Generation of Optimised Hybrid Electric Vehicle Body in White Architecture from a Styling Envelope

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Abstract - As focus on the world climate rises, so does the demand for ever more environmentally friendly technologies. The response from the automotive industry includes vehicles whose primary propulsion systems are not based upon fossil fuels, namely Full Electrical Vehicles (FEV). There is an opportunity to design and engineer new innovative FEV architectures, whilst minimising their mass in order to further reduce carbon emissions. This paper proposes an engineering process for optimising new FEV lightweight vehicle architecture based on a technique entitled topology optimisation, which extracts the idealised load paths for a given set of load cases. Subsequently shape and size optimisations are conducted in order to obtain detailed information of localised vehicle geometry such as individual BIW cross-sections. The research discusses each individual step of the overall process including successes, limitations and further engineering challenges and complications which will need to be resolved in order to automate the vehicle architecture design to include e.g. durability and (dynamic) crashworthiness performance.

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I. Introduction

Given the current state of the economy there is a global consensus to reduce Carbon Emissions (CE) in relation to the automotive industry. Stringent targets have been set in order to achieve a 30% reduction in CE by 2020 [Greencars (2010)] for reducing greenhouse gas emissions by a minimum of 20% relative to 1990 levels, to increase the share of renewable energy sources in our final energy consumption to 20%, and to increase energy efficiency by 20%. The public expectations to move towards the electrification of road transport are driven by a multitude of factors and concerns including: climate change, primary energy dependence, public health as well as cost and scarcity of raw materials. However, it is the growing awareness that the underlying technology has gained a sufficient level of maturity which is also driving the need for more rapid development thereof.

Users are demanding Electric Vehicles (EV) to perform well beyond those that the Original Equipment Manufacturers (OEMs) can deliver at present. However, the spread of "unsafe" vehicles, polluting vehicles, bad practices and inefficient infrastructures should be avoided. This EU initiative significantly affects the design of new vehicles, leading to new green technologies aimed at reducing CO_2 levels. These include automatic stop/start, KER (Kinetic Energy Restitution by braking) and better engine management systems. Electric battery vehicles are now being considered as potentials to replace current Fossil Fuelled Vehicles (FFV). EVs are however still in the early stages of development, and their acceptance as a full replacement for FFVs still not universal. As part of the Cabled project [Cabled (2011)] a fleet of 110 new vehicles fitted with electric technology is currently being tested in Coventry (UK) and Birmingham (UK), aimed at assessing customer attitude to initial purchase price as well as range anxiety for longer journeys which remains to be resolved before mass deployment of EVs.

All these new technologies will potentially be beneficial to aid in the reduction of CO_2 emissions. However, the electric components required for EVs most often lead to a substantial increase in overall vehicle mass, resulting in increased energy consumption for vehicle propulsion. Other significant questions also remain unanswered, primarily relating to the safety of batteries, particularly during impacts scenarios.

The Low Carbon Vehicle Technology Project (LCVTP) [LCVTP (2011)] addressed the problem of electrical vehicle light weighting, in order to compensate for the added mass of the battery. This was achieved by performing advanced Body In White (BIW) topology optimisation[4], mainly focussed on structures utilising isotropic materials. The vehicle BIW design optimisation primarily considered a multi-disciplinary approach to design optimisation, mainly focused at EuroNCAP equivalent static load cases as well a torsional rigidity. The Low Carbon Vehicle Technology Project has been instrumental in understanding vital attributes essential for engineering lightweight vehicle structures. Additional funded projects are presently underway, such as the EPSRC (UK) funded project, Towards Affordable, Closed-Loop Recyclable Future Low Carbon Vehicle Structures (TARF-LCV) project [EPSRC (2011)]. The overall aim of the TARF-LCV project is to define a comprehensive scientific and technological foundation for future LCV development in the strategic areas of

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advanced materials, low carbon manufacturing technologies, holistic mass-optimised vehicle structure design and closed-loop recycling of End Of Life Vehicles (ELV). Another example of a current project is the FP7 European funded research project entitled Ecoshell [Ecoshell (2012)], the overall aim of which is to develop bio-composite based super light electric passenger vehicles.

The project is concerned with the development of optimal structural solutions for superlight electric vehicles (category L6 and L7e, i.e. lighter than 400kg without batteries), decreasing the environmental footprint, and using an innovative bio-composite material for the vehicle body.

These projects demonstrates the timeliness and urgency of developing tools and techniques related to vehicle light weighting, especially within the field of electrical vehicles.

One of the major improvements needed from the LCVTP project was the improved definition of the architecture obtained by utilising topology optimisation techniques [Huang and Xie (2010)], [GACM (2011)] and [Duddeck (2007). Indeed, generating a BIW topology by means of optimisation does not provide detailed knowledge of the individual section properties, rather an indication of force flow throughout the structure [Duddeck (2007)].

This paper aims to utilise the findings of the results and techniques obtained from the research undertaken in the LCVTP [Bastien and Christensen (2011)], [Christensen et. al (2011)], [Christensen et. al (2011a)], [Bastien (2010)] propose a framework to automatically generate the BIW architecture including detailed cross-sectional properties of the vehicle architecture.

II. OPTIMISATION TECHNIQUE USED IN THE FRAMEWORK AND LIMITATIONS

The objective of the study was to minimise the BIW mass when exposed to the load cases illustrated by Figure 1. These include front impact Rigid Wall (RW) and Offset Deformable Barrier (ODB), pole impact, side barrier impact, roof crush on top of A-pillar, low speed centred rear impact, high speed rear impact and torsional rigidity.
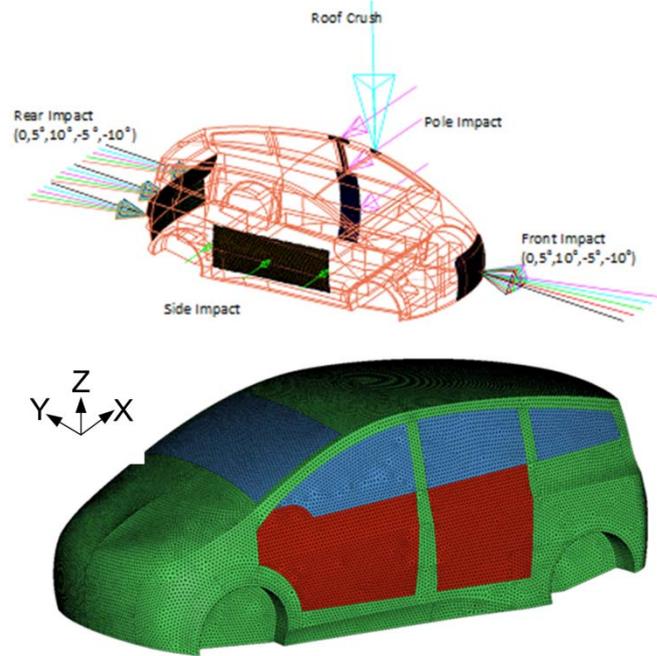

Figure 1 : Loads applied on the vehicle and associated analytical model

To solve the problem, two different types of constraints were considered, Single Point Constraints (SPC) and Inertia Relief, (IR).

The SPC constrains the Degree Of Freedom (DOF) for selected nodes, the model thereby seeks to obtain force equilibrium of the structure, by means of equation (1).

$$\{F\} = [k] \cdot \{u\} \qquad (1)$$

IR works by balancing the external loading with inertial loads and accelerations within the structure itself, without constraining any DOF. This is specifically done by "adding" an extra displacement-dependent load to the load vector, and subsequently adapting the stiffness matrix [k], as indicated in equation (2), where $[k_{add}]$ represents the additional terms of the stiffness matrix, [k] is the "original" stiffness matrix in equation (1), [Altair (2010)].

$$\{F\} = [k_{IR}] \cdot \{u\} = \begin{bmatrix} [k] & 0 \\ 0 & [k_{add}] \end{bmatrix} \cdot \{u\} \qquad (2)$$

Both methods were investigated and it was concluded that the IR method provided the most stable and adequate solution [Christensen et. al (2011)].

It has to be noted that the current state of the art optimisation methodology is based upon an implicit linear solving algorithm, which is very well suited for structural stiffness design. This method can however not predict non-linearity, let alone complex buckling events, such as the collapse of a front longitudinal member. Within these limitations it has been documented that the

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solution provided by the linear solver produces a "reasonable" topology for the safety (passenger) cell, roof and floor [Bastien and Christensen (2011)]. The linear static topology optimisation algorithms used were based on the Solid Isotropic Material with Penalisation (SIMP) interpolation scheme [Bendsøe and Sigmund (2003)], stipulating that the relationship between the stiffness matrix [k] or [k$_{IR}$] and the volumetric mass density (ρ) was defined by the "power law for representation of elasticity properties" as equation (3) [Altair (2010)]:

$$\underline{[k]}(\rho) = \rho^p [k] \qquad (3)$$

In equation (3), $\underline{[k]}$ is the penalised stiffness matrix, and p is the penalisation factor, which is used to determine the "type" of relationship between [k] and ρ. As long as ρ is equal to 1.0 the two are directly proportional, as illustrated in Figure 2.

This relationship can be adjusted, by varying ρ with the effects as indicated in Fig. 3. The reason for adjusting this relationship is typically to penalise intermediate density values, in order to avoid "vague" definitions of topology, this is also sometimes referred to as "checkerboard effect".
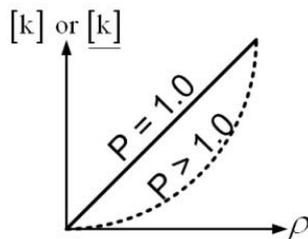

Figure 2 : Relationship between [k] and ρ.

However, initial analyses revealed that this was not a widespread problem for the models in question. Therefore in the remainder of this paper the value of p will be 1.0, i.e. a linear relationship between the stiffness matrix [k] and the mass density ρ will exist.

From the tools used, and within the current mathematical limitations for topology algorithms, it has been well documented that topology optimisation on its own is adequate for safety cage development (A-pillar, side rails, headers, roof structures and floor) [Bastien and Christensen (2011)], [Christensen et. al (2011)], [Christensen et. al (2011a)], [Bastien (2010)], but not for the generation of the front end crash structure, which is expected to plastically deform during crash scenarios, i.e. experience non-linear behaviour.

III. Automation of Design Process

The optimisation processes proposed in this paper, utilises the design envelope of the Tata Beacon [LCVTP (2011)]. The ultimate aim of this process is to complement the topology optimisation phase by providing further detailed definitions of the local BIW

structure (cross-sections) whilst keeping the vehicle architecture mass to a minimum. BIW development processes do in general not utilise both topology-, shape-, and size- optimisation in succession to each other, consequently leading to BIW designs not fully exploiting the potential of structural optimisation for minimising BIW mass [Duddeck (2007)].

The flow-chart of the proposed design process is illustrated in Figure 3; outlining the necessary steps to minimise BIW mass. The starting point is the styling envelope of the vehicle used to define the design volume for the topology optimisation process. The design volume definition is key for the success of a truly lightweight architecture characterisation.
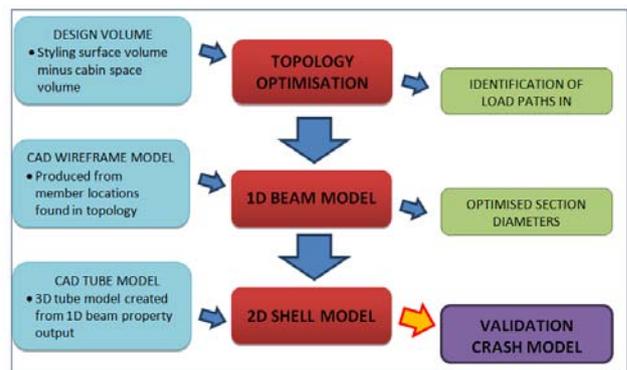

Figure 3 : Automatic Design Process

a) Design Volume

Firstly, the Design Volume was defined by removing the interior cabin volume from the volume created by the exterior styling surfaces. In locations where thin walls existed (i.e. roof and sides) design volume was created (e.g. a 50mm) to allow space for structural members to form during the topology optimisation process.

All non-structural components were excluded from the BIW design volume, such as the electric motor, the batteries and the range extender, as these were not assumed to transmit any load originating from crash scenarios. Excluding these from the design volume ensured that no structural members were defined in these areas during the topology optimisation, thus allowing sufficient space for these components and vehicle packaging in general.

Furthermore, vehicle apertures were only considered to be attached at hinges and locking points, hence these were detached from the main body (design volume) and were fixed to the main body in such a way that they only provided longitudinal stiffness for the appropriate load cases.

With the above considerations the design volume for the BIW was defined. This provides the starting point for the optimisation process, as dictated by Figure 3.

b) Topology Optimisation

The general load paths for the BIW architecture were then extracted by means of topology optimisation, removing inefficient material with respect to the structural integrity of the BIW, exposed to the pre-defined load cases.

The design volume was meshed with first order tetrahedral elements, and also included concentrated nodal masses to reproduce the inertial effects originating from e.g. battery mass. Vehicle apertures were constrained to the main vehicle body at the hinge and lock locations, in order to represent longitudinal stiffness in connection with the relevant load cases illustrated in Figure 1.

As previously discussed, the load cases represented equivalent static forces relative to those utilised for a dynamic crash scenario modelling, extracted from relevant crash tests. These included front-, rear-, side-, pole-impact as well as roof crush scenarios. The front and rear load cases also considered application angle sensitivities by adding load cases with the loads applied at 5°, 10°,-5° and -10° relative to the global x-axis, Figure 1. The roof crush loading was applied at the top of the A-pillar, thus representing a vehicle roll-over. The pole impact scenario was applied at the B-pillar. The side impact loading was evenly distributed spread over a rectangular area between the front and rear doors.

2D elements (shell barriers) were created at the locations of the applied forces, with coincident nodes to the 3D elements of the design volume. Subsequently the loading was applied to the 2D elements, allowing the entire vehicle body to undergo volume reduction optimisation. The purpose of this was to eliminate the requirement for non-design areas to maintain constant applied loading as material was removed (3D elements) during the topology optimisation.

c) Wireframe Model from Topology Design Fraction

Following the topology optimisation a wireframe model was created based upon the optimised load path, Figure 5.
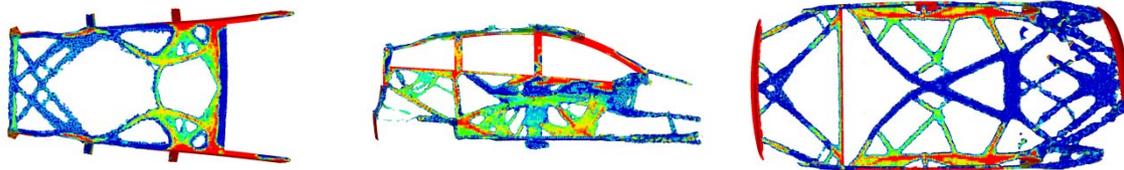

Figure 4 : Topology results. Roof (left), Side (centre) and floor (right)

As the final BIW design was required to be symmetrical (around the xz-plane, Figure 1), the topology optimisation was set up using symmetry constraints. Consequently it was sufficient to utilise "half" the wireframe model in the continued optimisation study. The wireframe model is illustrated in Figure 5.
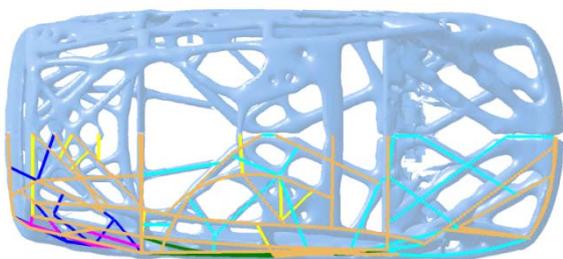

Figure 5 : Topology Optimisation result with wireframe overlay

In order to continue the BIW optimisation process of Figure 3, it was necessary to simplify the BIW topology, utilising beams to represent the individual load paths. This step was the only one of the entire process to be completed manually. The primary reason for this was the complexity associated with interpreting the results. This required profound "engineering intuition", which is extremely difficult, if not impossible to program. The location of these beams relative to the topology optimisation results are illustrated in Figure 5.

d) 1D Beam Model

The objective of the beam model was to create a model where each individual section (member) could be optimised independently of one another. This was to be achieved within the pre-set optimisation constraints, aimed at producing a lightweight structure. In order to transform the beams produced by the topology optimisation into hollow beam sections to be further optimised, an initial beam property needed to be specified. A tube section profile was chosen in order to find the ideal sectional stiffness' and dimensions using a minimal number of design variables. Since the topology optimisation produced in excess of 100 individual members, the starting cross-sectional properties of each individual member, as well as the associated design variables needed to be defined. This was achieved using an automatic script generation process, allowing the parameters to be automatically created in the architecture of the input deck. Each property specified a sequential property ID to which the relevant beam was associated. Each property ID had the relevant Design Relationship (DVPREL input card [Altair (2010)]) defined

and related to it. This was in order to define the variables of the cross-sectional dimensions, a Design Equation (DEQATN input card [Altair (2010)]) linking the section dimensions to prevent the crossing of the inner and outer radii and a Design Variable (DESVAR input card [Altair (2010)]) to specify the initial dimensions and the sizing limitations of the individual member.
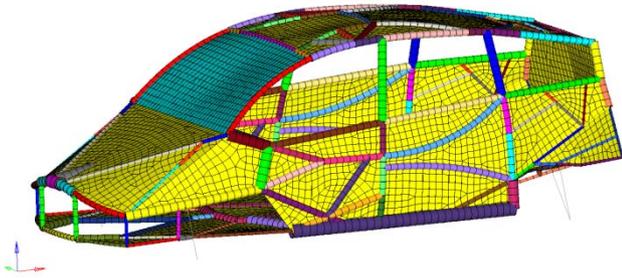

Figure 6 : 1D Beam model with shear panels

The wireframe model was used to position beam elements at the locations produced from the topology optimisation. Each line mesh was assigned relevant section property IDs which included the corresponding dimensions and general optimisation setup. Shell elements were used to represent shear panels between the beam elements, characterising the outside body panels of the BIW. The beam and shell elements in areas representing apertures were only attached at hinge and lock point locations, to represent the same fixing of that used for the topology optimisation.

It was imperative to ensure that the load steps of the 1D beam model were applied analogue to the ones used for the topology optimisation. In addition, the 1D model also utilised Inertia Relief boundary conditions.

At this point, an additional loadcase was added to ensure a static torsional rigidity between 16-20 kN/m. Previous studies had shown that this was not necessary to include during the topology optimisation stage, as this did not have any significant effects upon the topology optimisation results. However, this load case was fundamental in order to generate appropriate BIW topology to resist torsion and twist, even without monitoring the magnitudes thereof.

In addition to the optimisation constraints outlined above, it was also crucial to include considerations with respect to buckling of individual members. The importance of this can be realised by considering the consequences of roof members buckling during roll over cases. Existing linear buckling analyses models using eigenvalue extraction were unsuitable for the purpose of this model [Altair (2010)]. This was due to the incompatibility between inertia relief boundary conditions and eigenvalue models. Because severe crashes are one off events to the BIW, the deformation is only a concern when the limit load of the bifurcation point is reached.

Instead, the detection of buckling modes utilised Euler's buckling formula, equation (4), in order to calculate the critical buckling force F_{crit} for each member.

$$F_{crit} = \frac{\pi^2 \cdot E \cdot I}{k \cdot L^2} \qquad (4)$$

In equation (4), E is Young's modulus, I is the second moment of area, k is the slenderness ratio whilst L is the length of the beam member. The worst case buckling mode occurs when k in equation (4) is equal to 1.

By monitoring the second moment of area, the critical buckling load of the individual member could be monitored for each iteration. Furthermore, by extracting the axial forces in the members caused by the external loading, the likelihood of buckling could be monitored and evaluated. The likelihood of buckling occurring could thus be controlled by ensuring that the buckling factor, equation (5), remained true.

$$Buckling\ factor = \frac{Element\ axial\ force}{F_{crit}} < 1 \qquad (5)$$

The further below 1 the buckling factor is, the more reduced the likelihood of buckling occurring becomes. However, this may also be indicative of an over dimensioned member, thus defeating the purpose of the optimisation, thus the maximum buckling factor had to be globally adjustable. By doing so also provided additional control for later stages of the optimisation process, particularly if key members were found to buckle when utilising dynamic crash modelling.

With the above considerations the optimisation of the beam (and shell model) was conducted.

e) CAD Tube Model

Following the beam and shell optimisation, the wireframe CAD model was reused to produce tubular surfaces over the wireframe. The radii of the tube sections were parameterised with the corresponding member beam ID. The CAD model was then linked to the property output file from the last iteration of the beam model optimisation, thus automatically converting the 1D beam model into a 3D tubular CAD model.

f) 2D Shell Model

Following the generation of the 3D tubular CAD model, a loose shrink-wrap mesh was produced based upon the 3D geometry, this is illustrated in Figure 7.
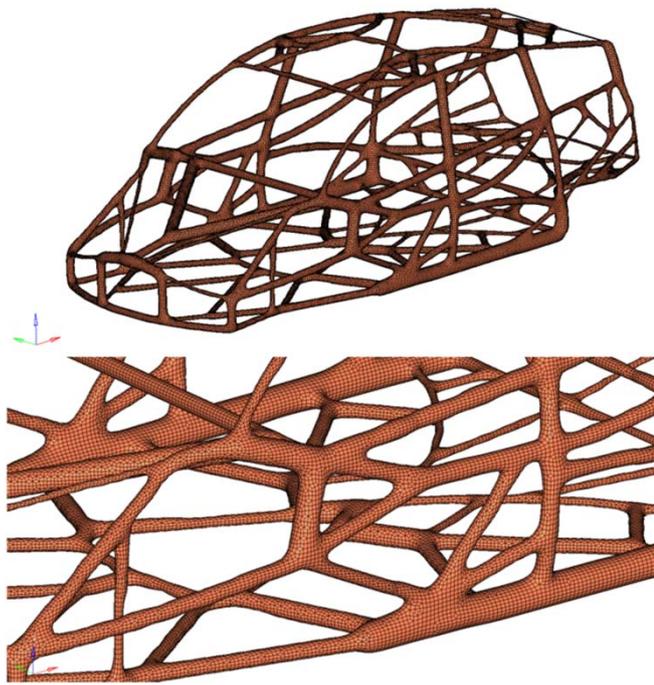
Figure 7 : 2D Shell Model using Shrink-wrap meshing

The shrink mesh produced a single shell (thickness) structural mesh with hollow member sections, representing the optimised dimensions. The shrink wrap mesh produced blended connections between the individual members. The cross-sectional dimensions were created from the tube sizing, however the sectional thicknesses were extracted from the beam model, and inserted into the shell element properties. This was automatically done by assigning an element located inside a "block" created by the coordinates of the member's line and radius.

g) Validation Crash Model

The 2D shrink map model was subsequently imported into commercial crash simulation software, and a non-linear dynamic impact analysis was completed. The purpose of this was to further validate the crashworthiness of the optimised design. Thus, it was possible to ensure that buckling of key members did not occur during individual load cases, particularly during the roof crush scenario, ODB and RW. Additional nodal masses across the entire structure were included in the model in order to replicate the total mass of the vehicle, including drivetrain and seven occupants, thus realistically replicating the inertial effects during all load case scenarios.

For the front crash scenario a rigid barrier was inserted, and subsequently collided with the BIW at a relative velocity of 35km/h.

As the BIW was developed based upon linear static topology optimisation, it was anticipated that the front crash scenario would propose the largest challenges to the optimised BIW during dynamic crash modelling, due to the maximum buckling effect caused by the overhang of the front crash structure. The results from the front crash analysis are represented by Figure 8.
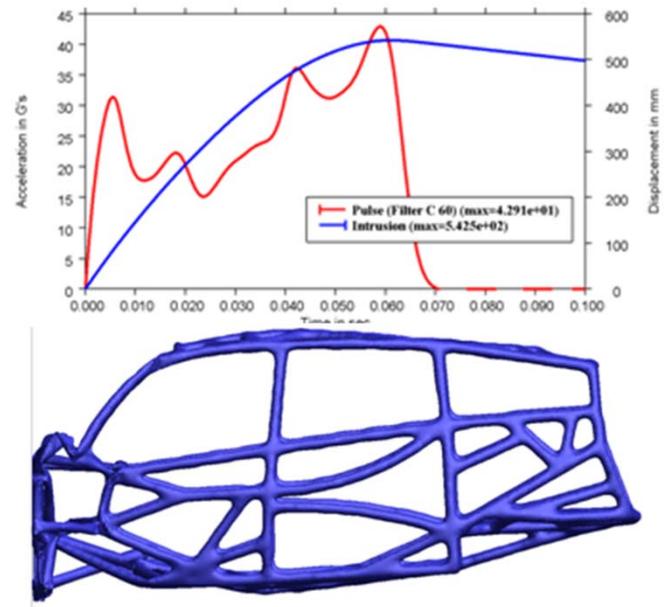

Figure 8 : Crash Model validation. Deformation at t=60ms; crash pulse/ displacement characteristic (top)

As indicated in Figure 8, the crash structure resisted the crash scenario, and that critical buckling of the safety cell was avoided. This indicates that the linear buckling sizing performed on the 1D beam elements were a success.

The small (or inexistent) magnitude of the overhang of the safety cell substantiates the low buckling failure is low, and that the optimised beams of these areas are suitably dimensioned for the impact scenario.

It should however be noted that the acceleration levels and crush length results obtained from this analysis could not have been predicted based upon the linear topology or sizing optimisation, as the solving was not transient dynamics. Therefore it was necessary that the optimisation process included a validation phase for the full structure, as illustrated by Figure 8, using a non-linear explicit solving technique.

IV. Conclusion

The skeleton of an automatic process to generate an optimised BIW architecture has been demonstrated and represents all steps needed to develop a crash model based upon basic styling surfaces. This process can be completed within a very short time, realistically within 1 working day.

The structure generated is very suitable for the definition of the vehicle performance (i.e. torsional rigidity) and the safety cell in general. However, caution

needs to be exerted, especially with respect to the front crash structure where the linear topology optimisation algorithm provides a load path which does not directly consider aspects such as buckling, bifurcation, material strain rates, material and structural damage etc.

Therefore, it would be strongly advisable to review the front end design after the full process has been completed and converged. This is in order to extract the necessary loads in the A pillar and the seals in order to propose a perhaps more suitable (conventional) front end crash structure, which subsequently can be optimised for mass, utilising the extracted loads as maximum loading objective functions.

There is a need to research alternative means of conducting topology optimisation for non-linear events, in large deformations, bucking and damage events.

The next stage of this research is to automate all the above steps in combination, thus increasing the solution turn-around time in order to parameterise the vehicle styling, to take into account for example aerodynamics, wheel base and pedestrian mark-up as well as investigating the best compromise between vehicle aesthetics and holistic engineering performance.

References Références Referencias

1. **Altair (2010)**
   Altair Engineering, Inc. 2010. *Altair Hyperworks manual,* Troy, Michigan, USA
2. **Bastien (2010)**
   Bastien, C. "Topology Optimisation of a Body In White for Low Carbon Vehicle Technology Project", Altair European conference, EHTC 2010, October 2010, Versaille, France
3. **Bastien and Christensen (2011)**
   'Towards the Light weighting of Low Carbon Vehicle Architectures using Topology Optimisation', C Bastien, J. Christensen, EHTC November 2011, Bonn, Germany
4. **Bendsøe and Sigmund (2003)**
   M. P. Bendsøe, O. Sigmund. 2003. *Topology Optimization - Theory Methods and Applications.* Springer Verlag, Berlin, Germany
5. **Cabled (2011)**
   Cabled Project: Ultra Low Carbon Car Trials within Birmingham and Coventry. http://www.cabled.org.uk/
6. **Christensen et. al (2011)**
   J. Christensen, C. Bastien, M. V. Blundell, A. Gittens, O. Tomlin, 2011, "Lightweight Hybrid Electrical Vehicle Structural Topology Optimisation Investigation Focusing on Crashworthiness", *International Journal of Vehicle Structures and Systems, Volume 3, Issue 2.*
7. **Christensen et. al (2011a)**
   'Effects of Roof Crush Loading Scenario Upon Body In White Using Topology Optimisation', C Bastien, J. Christensen, ICRASH Journal, December 2011.
8. **Duddeck (2007)**
   F. Duddeck. 2007. *Multidisciplinary optimization of car.*
   /www.springerlink.com/content/2741p87038110l7, London, UK
9. **Ecoshell (2012)**
   Ecoshell project. FP7: Development of Bio-composite based super light electric passenger vehicle
10. **EPSRC (2011)**
    http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/I038616/1
11. **Europa (2010)**
    COM(2010) 2020 final COMMUNICATION FROM THE COMMISSION EUROPE 2020 A strategy for smart, sustainable and inclusive growth http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2010:2020:FIN:EN:PDF
12. **GACM (2011)**
    4th German Association of Computational Mechanics (GACM) colloquium on Computational Mechanics, August 31st - September 2nd 2011, Dresden, Germany,: <http://gacm2011.bau.tu-dresden.de/>
13. **Greencars (2010)**
    European Roadmap Electrification of Road Transport. http://www.green-cars-initiative.eu/documents/Roadmap%20Electrification.pdf/view
14. **Huang and Xie (2010)**
    X. Huang and Y. M. Xie, 2010, "A further review of ESO type methods for topology optimization ", *Structural and Multidisciplinary Optimization*, *volume 41, issue 5*, *pp. 671-683*, Springer Verlag, Berlin, Germany.
15. **LCVTP (2011)**
    Low Carbon Vehicle Technology Project. Re: BG/AM1011, partly funded by ERDF and AWM.
    Project based on Tata 'Beacon' vehicle layout. Participation of Coventry University for vehicle aerodynamics,
    HVAC and Vehicle Body Structure