolt postion	Axial load (kN)	Shear load (kN)
fuel cell front LH	4.3	1.1
fuel cell front RH	3.3	2.7
fuel cell rear LH	4.4	1.1
fuel cell rear RH	6.1	2.3
H2 tank front xmember LH	4.7	5.7
H2 tank front xmember RH	4.3	4.9
H2 tank rear xmember LH	11.1	1.1
H2 tank rear xmember RH	12.7	1.6

The results showed M8 bolts were the minimum required in all locations, and only the front hydrogen tank mounts required additional stack thicknesses, in order to reduce pull through risk (thin sheet bearing failure mode).

4 Conclusions

This paper proposes a new rear impact methodology aiming to protect vehicles with hydrogen fuel tank in city accidents. The scenario proposed simulates a 1500kg rigid trolley impacting a stationary vehicle at 30mph with 100% overlap. The vehicle mass is derived from the average vehicle fleet mass with the mass of the driver and luggage. The Microcab vehicle was then subjected to this new assessment method and displayed some deficiencies in rear floor stiffness due to excessive bending, hence causing contact with the fuel tank. Due to limited material properties for fuel tanks and in some case their design complexity, it was proposed to use a force based failure criteria to assess the hydrogen tank integrity.

A detailed study was performed to investigate the feasibility of reinforcing the Microcab floor as well as reducing the deflection of the rear structure. This led to the successful development of a design concept reinforcing the heelboard thickness and bending capabilities by using an added gusset structure.

The study showed in details the design steps necessary for reinforcement of the Microcab rear structure. Two different reinforcement concepts were introduced and their performance was investigated to ensure the best protection of the fuel tank.

The proposed design process will be improved further in the near future by parameterising the dimension and masses of a fleet bullet vehicles to reflect more possible rear end accidents as part of the design process to ensure that hydrogen fuel tanks always remain intact whatever the scenario.

5 Future work on fuel tank assessment

The next step of the fuel tank rear crash assessment considers the influence of the impacting car frontend geometry, masses and moments of inertia on the crash performance of the Microcab rear structure. The parametric car developed at Coventry University enables for quick generation of different car frontends (see Figure 17). In conjunction with the stiffness evaluation obtained from the APROSYS project [10] it enables for investigation of the car front geometry influence on the crash performance of impacted structures.

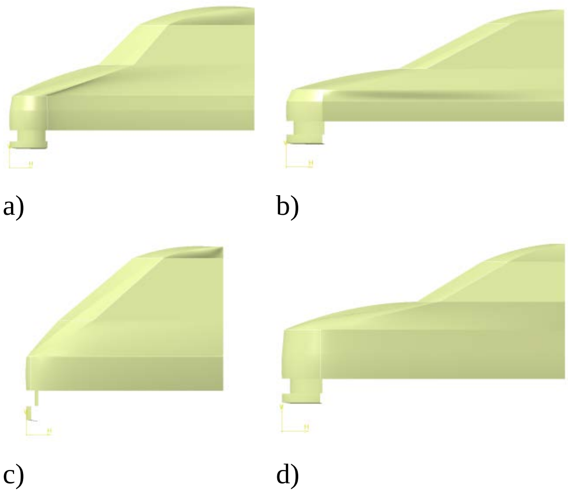


Figure 17 Different car front ends obtained with parametric car software – a) Mini, b) Audi A4, c) Smart, d) BMW X3

As the final assessment of the Microcab rear structure different level of overlap will be investigated.

References

[1] Amaseder F, Krainz G. Liquid Hydrogen Storage Systems Developed and Manufactured for the First Time for Customer Cars. 2006;2006-01-0432.

[2] Suzuki J, Tamura Y, Watanabe S, Takabayashi M. Fire Safety Evaluation of a Vehicle Equipped with Hydrogen Fuel Cylinders: Comparison with Gasoline and CNG Vehicles. Fire Safety 2006 2006;2006-01-0129.

[3] Fell S, Schuetz T, Schultheis V, Kang S, Gama B. Crash Modeling of High-Pressure Wet Wound Composite Vessels. 2011;2011-01-0016.

[4] Veenstra M, Hobein B. On-Board Physical Based 70 MPa Hydrogen Storage Systems. SAE Int. J. Engines 2011;4(1):862-1871.

[5] Bakker J, Sachs C, Otte D, Justen R. Analysis of Fuel Cell Vehicles Equipped with Compressed Hydrogen Storage Systems from a Road Accident Safety Perspective. SAE International Journal of Passenger Cars – Mechachnical Systems 2011;4(1):332-342.

[6] ICCT. European Vehicle Market Statistics. 2015;.

[7] National Highway Traffic Safety Administration. FMVSS 301, Fuel System Integrity. 2007;TP-301-04.

[8] National Highway Traffic Safety Administration. FMVSS 305, Electric Powered Vehicles: Electrolyte spillage and electrical shock protection. 2008;TP-305-01.

[9] Christensen J, Bastien C. Non-linear Strcutural Optimisation of Vehicle Safety Structure. 1st ed. : Butterworth-Heinemann; 2015.

[10] Leaders SP. APROSYS Dissemination and Use Plan M1-M60. 2011;AP-SP91-0293.

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