MULTI-DISCIPLINARY DESIGN OPTIMIZATION OF A COMPOSITE CAR DOOR FOR STRUCTURAL PERFORMANCE, NVH, CRASHWORTHINESS, DURABILITY AND MANUFACTURABILITY

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Abstract

Among various efforts pursued to produce fuel efficient vehicles, light weight engineering (i.e. the use of low-density structurally-efficient materials, the application of advanced manufacturing and joining technologies and the design of highly-integrated, multi-functional components/sub-assemblies) plays a prominent role. In the present work, a multi-disciplinary design optimization methodology has been presented and subsequently applied to the development of a light composite vehicle door (more specifically, to an inner door panel). The door design has been optimized with respect to its weight while meeting the requirements /constraints pertaining to the structural and NVH performances, crashworthiness, durability and manufacturability. In the optimization procedure, the number and orientation of the composite plies, the local laminate thickness and the shape of different door panel segments (each characterized by a given composite-lay-up architecture and uniform ply thicknesses) are used as design variables. The methodology developed in the present work is subsequently used to carry out weight optimization of the front door on Ford Taurus, model year 2001. The emphasis in the present work is placed on highlighting the scientific and engineering issues accompanying multi-disciplinary design optimization and less on the outcome of the optimization analysis and the computational resources/architecture needed to support such activity.

Keywords
Multi-disciplinary Optimization, Automotive Engineering, Composite Structures, Altair Engineering Inc
1. Introduction

With continuously rising environmental demands and ever-tougher emissions standards, lightweight engineering for the automobiles is steadily gaining in importance as a viable technological avenue. Current efforts in the automotive lightweight engineering involve at least the following five distinct approaches [1]: (a) Requirement lightweight engineering which includes efforts to reduce the vehicle weight through reductions in component/subsystem requirements (e.g. a reduced required size of the fuel tank); (b) Conceptual lightweight engineering which includes the development and implementation of new concepts and strategies with potential weight savings such as the use of a self-supporting cockpit, a straight engine carrier, etc.; (c) Design lightweight engineering which focuses on design optimization of the existing components and subsystems such as the use of ribs and complex cross-sections for enhanced component stiffness at a reduced weight; (d) Manufacturing lightweight engineering which utilizes novel manufacturing approaches to reduce the component weight while retaining its performance (e.g. a combined application of spot welding and adhesive bonding to maintain the stiffness of the joined sheet-metal components with reduced wall thickness); and (e) Material lightweight engineering which is based on the use of materials with a high specific stiffness and/or high specific strength such as aluminum alloys and polymer-matrix composites or a synergistic use of metallic and polymeric materials in a hybrid architecture (referred to as polymer metal hybrids, PMHs).

The development of a vehicle body-in-white (BIW) and its bolt-on components is a very complex process, as the fulfillment of various, often-conflicting, functional requirements has to be considered. Today, the development of the BIW and its components is greatly facilitated by the use of computational engineering analyses and simulations. Such analyses and simulations are at the core of the Multi-Disciplinary Optimization (MDO) and Design of Experiments (DOE) tools, used to support the process of finding “the best” design. Since the iterative evolution of the design topology, size and shape can be formulated mathematically as an optimization problem, the results of the associated computational optimization analyses can be used to guide the design and facilitate the decision-making process. This, in principle, can lead to significant cost reductions in at least three different ways [2]: (a) the design cycle may be shortened resulting in reduced development time and costs; (b) the tooling and manufacturing costs may be lowered leading to higher profit margins; and (c) the costs of ownership of the product may be reduced leading to more cost-competitive products.

In their current practice, automotive OEMs and suppliers employ the design optimization analyses, yet such analyses are typically concerned with either a single engineering discipline or deal with different disciplines independently. Once the optimal design(s) have been found, they have to be reconciled across all the relevant disciplines. In most cases this procedure leads to significant design changes and unwanted compromises. Hence, it is desirable to employ simultaneously all the participating disciplines in the optimization process. It should be noted that, in general, the use of design optimization methods and tools by the automotive OEMs and suppliers is greatly affected by the availability of efficient, user-friendly commercial software with adequate user-support service. For the optimization problems relying on the use of linear statics and dynamics analyses, such software is available and fairly well supported. However, if crashworthiness or manufacturability need to be considered as part of an
MDO effort, no algorithms are currently available to perform the required non-linear sensitivity analyses, like the ones conducted within the linear optimization routines. Alternative approaches based on response surface techniques have been proposed, nevertheless, in order to handle non-linear optimization analyses. There is a variety of such approaches and they differ with respect to the type of response surface, the method used to sample the design space, the number (fixed number of pre-defined vs. sequentially-created set) of design alternatives considered, etc.

In the present work, a novel use of HyperWorks, commercial CAE/MDO software from Altair Engineering Inc. [3] is demonstrated. The software is used to carry out a multi-disciplinary design optimization of a light-weight composite passenger-vehicle door with respect to meeting structural and (Noise, Vibration and Harshness) NVH performance requirements, crashworthiness, durability and manufacturability. The starting point for design optimization is an existing all-metal (inner shell/outer-shell) door. In the new design, the inner (initially metal) shell (panel) is replaced with a composite-laminate alternative. The existing inner reinforcements initially attached to the inner panel have been removed and their functionality restored by introducing a spatial variation in the composite-panel thickness and in the \(0^\circ, +45^\circ, -45^\circ,\) and \(90^\circ\) ply/lamina thicknesses and orientations. The design optimization of the replacement composite inner panel is carried out in two steps: (a) In the (first) conceptual step, based on the sole use of linear structural and NVH analyses, the number of composite-laminate patches (each characterized by a uniform distribution of the \(0^\circ, +45^\circ, -45^\circ,\) and \(90^\circ\) ply/lamina thicknesses) and tentative locations of inter-patch boundaries are determined; and (b) in the (second) detailed-design step, fully multi-disciplinary (structural, NVH, crashworthiness, durability and manufacturability) size and shape optimization analysis is carried out to determine the final ply thicknesses and the location of patch boundaries. A schematic of the two-step optimization process is depicted in Figure 1.

![Fig.1 Two-step multi-disciplinary optimization procedure used for redesign of Ford Taurus model year 2001 front left door](image-url)
In the first optimization step, the Free Element Sizing (FES) composite-laminate architecture/thickness optimization technique, developed by Altair Engineering Inc. [4], was employed. The FES technique is quite similar to the well-established topology optimization method [5] except for the fact that the shell-elements’ thicknesses and ply thicknesses for composite lay-ups are used as design variables, in place of the material density. In the second optimization step, HyperStudy software from Altair Engineering inc. [6] is used. This software allows the set-up and the highly automated execution of a multi-disciplinary optimization problem. In addition, HyperStudy offers Design of Experiments (DOE) methods which can be used for screening of the design space and for generation of the approximation models based on the Response Surface Method (RSM) [7]. Consequently, the software enables the application of the global or local, single or multi objective, non-linear optimization techniques on either the original (highly computationally demanding) analyses or on the approximate models. Finally, several resource management systems are available for the parallel execution of the MDO analyses.

The main objective of the present work is to introduce the aforementioned two-step MDO procedure and apply it to the case of a passenger-vehicle door inner panel made of a carbon-fiber epoxy-matrix composite-laminate material. Within the first (conceptual-design) step, the local laminate thickness (as well as the thicknesses of the individual 0°, +45°, -45° and 90° laminas within the laminate) are determined, as well as the number of composite patches (each characterized by a nearly uniform distribution of the lamina thicknesses). Within the second (detailed-design) step, a fully multi-disciplinary single-objective (mass) size and shape optimization analysis is carried out in order to establish the final locations of the inter-patch boundaries (“weld lines”) and ply thicknesses within each patch while meeting the structural, NVH, crashworthiness, durability and manufacturability functional requirements/constraints.

The organization of the paper is as follows: Brief descriptions of the geometrical model and the functional/performance requirements for the car door are presented in Sections II.1 and II.2, respectively. More specific accounts of the conceptual and detailed design optimization methods used in the present work are provided in Section II.3. The results obtained in the present work are presented and discussed in Section III. The main conclusions resulting from the present work are summarized in Section IV.

2. Computational Procedure

2.1 Geometrical Model of the Car Door

Within the present work, the front door of the Ford Taurus Model Year 2001 has been considered. The mesh model for this door was obtained from the National Crash Analysis Center website [8]. The model consists of the following 13 parts: (a) an outer body trim; (b) a sheet-metal outermost panel; (c) a sheet-metal inner lower panel; (d) a sheet-metal inner panel upper frame; (e) an upper reinforcement inner panel; (f) a plastics molded inner panel; (g) an inner panel reinforcement; (h) a tailor-welded blank inner panel; (i) a lower hinge mount; (j) a lower hinge bracket/arm; (k) an upper hinge mount; (l) an upper hinge bracket/arm; and (m) a door bracket.

Adjacent parts are joined by having them share nodes or by either spot welds or seam welding/adhesive bonding. A summary of the door parts considered their shell
thicknesses and materials, as well as the finite-element mesh details are given in Table 1. An exploded view of the door is displayed in Figure 2. For improved clarity, some of the parts are omitted in Figure 2.

Table 1 Geometry, Mesh and Materials Used in the Original Ford Taurus Model Year 2001 Front Left Door: $E$ — Young’s Modulus (GPa), $\nu$ — Poisson’s Ratio, $\sigma_y$ — Yield Strength (MPa)

<table>
<thead>
<tr>
<th>Part Number</th>
<th>Part Name</th>
<th>Number of Shell Elements</th>
<th>Material</th>
<th>Thickness mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Outer Body Trim</td>
<td>5</td>
<td>346 Thermoplastics: $E=2.8$; $\nu=0.3$; $\sigma_y=45$</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>Sheet-metal Outermost Panel</td>
<td>54</td>
<td>5826 Steel: $E=210$; $\nu=0.3$; $\sigma_y=240$</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>Sheet-metal Inner Lower Panel</td>
<td>423</td>
<td>4761 Steel: $E=210$; $\nu=0.3$; $\sigma_y=300$</td>
<td>1.2</td>
</tr>
<tr>
<td>4</td>
<td>Sheet-metal Inner Panel Upper Frame</td>
<td>22</td>
<td>970 Steel: $E=210$; $\nu=0.3$; $\sigma_y=300$</td>
<td>1.2</td>
</tr>
<tr>
<td>5</td>
<td>Upper Reinforcement Inner Panel</td>
<td>140</td>
<td>1562 Thermoplastics: $E=2.8$; $\nu=0.3$; $\sigma_y=45$</td>
<td>4.8</td>
</tr>
<tr>
<td>6</td>
<td>Plastics Molded Inner Panel</td>
<td>247</td>
<td>4585 Thermoplastics: $E=2.8$; $\nu=0.3$; $\sigma_y=45$</td>
<td>2.31</td>
</tr>
<tr>
<td>7</td>
<td>Inner Panel Reinforcement</td>
<td>15</td>
<td>153 Thermoplastics: $E=2.8$; $\nu=0.3$; $\sigma_y=45$</td>
<td>2.9</td>
</tr>
<tr>
<td>8</td>
<td>Tailor-welded Blank Inner Panel</td>
<td>196</td>
<td>1854 Steel: $E=210$; $\nu=0.3$; $\sigma_y=340$</td>
<td>1.2</td>
</tr>
<tr>
<td>9</td>
<td>Lower Hinge Mount</td>
<td>3</td>
<td>47 Steel: $E=210$; $\nu=0.3$; $\sigma_y=300$</td>
<td>4.4</td>
</tr>
<tr>
<td>10</td>
<td>Lower Hinge Bracket (Arm)</td>
<td>4</td>
<td>69 Steel: $E=210$; $\nu=0.3$; $\sigma_y=300$</td>
<td>4.4</td>
</tr>
<tr>
<td>11</td>
<td>Upper Hinge Mount</td>
<td>5</td>
<td>73 Steel: $E=210$; $\nu=0.3$; $\sigma_y=300$</td>
<td>4.4</td>
</tr>
<tr>
<td>12</td>
<td>Upper Hinge Bracket (Arm)</td>
<td>6</td>
<td>73 Steel: $E=210$; $\nu=0.3$; $\sigma_y=300$</td>
<td>4.4</td>
</tr>
<tr>
<td>13</td>
<td>Door Bracket</td>
<td>1</td>
<td>35 Steel: $E=210$; $\nu=0.3$; $\sigma_y=300$</td>
<td>1.14</td>
</tr>
</tbody>
</table>
2.2 Performance Requirements for the Car Door

In this section, a list of performance targets (constraints) for the light composite vehicle door is defined. These targets are obtained by first carrying out a series of structural, NVH, crashworthiness and durability analysis using the original door design. The results of these baseline analyses were then used as the performance targets for the new design. In other words the new door design had to be lighter than the original design while performing at least as well as the original design. In the remainder of this section a more detailed description is provided for each of the specific performance targets.

2.2.1 Structure Performance Requirement

The structural performance requirements for a car door typically include the conditions which the door must meet with respect to its frame rigidity and sag resistance. The two requirements pertain to the ability of the door to withstand without excessive outward deflection of an interior/exterior pressure difference associated with aerodynamic effects at high vehicle speeds and the ability of the door to withstand its weight, respectively without excessive downward deflection.

To define quantitatively the two structural requirements for the door, the following two linear structural finite-element analyses were conducted: (a) The closed door has been fixed on one side at the locations of its hinges and on the other at the location of its lock and a uniform pressure of 5.8kPa applied over the interior surface of the door. The pressure of 5.8kPa was obtained in a separate CFD (Computational Fluid Dynamics) analysis in which the outer shell of the entire (rigid) body of the Ford Taurus (model year 2001) was moving in the forward direction at a speed of 100 km/h. No further
details of this analysis will be provided; and (b) the door is fixed only at the locations of its hinges and subjected to the gravitational load. In both cases the maximum displacements were recorded. In case (a), a maximum deflection in y-direction of 15mm was found, while in case (b) a maximum displacement in the z-direction of 0.18mm was found. These values are then used as the optimization constraints for the composite car door. The coordinate system used throughout this paper was defined as follows: x-direction coincides with the length, y-direction with the width, z-direction with the height of the vehicle. The results obtained for the structural analyses (a) and (b) are summarized in Figures 3(a)-(b), respectively.

![Figure 3](image)

**Fig.3** Linear structure finite element analysis results obtained for (a) y-component of the displacement (used to define the door frame-rigidity functional requirement and (b) z-component of the displacement (used to define the door sagging resistance))

2.2.2 Noise Vibration Harshness (NVH) Requirement

The noise, vibration and harshness requirements for the car door were defined by determining the lowest natural vibrational frequency for the door in the close position.
Toward that end, an eigen-value analysis of the closed car door was conducted and the eigen-modes and their corresponding eigen-frequencies obtained using the Lanczos numerical eigen-solver [10]. The lowest natural frequency for the closed door was found to be 30.7Hz and the corresponding modal shape is displayed in Figure 4. The lowest natural frequency for the composite car door is then required to be at least 30.7Hz.

![Figure 4](image)

**Fig.4** The shape mode associated with the lowest natural frequency

### 2.2.3 Crashworthiness

The crash worthiness functional requirement for the car door pertains to the door’s ability to protect the driver/passenger in the case of a side impact collision. Typically these requirements are defined as a maximum inward intrusion allowed under different conditions.
side-collision scenarios, and there are a number of regulations (in US, Europe, Japan, etc.) mandating and defining in detail the side-collision crash requirements for the door. Since the emphasis of the present work is on demonstrating the potential of the MDO approach and not on complying with specific vehicle-safety regulations, a simple “single-scenario” (i.e. one crash loading case) crashworthiness analysis was carried out. In such an analysis, the bumper of the same vehicle (with an addition mass of 1,500kg attached to it) is driven into the car door at an incident angle of 30 degrees and at an initial velocity of 25km/h. The maximum inward intrusion at the interior panel of the car door was found to be 223.5mm and this (maximum intrusion) value is defined as the crashworthiness functional requirement for the composite-laminate car door. An example of the results obtained in the crashworthiness analysis is displayed in Figure 5.

Fig.5 (a) Simple collision analysis used to quantify the car-door crashworthiness; and (b) y-component of the displacement used to quantify inward intrusion during side collision

2.2.4 Durability Requirement

While durability of an automotive component/sub-assembly is generally controlled by either the damage inflicted to it or by corrosion of failure due to cyclic/fatigue loading, only the fatigue-controlled durability will be considered in the present work. This is
justified by the fact that the component in question is an inner door panel and, thus, is not usually exposed to common corrodants (rain, snow, road salt, etc.). In addition, as is generally observed, durability of the inner door panel will be assumed to be controlled by fatigue-induced failure of its spot welds to the connecting door components and not by the failure of the panel itself. The durability of the metal door inner panel will, hence, be defined by the number of loading cycles before the first evidence of fatigue-induced failure is observed in any of its spot welds.

Resistance spot welding is nowadays the predominant joining technique in the automotive industry. The components of the BIW are typically made of thin sheet metals that are connected using spot-welded joints (i.e. spot welds). To create a spot weld, two or more sheet-metal components are pressed between two electrodes and an electric current is passed through. The resulting Joule resistance heating and the pressure applied via the electrodes give rise to local fusion/welding. No filler material is used in the spot welding process. Three distinct regions with different material properties can generally be identified in a spot weld: (a) a cylindrically-shaped weld nugget; (b) a surrounding heat-affected zone; and (c) the base sheet metals. Due to the applied pressure by the electrodes, the thickness of the nugget is generally smaller than the combined thicknesses of the spot welded components. The change in weld thickness at the edges of this so-called “nugget indentation” typically gives rise to stress concentrations at the indentation edges. In addition, stress concentrations are present at the root of the notch created by spot welded components. The places associated with stress concentrations are likely places where the initiation of durability-controlling fatigue cracks takes place.

Two spot-weld fracture modes are generally observed: (a) “Interfacial or nugget fracture”, i.e. fracture of the weld nugget along the plane of the weld (predominantly observed in small (<2mm) diameter spot welds; and (b) “Nugget pullout” or “sheet fracture” which involves fracture of the sheet metal around the weld that leaves the nugget intact (predominantly observed in large-diameter spot welds). Since small-diameter spot welds are quite deficient relative to their load-carrying and energy-absorbing capabilities, large-diameter (ca. 5mm) spot welds are typically used in automotive industry. Spot welds of this diameter are used in the present work.

A review of the literature shows numerous fracture-mechanics [e.g. 28], structural-stress analysis [e.g. 29] and numerical analysis [e.g. 30] based efforts aimed at fatigue-life predictions for spot welded joints. The predictions of these efforts were subsequently correlated at different levels of success with experimental fatigue-test results. Fatigue durability of the spot welds is modeled in the present work using the equivalent structural stress approach proposed by Kang [27]. Within this approach, the maximum equivalent (von Mises) structural stress at the edges of the weld nugget, \(\sigma_{eq,max}\) (MPa), is directly related to the fatigue life of the spot welded joint, \(N_f\) (cycles), as:

\[
N_f = 2.8 \times 10^9 \sigma_{eq,max}^{-5.94}.
\]

Cyclic loading experienced by a car door is quite complex and depends on a number of factors such as: (a) the source of loading, e.g. engine vibrations, wheel vibrations, etc.; (b) vehicle driving speed; (c) surface condition of the road; (d) the way the door is mounted to the BIW frame, since the loads diffuse into the door through its contacts with the frame; etc. A detailed (multi-scenario) fatigue-based durability analysis is beyond the scope of the present work. Instead, a single-scenario (i.e. a single loading case) analysis is carried out in order to include durability into the MDO analysis. Within this approach, the door is fixed at the locations of its hinges and twisted along an axis.
parallel with the $x$-direction and passing through the center point of its lock. Contour plots displayed in Figures 6(a)-(b) are provided to help understand the nature of the cyclic loading used in the present work.

![Fig.6](image-url)  
(a) Von Mises stress amplitude field plot projected onto the un-deformed door and (b) $y$-displacement field plot projected onto the (cyclic-loading) deformed door.

Since the present door design has passed the durability requirements, these are replicated by computing the total number of loading cycles experienced by the car door during its lifetime. In such calculations it was assumed that: (a) the vehicle at hand has six cylinders; (b) total mileage=270,000km; (c) average vehicle speed=80km/h; (c) average engine speed=2500rpm. The computation yielded 1.5 billion cycles. From the fatigue-life equation given above, the maximum equivalent stress corresponding to this fatigue life is computed as $\sigma_{eq,max}=54\text{MPa}$. Next, a static finite element analysis is carried out to determine the torsional angle which has to be applied to the all-metal car door so that the maximum value of the equivalent stress at the most highly-stressed spot weld is equal to this value. The analysis was conducted using Abaqus/Standard finite-
element code [15] since this software enables the definition of spot welds as deformable connectors with their own material properties and the range of influence in the surrounding sheet metal. To account for the fact that the yield strength in the nugget may be up to three times higher than in the base metal, a conservative increase of 50% in the yield strength was used for the spot welds. A torsional angle of 3 degrees is obtained. Finally, the durability requirement for the composite-laminate car door is defined as the condition that the door must endure $1.5 \times 10^9$ cycles of torsional loading described above without failing when subjected to the 3-degree torsion.

2.2.5 Manufacturability Requirement

Since in the present MDO analysis, the replacement of the initially metal inner panel with a composite-laminate alternative is considered, the original all-metal door design can not be used to define the manufacturability requirements for the new design. Instead, it is recognized that the composite inner panel will be made by a Resin Transfer Molding (RTM) process and that it will be made of an epoxy-matrix composite material reinforced with 50-60% carbon-fiber plies/laminas. Furthermore, it is recognized that the local composite-laminate thickness and architecture affect the permeability of the carbon-fiber preform with respect to resin flow through it during the mold-filling stage of the RTM process.

Taking all these facts into consideration and assuming that the “standard” RTM processing conditions (the specification given in Section II.3.2) is used, manufacturability requirements are defined as: (a) the filling stage of the RTM process should result in a completely filled preform and (b) the RTM weld lines (places where the converging resin flow fronts meet) located in the areas where the stress-levels experienced by the panel during the crashworthiness analysis are the lowest (to ensure that the detrimental effect of RTM weld lines on the inner-panel crashworthiness performance is minimal).

2.3 Multidisciplinary Design Optimization of the Car Door

The design-optimization process for the light composite car door has been divided into two distinct steps: (a) a conceptual design step whose main objective was to help identify the number of composite patches (each patch is characterized by a unique set of four ($0^\circ$, $+45^\circ$, $-45^\circ$ and $90^\circ$) composite-ply thicknesses and to define preliminary boundaries (“weld boundaries”) between the patches; and (b) a fully-multi-disciplinary size and shape detail design optimization step used to define the final set of ply thicknesses within each patch and the final position of patch boundaries. A schematic of the two-step optimization procedure used in the present work is depicted in Figure 1. In the remainder of this section, a more detail account is provided for the two design optimization steps.

2.3.1 Conceptual-Design Optimization Step

Within this step, the free element sizing (FES) technique implemented into the linear optimization computer program OptiStruct from Altair Engineering Inc. [9] has been used. Within the FES technique, the thicknesses for each of the four ($0^\circ$, $+45^\circ$, $-45^\circ$ and $90^\circ$) ply thicknesses for each shell element are considered as design variables. However, the optimization procedure implemented in the FES technique does not consider single-
ply thicknesses in different elements as completely independent variables, since such an approach would make the optimization procedure intractable due to a large number of design variables. Instead, the variation of each of the four ply thicknesses is represented using a continuous (field) functions, and the coefficients in these functions are, in fact, used as design variables. The number of these function coefficients is substantially smaller than the number of shell elements making the FES optimization procedure not only feasible but also computationally very efficient. To further clarify the FES technique, it could be stated that it is essentially analogous to the well established topology optimization method [5] except that ply-thicknesses are used as design variables in place of the material density. While the FES technique implemented in OptiStruct is highly computationally efficient, it can currently be utilized only for the optimization problems relying on the linear computational analyses. Consequently, only the (linear-analyses based) structural and NVH functional requirements could be considered within the conceptual design stage. The remaining (crashworthiness, durability and manufacturability) requirements are addressed in the detailed design step. In the remainder of this section, a more detailed account is provided for the FES technology.

As stated above, within the conceptual design stage, the FES technique [4] is utilized to determine the local composite-laminate make-up (i.e. the thickness of $0^\circ$, $+45^\circ$, $-45^\circ$ and $90^\circ$ laminas) and the boundaries between different laminate patches, where a patch is defined as a segment of the laminate which contains a nearly uniform distribution of the thicknesses of laminas of a given ($0^\circ$, $+45^\circ$, $-45^\circ$ and $90^\circ$) type. Furthermore, the FES method utilizes the concept of a super-ply (a subset of plies located within the same element and having the same $0^\circ$, $+45^\circ$, $-45^\circ$ or $90^\circ$ orientation). The super-ply concept thus significantly reduces the number of plies in the model. Also, as the super-ply thicknesses are varied in the conceptual-design optimization step, the process of ply addition or removal is simulated. Moreover, the solver package OptiStruct [9] within which the FES method is implemented allows a shell-element formulation which effectively homogenizes the stiffness matrix associated with each super-ply uniformly throughout the element thickness. This process is analogous to dividing each super-ply into infinitely-thin plies and mixing the infinitely-thin plies into a homogeneous ply-less composite material. A schematic of the super-ply concept and the subsequent homogenization process is depicted in Figure 7.
The results obtained in the conceptual-design optimization step are shown in Figures 8(a)-(d) in which distributions of the four $(0^\circ, +45^\circ, -45^\circ$ and $90^\circ)$ ply thicknesses are displayed, respectively. It should be noted that unlike most of the previous figures, Figures 8(a)-(d) show only the composite-laminate inner panel (and not all the door components). The results displayed in Figures 8(a)-(d) are next used to partition the composite-laminate inner panel into a number of patches (within each of which, the thickness of individual plies will be kept constant). While this process requires subjective engineering judgment and a larger number of patches more realistically
approximate the conceptual-design optimization results, seven patches (each containing a fixed ply layup) were selected in the present work in order to keep the number of design variables reasonable. The partitioning of the composite-laminate inner panel into seven patches is displayed in Figure 9.

**Fig. 8** Distribution of ply thicknesses obtained in the conceptual-design optimization step of the inner panel: (a) 0°C; (b) +45°C; (c) -45°C; and (d) 90°C. Blue=0.3mm, Yellow=0.6mm, Red=0.9mm.

**Fig. 9** Seven composite-panel patches defined after analyzing the results displayed in Figures 8(a)-(d).
2.3.2 Detailed-Design Optimization Step

Within the detailed design step, the final-design (size and shape) optimization procedure is applied to the car-door composite-laminate inner panel. As stated earlier, the objective of this optimization procedure was to minimize the car-door weight, while meeting all the structural, NVH, crashworthiness, durability and manufacturability requirements, as defined in Section II.2. To carry out the MDO analysis at hand, the HyperStudy optimization toolbox from Altair Engineering Inc. [6], was used. HyperStudy enables the set-up of an MDO analysis through the definition of design variables (and their ranges) as well as of the system responses (used to define the objective function(s) and the constraints). In addition, a Design of Experiments (DOE) analysis can be carried out within HyperStudy in order to either: (a) identify the design variables which have a minor to negligible effect on the system responses and could be, hence, eliminated from the design-variables list used in the MDO analysis; and/or (b) to construct approximate models (i.e. the response surfaces) for the system responses.

Within HyperStudy, the HyperOpt module was used in the present work. HyperOpt enabled automatic execution of the highly-complex MDO analyses employing the following solvers: (a) OptiStruct [9] to carry out structural and NVH analyses; (b) Radioss, a transient non-linear dynamic finite-element program from Altair Engineering Inc. [11] to conduct the crashworthiness analysis; (c) Matlab, a general-purpose mathematical package from MathWorks Inc. [12] and Abaqus/Standard, a non-linear finite-element program from Abaqus Inc. [15] to execute an in-house developed durability analysis program; and (d) Moldflow Plastics Insight, a general purpose plastics processing program from Moldflow Inc. [13] to carry out resin transfer molding of the car-door inner panel. The execution of the MDO analyses was orchestrated by HyperStudy in such a way that the design variables are varied automatically (following directions of a pre-selected optimization algorithm) to optimize the car-door composite inner panel with respect to its (minimal) weight, while ensuring that all the (structural, NVH, crashworthiness, durability and manufacturability) constraints are met. The overall geometry of the composite inner panel is kept identical to its metal counterpart, except for the (local) patch thicknesses and geometries. In other words, the patch thicknesses (more specifically the four laminas thicknesses within each patch are defined as the design size variables while the weld boundaries (the boundaries separating neighboring patches) are defined as the shape variables. To define the weld boundaries as the design shape variables, HyperMorph module within HyperMesh pre-processing program from Altair Engineering Inc. [14] was used. This module enables the weld boundaries to be defined as shape functions while the number of nodes (but not their coordinates) and the nodal connectivity are retained. In other words, as the boundaries between the patches are repositioned during the MDO analysis, the same (initial) finite-element mesh is morphed to prevent excessive distortions of the elements. The shape variables applied to the composite-laminate patch boundaries consist of both linear and harmonic shape variables. The HyperMorph tool within HyperMesh enables the user to specify a family of harmonic functions [14] which can be superimposed to allow increased generality of the evolved geometry.

The starting point in the detailed MDO analysis is the conceptual design obtained in Section II.3.2. When the complete set of multi-disciplinary analyses was applied to this design, the so-called base-line (also known as the “nominal run”) response of the system was obtained. Then, an Adaptive Response Surface optimization algorithm is
employed to guide the search of the design space in the attempt to continue to improve the design of the car door. A flow chart of the detailed design optimization step is given in Figure 10.

**Fig.10** A flow chart of the detailed-design multi-disciplinary optimization procedure used in the present work.

In the remainder of this section, more details are provided regarding each of the five analyses used in the MDO procedure.

**Structural Analysis**

Structural analysis of the car door was conducted in the present work using the standard small-strain linear-elastic finite element analysis as implemented in OptiStruct. Within such an analysis, the meshed finite-element model is subjected to boundary conditions, concentrated and/or distributed loads and the resulting system of linear algebraic equations (defining the mechanical equilibrium) solved for the nodal displacements and reaction forces. In the two structural analysis carried out in the present work, surface (in the case of frame-rigidity analysis) and (gravitational) volume (in the case of door-sagging analysis) distributed loads were used.

**NVH Analysis**
As mentioned earlier, the NVH analysis entailed determination of the lowest natural frequency of the car door. This was accomplished by using the Lanczos algorithm, an iterative algorithm that is an adaptation of power method for finding eigen-values and eigen-vector of a square matrix or the singular value decomposition of a rectangular matrix [e.g. 16]. The power method is first used for finding the largest eigen-value of a matrix. After the first eigen-vector/value is obtained, the algorithm is successively restricted to the null space of the known eigen-vectors to get the other eigen-vector/values. In practice, this simple algorithm does not work very well for computing a large number of the eigen-vectors because any round-off error will tend to degrade the accuracy of the computation. Also, the basic power method typically converges slowly, even for the first eigen-vector. Lanczos algorithm is a modification of the basic power algorithm in which each new eigen-vector is restricted to be orthogonal to all the previous eigen-vectors. In the course of constructing these vectors, the normalizing constants used are assembled into a tri-diagonal matrix whose most significant eigen-values quickly converge to the eigen-values of the original system.

**Crashworthiness Analysis**

The crashworthiness analysis of the car door has been carried out using the dynamic-explicit non-linear finite element method as implemented in Radioss [11]. The analysis was conducted by prescribing zero-velocity boundary conditions to the car door at the locations of door hinges and the lock. The (other vehicle) bumper (with a 1,500kg added mass) was rotated about the vertical z-axis and its vertical plane of symmetry position at an angle of 30 degrees with respect to the longitudinal vertical plane of symmetry of the vehicle and imparted an initial velocity of 25km/h. To model the contact and friction between the bumper and the outer panel as well as between various parts of the door during crash, a parts interaction option is used. For each pair of contacting parts, the interaction option is based on the definition of a master surface (belonging to one part) and slave nodes (belonging to the other part). The master surface and slave nodes are used to compute the interaction gap between the contacting parts, and can both belong to the same part for modeling self-interactions. Standard values for the part-interaction parameters are used [17] and sensitivity of the crashworthiness results to variations in these parameters was not investigated. Particular attention was given, however, to developing and using the appropriate material models which can capture materials behavior under dynamic, large strain conditions involving plasticity and damage initiation and evolution. A detailed account of the material models used in the crashworthiness analysis is presented in the Appendix.

**Durability Analysis**

While the predominant joining mode in all-metal car door is spot welding (supplemented by seam welding), the introduction of a composite-laminate inner panel in the new door-design will necessitate the use of alternative joining technology, primarily adhesive bonding and riveting. Durability of metal/composite adhesively-bonded and mechanically-fastened joints is an area of intensive current interest [e.g. 18]. Fatigue life predictions of such joints are based on either interfacial fracture mechanics approach [e.g. 18] or using cohesive-zone formalism [e.g. 19]. In the present work, the cohesive-zone formulation is adopted and the effect of rivets is included only implicitly.
In other words, joints between the composite-laminate inner panel and thread joining components will be treated as adhesively bonded, but the cohesion-zone stiffness and strength parameters of the joint will be increased in order to account for the effect of the rivets. Such an approach was developed in our recent work [20] and hence, will not be discussed in great details here.

The composite/metal joints have been modeled in the present work using the "cohesive zone framework" originally proposed by Needleman [21]. The cohesive zone is assumed to have a negligible thickness when compared with other characteristic lengths of the problem, such as the composite-laminate/sheet-metal wall thicknesses, or the characteristic lengths associated with the stress/strain gradients. The mechanical behavior of the cohesive zone is characterized by a traction–displacement relation, which is introduced through the definition of an interfacial potential. The perfectly bonded composite-laminate/sheet-metal joint is assumed to be in a stable equilibrium, in which case the interface potential has a minimum and all tractions vanish. For any other configuration, the value of the potential is taken to depend only on the displacements discontinuities across the joint interface. The interface potential initially proposed by Socrate [22] is used in the present work. Within the finite-element durability analysis carried out here, cohesive elements available in Abaqus/Standard were used to represent the adhesive-bonded composite-laminate/sheet-metal joints. A detailed account of this approach including the assessment of the initial (intact) cohesive zone parameters and their finite element implementation can be found in our recent work [20].

To assess fatigue-induced reduction in stiffness and strength of the cohesive zone, a detailed finite element study of composite-laminate/sheet-metal adhesively-bonded double cantilever beams was carried out in our recent work [20] and the results compared with the experimental cyclic-loading data from Ref. [18]. To obtain a fatigue life vs. maximum joint-interface equivalent stress relation, the joint is assumed to have failed when the crack length exceeds 1 cm, and the interface has failed locally when the composite-laminate/sheet-metal normal separation exceeds 100 µm. The fatigue-life predictions are found to be affected by the choice of these two parameters, but the effect was relatively weak. A more detailed account of the procedure used to quantify fatigue-controlled durability of adhesively-bonded composite-laminate/sheet-metal joints can be found in Ref. [20]. While the procedure presented in Ref. [20] was found to yield realistic results, it was not implemented in the present work due to its high computational cost. Instead, a simpler procedure (producing comparable results) presented below is used.

The interface potential used in the present work contains four parameters: (a) a (normal) decohesion strength, $\sigma_n$; (b) a (normal) critical interface separation distance, $\delta_n$; (c) an interface shear strength $\sigma_s$; and (d) a critical interfacial displacement, $\delta_s$. Following our previous work [20], $\sigma_n / \sigma_s$ ratio is assumed to remain constant as the adhesion bonding degrades with time, while $\delta_n$ and $\delta_s$ remain constant. Consequently, only a fatigue-induced decrease of $\sigma_n$ needs to be specified in order to account for the loss of interfacial strength of adhesively-joined components with time in service. Following the analysis presented in our previous work [20], the following recursive relation was adopted: $\Delta \sigma_n = C \sigma_n \left( F_n / \sigma_n \right)^{14.7}$, where $\Delta \sigma_n$ is a loss of adhesion strength per one loading cycle, $C$ is 2.77e-4, a constant and $F_n$ normal interface traction.
The formula is solved for \( F_n \), subjected to the constraint that failure (defined by the condition \( F_n = \sigma_n \)) will occur after 1.5 billion cycles. For the initial value \( \sigma_n = 40 \text{MPa} \) (includes contributions of the adhesive and the rivets), it was found that if \( F_n \leq 12.7 \text{MPa} \), the adhesively-bonded joint sill survive 1.5 billion cycles. Consequently, \( F_n \leq 12.7 \text{MPa} \) (in any of the interfacial cohesive elements) was defined as the durability requirement for the composite-laminate car door.

Manufacturability Analysis

As mentioned earlier, the composite-laminate door inner panel analyzed in the present work is expected to be fabricated using Resin Transfer Molding (RTM). RTM is a liquid thermosetting-polymer composite molding process in which the chemical reaction in the resins are thermally activated by heat from the mold wall and fiber mat (preform). The reaction rate in RTM processes is relatively slow allowing a longer fill time at lower injection pressure. The resulting lightweight, high-strength material is widely used in variety of automobile components. In the RTM process, dry fiber reinforcements, or fiber preform, is packed into a mold cavity which has the shape of the desired part. The mold is then closed and resin is injected under pressure into the mold where it impregnates the preform. After the mold-fill cycle, the cure cycle begins, during which the mold is heated and resin polymerizes to become rigid plastic.

The greatest benefit of RTM relative to other polymer-based composite manufacturing techniques is the separation of the injection and cure stages from the fiber-preform fabrication stage. In addition, RTM also enables high levels of microstructural control and part complexity compared with processes like injection molding and compression molding. Additional benefits offered by RTM include: low capital investment, good surface quality, tooling flexibility, large and complex shapes, relatively large range of reinforcements.

Fabrication of the car inner panel using the RTM process has been modeled in the present work using the Reactive Molding module of the Moldflow Plastics Insight 6.1 [13]. Reactive Molding provides important information used to detect various molding problems and to optimize part, mold, and molding process. Specifically, insights can be gained into how the mold fills in the presence of fiber reinforced preforms, whether short shots due to pre-gelation of the resin can occur, the locations of potential air traps or weld lines, selection of the proper molding machine size, and evaluation of different reactive resins.

Within Reactive Molding module, mold filling in the presence of fiber mat reinforcements is modeled by Darcy's Law [e.g. 13]. Darcy's Law states that the flow velocity at a given point, in a given direction, is proportional to a negative of the component of pressure gradient in that direction. The proportionality constant is a ratio of permeability of the porous medium and viscosity of the fluid, where permeability quantifies the ability of a fluid to flow through a porous medium. The numerical method used is based on a hybrid finite-element/finite-difference method for solving the governing mass, momentum and energy conservation equations for pressure, flow rates, and temperature, and a control-volume method is used to track moving resin fronts. Resin viscosity is calculated as a function of temperature, the extent of cure and shear.
rate. Resin curing kinetics is also included in both the calculations dealing with flow dynamics and with temperature.

In the RTM process involving preform, resin is forced to flow through the porous preform. Since the composite laminates used in the present work are expected to be stitched or woven, the preform structure will generally be two-dimensional and anisotropic. Consequently, in terms of the pore-area distribution, the preform will show a maximum in one in-plane direction and a minimum in the direction at right angles to the first direction. When resin flows through such a preform, the flow in the direction of maximum pore area advances more quickly, because it encounters less resistance. In other words, permeability will be larger in the first than in the second direction. Consequently, permeability becomes a 2 by 2 \( K_{11}, K_{12}, K_{21}, K_{22} \) matrix quantity.

In the RTM computational analysis carried out in the present work, un-filled epoxy resin EMC CEL-9200-XU (LF) from Hitachi Chemical [13] was used. The following general and thermal properties of this material were adopted: density - 1.23g/cm\(^3\); specific heat - 975J/kg K and thermal conductivity-0.97W/m K in the analysis, a reactive viscosity model [23] was used which states that:

\[
\eta(\alpha, T, \gamma) = \frac{\eta_0(T)}{1 + \left(\frac{\eta_0(T)\gamma}{\tau^*}\right)^{1-n} \left(\frac{\alpha_g}{\alpha_g - \alpha}\right)^{C_1+C_2\alpha}}
\]

(1)

\[
\eta_0(T) = B \exp\left(\frac{T_b}{T}\right)
\]

(2)

where \( \eta \) is the viscosity (Pa·s); \( \gamma \) the shear rate (1/s), \( T \) the temperature (K), \( \alpha \) the degree of cure (0-1) and \( n, \tau^*, B, T_b, C_1, C_2 \) and \( a_g \) (gelation conversion) are material-specific coefficients whose values for EMC CEL-9200-XU (LF) are given in Table 2.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( n )</td>
<td>N/A</td>
<td>0.6941</td>
</tr>
<tr>
<td>( \tau )</td>
<td>Pa</td>
<td>7.327 \times 10^{-5}</td>
</tr>
<tr>
<td>( B )</td>
<td>Pa.s</td>
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</tr>
<tr>
<td>( T_b )</td>
<td>K</td>
<td>5366</td>
</tr>
<tr>
<td>( D_1 )</td>
<td>K/Pa</td>
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</tr>
<tr>
<td>( C_1 )</td>
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</tr>
<tr>
<td>( C_2 )</td>
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</tr>
<tr>
<td>Gelation Conversion</td>
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<td>0.5454</td>
</tr>
</tbody>
</table>

Table 2 Reactive Viscosity Model Parameters for EMC CEL-9200-XU (LF) Epoxy Resin from Hitachi Chemical

To calculate the curing behavior of EMC CEL-9200-XU (LF), the \( N \)-th order (Kamal's reaction) kinetics model [24] is used. Within this model, the reaction kinetics is defined by the following relations:

\[
da / dt = (K_1 + K_2\alpha^n)(1-\alpha)^n
\]

(3)

\[K_1 = A_1 \exp\left(-E_1 / T\right)
\]

(4)

\[K_2 = A_2 \exp\left(-E_2 / T\right)
\]

(5)
where $\alpha$ is the degree of cure (0-1), $T$ temperature (K), $t$ time (s), and $m$, $n$, $A_1$, $A_2$, $E_1$ and $E_2$ are material-specific constants. The model also includes induction time (i.e. the period before curing starts to take place) which is calculated using the following equation:

$$t_i = B_1 \exp \left( \frac{B_2}{T} \right)$$

where $t_i$ is the induction time, $B_1$ (s) and $B_2$ (K) material-specific constants. A summary of the reaction kinetics model parameters for EMC CEL-9200-XU (LF) is given in Table 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$H$</td>
<td>J/kg</td>
<td>0.6941</td>
</tr>
<tr>
<td>$M$</td>
<td>N/A</td>
<td>0.07329</td>
</tr>
<tr>
<td>$N$</td>
<td>N/A</td>
<td>1.103</td>
</tr>
<tr>
<td>$A_1$</td>
<td>1/s</td>
<td>10000</td>
</tr>
<tr>
<td>$A_2$</td>
<td>1/s</td>
<td>1.227.108</td>
</tr>
<tr>
<td>$E_1$</td>
<td>K</td>
<td>26820</td>
</tr>
<tr>
<td>$E_2$</td>
<td>K</td>
<td>9790</td>
</tr>
</tbody>
</table>

The RTM analysis was carried out under the following recommended processing conditions: (a) initial resin temperature - 323K; (b) mold surface temperature - 453K; (c) ejection conversion - 0.5; (d) cooling rate - 0.3333 K/s; (e) nominal injection time - 5s; (f) curing time - 30s; (g) maximum machine injection pressure - 20MPa; and (h) intensification ratio - 10.

In the present work it was assumed that individual plies are made of carbon roving (consisting of 6000 439THTA fibers from Cramer) weaved into a 5H satin fabric and stitched using Titre 150 polyester thread. Such plies were investigated in the work of Talvensaari et al. [25], who measured their permeability as a function of the stitching pattern, ply-stacking sequence, and stitching-thread tension level. The following typical permeability values corresponding to $0^\circ$ plies, cross-stitched at a 10mm x 10mm line spacing and an average thread tension of 5N obtained in Ref. [25] were used: $K_{11}=1.4 \times 10^{-11}$ m$^2$, $K_{22}=0.9 \times 10^{-11}$ m$^2$ and $K_{12}=K_{21}=0$ m$^2$.

### 2.3.3 Optimization and Parameter Study

The multi-disciplinary optimization problem studied in the present work falls into a class of engineering optimization problems in which the evaluation of an objective function(s) or constraints requires the use of structural and manufacturing-process simulation analyses. The design objectives for structural (load-bearing) automotive components are the fulfillment of certain expectations with respect to the components’ weight, cost, functionality and appearance. The design problem can, for example, be formulated as weight minimization subject to the cost, performance, manufacturability and aesthetics constraints. In a compact form, the optimization problem can be symbolically defined as:

- Minimize the objective function (the car-door panel weight, in the present work), $f(x)$.
• subject to the non-equality constraints (various functional, NVH, crashworthiness, durability and manufacturability constraints defined in Section II.3.2), \( g(x) < 0 \),
• to the equality constraints (none used in the present work), \( h(x) = 0 \), and
• to the condition that design variables (e.g. ply thickness must be positive, inter-patch boundaries must lie within the component, etc.), \( x \) belong to a domain (design space) \( D \).

where, in general, multiple non-equality and equality constraints are present making \( g(x) \) and \( h(x) \) vector functions. The design variables \( x \) form a vector of parameters usually describing the geometry and/or the material(s) of a product. For example, \( x, f(x), g(x) \) and \( h(x) \) can be product dimensions, product weight, a stress condition defining the onset of plastic yielding, and constraints on product dimensions, respectively. Depending on the nature of design variables, its domain \( D \) can be continuous (e.g. a continuous range of the length of a bar), discrete (e.g. the standard gage thicknesses of a plate or the existences of structural member in a product), or the mixture of the two. Furthermore, an engineering optimization may have multiple objectives, in which case the objective function, \( f(x) \), becomes a vector function. Objective and constraints are evaluated using different (multi-disciplinary) computational analyses.

The solution of an optimization problem involves multiple iterations through the following steps:
1. An initial design is first selected;
2. The initial design is analyzed by evaluating its objective function(s) and constraints;
3. Fulfillment of the constraints is examined and if the requirements are not met, changes are made in the design and the procedure repeated starting with step 2. Otherwise, an optimal and feasible design has been found and the optimization procedure is terminated.

The selection of a new design in Step 2 is usually done using one of the following two approaches:
(a) Design variables are updated along a "search direction" in the design space. The search direction is obtained using the design sensitivities (partial derivatives of the objective and constraints functions with respect to the design variables at a given point in the design space). Such design sensitivities are typically computed as part of the multi-disciplinary analyses used to evaluate the objective and constraints functions. In this approach, the objective and constraints functions are essentially linearized around the current design and it is assumed that only small changes in the design occur in each optimization iteration. Typically very few evaluations of the objective and constraints functions are necessary and the result is a local "optimal" design; and
(b) Higher-order algebraic-function approximations (typically referred to as "Response Surfaces") are constructed to represent functional relationships between the objective and the constraints equations, on one end, and the design variables, on the other. Response surfaces are normally obtained by employing a parametric study (i.e. the Design of Experiments approach) in which design variables (i.e. designs) are selected by sampling the design space in accordance with a given sampling scheme [31] and the objective and constraints functions are evaluated for each design. In response surface functions, the terms depending on the value of a single design variable are commonly referred to as "effects" while those depending on the values of two or more design variables are referred to as "interactions". Once response surfaces are generated for the objective and constraints equations, they can be treated as a proxy for the design
model at hand and used in the multi-disciplinary optimization procedure. The optimization problem is then solved using mathematical programming and the result represents an approximate solution. This approach enables identification of the optimal design in a very efficient manner without a need for running additional computationally-expensive multi-disciplinary analyses (beyond those used in the construction of the response surfaces). The response surface approach is usually employed for the highly non-linear problems and/or in the cases in which the design space is too large. After response surfaces for the objective and constraints functions are constructed, they are examined and, if necessary, the search/design domain is redefined. Then a parameter study procedure can be invoked again the whole procedure repeated until convergence is reached. An alternative response-surface method called “The Adaptive/Sequential Response Surface Method” [2] (used in the present work) is also available. Within this method, the response surface is updated after each optimization iteration which, typically, results in a smaller number of functional evaluations relative to that needed in the ordinary response-surface method, making the former approach computationally more efficient.

In addition to helping create the response surfaces, parameter studies are also useful in reducing the number of design variables to be used in the optimization analysis. Reducing the number of design variables to no more than ten is highly critical since some computational analyses, like crashworthiness analyses, are associated with computational times of several hours. To reduce the number of design variables, the so-called “Screening Design of Experiments” approach can be employed to identify the design variables which have large effects on the objective and constraints functions and, hence, should be considered in the optimization analysis.

In the present work, (Screening) Design of Experiments approach, parameter studies and the Adaptive Response-Surface method are combined within HyperStudy to carry out multi-disciplinary optimization of a car door with respect to meeting the weight, structural, NVH, crashworthiness, durability and manufacturability requirements. As explained earlier, HyperStudy provides interfaces to different solvers enabling multi-disciplinary optimizations to be performed.

3. Results and Discussion

3.1 Conceptual Design

As mentioned earlier, within the conceptual design, the car-door composite-laminate inner panel is optimized with respect to its weight while meeting the structural (frame-rigidity and sagging-resistance) and NVH requirements as defined in Sections II.2.1 and II.2.2, respectively. The FES optimization method was used within which the thicknesses of the four (0°, +45°, -45° and 90°) ply-types within each inner-panel finite element were used as design variables. The results of this optimization step are displayed in Figures 8(a)-(d) in which the spatial distributions of the four-ply thicknesses are shown. It should be recalled that composite-laminate lay-out (i.e. the stacking sequence of the plies) is not considered. Rather, plies are homogenized into a monolithic composite laminate. The conceptual design for the car-door inner panel represented by the ply-thicknesses distributions displayed in Figures 8(a)-(d), meets all the structural and NVH requirements while having a ~16% lower mass than its metal
counterpart. The computational analysis employed was found to be quite efficient and a typical conceptual-design optimization run took about 20min to complete and entailed 7 iteration steps.

The conceptual design displayed in Figures 8(a)-(d) needs to be modified before it can be subjected to the detailed design optimization procedure. More specifically, the regions of the inner-panel characterized by nearly uniform ply thicknesses of the four plies are defined as composite patches. In the detailed-design optimization step, the plies within each patch will have uniform thicknesses. These thicknesses are used as size design variables while the boundaries between the adjacent patches are used as shape variables within the detailed design optimization step. Furthermore, to ensure an orthotropic character of the composite laminate, the thicknesses (i.e. the numbers) of the +45\(^\circ\) and -45\(^\circ\) plies are constrained to remain the same.

To keep the number of design variables in the detailed-design optimization step relatively low, the composite-laminate inner panel is partitioned into 7 patches. The shapes of the initial patches are depicted in Figure 9.

3.2 Detailed-Design Optimization

As explained earlier, within the detailed design optimization step, not only the structural and NVH requirements, but also crashworthiness, durability and manufacturability requirements are considered. These requirements were identified in Sections II.2.3 through II.2.5 and II.3.2. The position of the composite-laminate inner-panel inter-patch boundaries obtained at the end of the detailed-design optimization step is displayed in Figure 11. The thicknesses of the three (0\(^\circ\), +45\(^\circ\)/-45\(^\circ\) and 90\(^\circ\)) plies in each of the composite patches are also displayed in this figure. The extent of adjustment of the inter-patch boundaries can be obtained by comparing the results displayed in Figure 11 with the starting inner-panel design shown in Figure 9.

![Fig.11](image-url) Seven composite-panel patches obtained after the application of the detailed-design optimization analysis. The numbers (e.g. 0.6/0.3/0.9mm) refer to the thicknesses of 0\(^\circ\), +45\(^\circ\)/-45\(^\circ\) and 90\(^\circ\) plies rounded off to the nearest multiple of 0.3mm (the single-ply thickness).
The optimal design displayed in Figure 11 needs all the structural, NVH, crashworthiness, durability and manufacturability requirements. This can be seen in Figures 12-14.

Fig. 12 Detailed-design optimization results pertaining to the: (a) frame rigidity and (b) sagging resistance of the composite-laminate car door.
Fig. 13 Detailed-design optimization results pertaining to the crashworthiness of the composite-laminate car door.

Fig. 14 Detailed-design optimization results pertaining to manufacturability of the composite-laminate inner panel using the standard resin transfer molding process: (a) a mold-filling time contour plot (with weld lines and air traps indicated) and (b) orientation of the 0°C plies throughout the composite laminate.
In Figures 12(a)-(b), it is seen that the maximum $y$-displacement resulting from the 5.8kPa pressure is lower than 15mm (the frame-rigidity requirement), while the gravity-induced $z$-component is lower than 0.18mm (the sagging-resistance requirement). In order to help visual comparisons between the results displayed in Figures 3 and 12, the same displacement contour levels were used.

The lowest natural frequency of the door was found to be 30.8Hz and is, thus, effectively identical to its counterpart in the all-metal door. In other words, the final design of the composite-laminated inner panel was controlled by the condition that the NVH requirement must be met. This finding is consistent with the fact that the low density of the composite-laminate material reduces the structural frequencies.

The results presented in Figure 13 show that the maximum inward intrusion resulting from the crash is lower than 223.5mm (the crashworthiness requirement). Again, in order to help visual comparison between the results displayed in Figures 5 and 13, the same displacement contour levels were used.

The maximum normal traction $F_n$ was found to satisfy the durability requirement $F_n \leq 12.7\text{MPa}$. Furthermore, since in a number of cohesive elements $F_n$ was found to be ca. 12.5MPa, it appears that the durability requirement also plays a dominant role in controlling the final design of the composite-laminate inner panel.

Finally, as can be seen in Figure 14(a), under the standard RTM processing conditions, the infiltration of the carbon-fiber perform is complete. Thus the manufacturability constraint is also satisfied. The corresponding orientation of the 0o plies in the panel is displayed in Figure 14(b). The results displayed in Figure 14(a) also show that the resin flow is balanced (ensuring minimal post-curing distortions), that the weld lines are equally spaced (ensuring a fairly uniform distribution of potential resin-infusion flaws) and that the number of (undesirable) air traps is relatively small. All these findings suggest that the optimized composite-laminate inner panel is not only manufacturable under the standard process conditions, but also that its structural integrity and performance/reliability should be quite high.

The weight of the composite laminate inner panel resulted from the detailed-design optimization process is 5% lower than its metal counterpart. This weight reduction is somewhat lower than that obtained at the end of the conceptual design stage. This finding is consistent with the fact that the detailed-design optimization is subjected to additional constraints i.e., crashworthiness, durability and manufacturability constraints and the number of design variables is lower (due to the fact that the thickness of each ply within a given patch was kept uniform and that the numbers of the $+45^\circ$ and $-45^\circ$ plies was kept the same within a given patch).

The present detailed-design multi-disciplinary optimization problem was solved on a PC with 16GB RAM and two four-core CPUs (each having a 3GHz clock speed). Upon the completion of the optimization-study set up, it took around 11 hours to obtain the final optimal design, Figures 11-14. As mentioned earlier, however, the multi-disciplinary optimization analysis presented in this work is highly simplified since single scenarios (i.e. single loading conditions) are used to describe particular functional requirements (e.g. frame rigidity) and the definition of crashworthiness, durability and manufacturability were greatly oversimplified. Nevertheless, in the present work an attempt was made to identify and model some of the most critical scientific and engineering phenomena and concepts which currently limit the viability of the MDO analyses (e.g. consideration of component-joints fatigue controlled durability, proper
modeling of materials under large deformation/high strain-rate conditions and consideration of manufacturability within the design process. While there are many examples of the MDO analyses applied to automotive components, they are mostly concerned with NVH and crashworthiness requirements and with all-metal components. Inclusion of the additional concepts presented in the present work in the multi-disciplinary design optimization of structural automotive components is considered by the present authors as highly critical before the MDO can be expected to become a viable design alternative.

4. Summary and Conclusions

Based on the results obtained in the present work, the following summary and main conclusions can be made:

1. A two-step multi-disciplinary optimization procedure is proposed and applied to the design of a car-door composite-laminate inner panel. Within the first (conceptual-design) step, the free element sizing method is used while, within the second (detailed-design) step, an adaptive response surface method is used to obtain a weight optimized design which meets specific structural, NVH, crashworthiness, durability and manufacturability constraints.

2. The work revealed the variety and the complexity of concepts (particularly those related to components joining, durability and manufacturability) which must be included into comprehensive multi-disciplinary optimization analysis.

3. The use of HyperStudy computer program is demonstrated in setting up and running in an automatic manner a multi-disciplinary optimization analysis which employs a large number of linear and non-linear structural-mechanics finite-element codes, durability prediction algorithms and manufacturability-process simulation software.

4. While some of the aspects of the multi-disciplinary optimization were oversimplified, the approach showed, nevertheless, the potential of composite materials to reduce the weight of automotive structural components.

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References:


