Experimental and numerical analysis of hovering multicopter performance in low-Reynolds number conditions

Innovative optimization approach to improve NVH and lightweight in lower control arm

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Keywords: Vibration and Noise Control, Composite Structures, FEA, Design Optimization, Lightweight design

Abstract

This paper presents a multi-material design for a lightweight swing arm of a McPherson suspension. Starting from a stamped steel lower control arm of a C-segment vehicle a hybrid arm made of a metal core and two CFRP covers has been hand sketched, CAD designed, and FEM tested. To fully exploit hybridization potential, it has been developed a specific methodology which combines the topological optimization of the metal core, and the 3-phase optimization of the composite covers. Also, an innovative viscoelastic material has been included in the laminates to enhance the damping properties of the arm and a FRF analysis has been performed. The results in terms of mass, stiffness and stress distribution have been compared with the original stamped steel LCA and with another hybrid LCA design. The final comparison has shown that with the redesign approach it has been possible to reduce the mass to a greater extent without affecting stiffness performance and stress distribution.

1. Introduction

Mass reduction plays a fundamental role in modern suspension components design. Besides keeping the unsprung mass fraction as low as possible to improve comfort, the trend towards lightweight parts is the result of the upcoming restrictive regulations in terms of CO_2 emissions [1,2]. Although for different reasons, both internal combustion and electric vehicles benefit from a reduction in mass. A lighter ICE **(Internal Combustion Engine)** vehicle means lower fuel consumption which results in lower CO_2 emissions. Likewise, for EVs **(Electric Vehicles)** mass reduction is a key factor in increasing vehicle range. Initially, mass reduction process mainly involved micro or small EVs and less structure-sensitive components [3-6]. Until, thanks also to the research progress in the field of advanced component health monitoring techniques [7], it was realized that the effort towards lighter vehicles must involve all areas. **Today's conventional suspension arms designs are made of either ferrous materials or aluminium alloys while casting, forging, and stamping are the most common technologies [8]. As emerges from [9], control arms made out of metal may have lightweight potential if research in terms of new high strength alloys and advanced shape optimization techniques are considered. Unfortunately, most of these manufacturing processes have already reached their limit also considering the trade-off between cost and mass reduction targets. Therefore, automotive industry is challenging OEMs (Original Equipment Manufacturers) towards innovative solutions, as evidenced by the considerable amount of research applications found in literature. New trends involve different materials and manufacturing processes, such as:**

- ***Forged Composite®* [10], which is an advanced compression moulding process involving Carbon Fiber Sheet Molding Compound developed by Lamborghini's R&D department;**
- **Thermoplastic matrix composite and related processes for medium production volumes developed by ENLIGHT project [11].**

It is also worth mentioning the thermoplastic composite arm design conceived by the partnership between CETIM, PSA group, Onera and Compose [12]. Material and process used make this concept very interesting. The final part is the result of two Carbon-PA organo-sheets simultaneously thermoformed and then welded together in automated press to obtain a hollow body structure. This principle was never introduced before for composite parts reinforced with continuous fibers.

In this context, the idea that a multi-material approach can offer further lightweight potential and an improved trade-off between cost and mass reduction targets is becoming increasingly convincing.

In recent years, especially in aerospace industry, metal-composite hybrid solutions have been proposed also for structural components thanks to their many advantages which include their good crash and safety

performances [13,14]. On the other hand, research in the field of hybridization is still in its early stages when compared to the state of the art of traditional techniques. This leads to a certain number of drawbacks such as:

- **Corrosion: due to different electrochemical potentials of materials (e.g. Al and CFRP). This situation can lead to the failure of the bond;**
- **Thermal expansion: due to the different thermal expansion of CFRP/metals and of CFRP itself (balanced stacking sequence);**
- **Joints: there are several methods to join metal and CFRP, each with its pros and cons, the most adopted is adhesive bonding. It avoids stress concentrations but features limited application temperatures, long curing times and the presence of an irreversible bond.**

This suggests that further research is still needed to fully understand the capabilities of complex multi-material components. It is necessary to develop knowledge that may be self-evident in the case of separate materials but must be renewed when adopting multi-material technologies. Hence, the importance of works such as [15], which investigates the mechanical behavior of a tensile loaded hybrid composite-metal panel, and [16] which analyses the effects of drilling metal-CFRP stacks.

Moving back to the automotive field there are already examples of hybrid components optimization [17] and of suspension arms made with multi-material technologies [18,19]. However, solutions applying short fibers and reinforcement ribs can be obtained with traditional metal-oriented optimization techniques. In this way it is not possible to exploit the capabilities and outstanding mechanical properties of continuous fiber reinforced composite materials.

Thus, the objective of this paper is to further investigate multi-material design potential **using a new optimization strategy specifically engineered for structural hybrid components featuring long fibers composite. This has been possible** thanks to the know-how acquired from **[20,21].** For these reasons, the component used as reference in this work, the so-called baseline geometry, is the same C-segment stamped steel control arm described in **[20]**. Additionally, based on what defined in **[22],** an innovative viscoelastic material has been introduced in the design phase to enhance the damping properties of the suspension arm. In the automotive industry noise and vibration are increasingly important issues also due to electrification and in the hybridization process NVH **(Noise Vibration Harshness)** is a matter of concern considering that lightweight materials can significantly change the NVH behaviour of a component **[23].**

This new component, hereafter called “hybrid evo”, has been subjected, through FEM **(Finite Element Method)** analysis, to series of special and misuse load cases calculated according to a multi-body model. Their characterization also in terms of mass and stiffness has been necessary to define the targets for the hybrid solutions. Then, starting from the stamped steel control arm a multi-material arm made of a metal core and two CFRP **(Carbon Fiber Reinforced Plastics)** covers has been completely redesigned: hand sketched, CAD **(Computer Aided Design)** designed, and FEM tested. Both the original position of the hard points and the original size of the bushing sleeves have been integrated into the new hybrid design. The approach used is referred to as tailored design **[24]** because employs a combination of metal and continuous fiber reinforced plastics. An innovative methodology, based on the separate contribution of the metal core and composite covers to the overall stiffness, has been developed. In this way it was possible to perform both a topological optimization on the metal and a three-phase optimization on the composite to fully exploit hybridization potential. Finally, the redesigned and optimized hybrid swing arm achieved and even exceeded the 25% of mass reduction target ensuring at least the same performance as baselines in terms of longitudinal and lateral stiffness. The results were also compared with a previous version of hybrid arm obtained with a different approach so that the advantages of the component redesign could be successfully proven.

2. Load Case configurations

The lower control arm used as reference in this work is a single shell stamped steel LCA **(Lower Control Arm)** of a C-segment vehicle which will be often referred to as swing arm. This suspension arm is made of micro-alloyed HSLA **(High-Strength Low-Alloy)** steel with a sheet metal thickness of 4 mm. The mass of the assembly not including lower ball joint and bushings is equal to 2,16 kg.

Defining the load conditions on a lower control arm is challenging. They include road loads resulting, for example, from accelerating, braking, cornering, striking potholes and driving on a bump. These load cases can be divided into:

- Operational or service loads.
- Misuse or abuse loads.
- Special loads (e.g., track day).

In this paper a well-established workflow, which can also be found in **[20],** has been followed to define the vehicle load case configurations. This approach was mandatory to be able to compare the results obtained from the previous version of hybrid LCA and the ones of the hybrid evo redesign.

As input to setup the working conditions to calculate the forces acting on the LCA, some reference vehicle data have been used such as:

- **total vehicle mass in standard A, which is the sum of kerb vehicle mass, 75 kg representing the driver, and 10 kg of luggage and it is equal to 1405 kg**
- **70% of GVM (Gross Vehicle Mass) which is equal to 1870 kg.**

Most severe conditions for the control arms occur when load resultants have a major component acting on longitudinal or lateral direction. Taking into account this consideration six loads case for the test have been selected and summarized in Table 1, including the respective vehicle configuration and the resultant force.

MSC ADAMS/Car has been used to create a customized multibody model developed specifically for this application **[25].** Finally, special and misuse maneuvers have been simulated using the multibody model to obtain the entity of the resultant forces which will be used in FEA **(Finite Element Analysis)**.

Table 1 Load Cases

Load Case	Vehicle Configuration	Resultant Force [kN]
Skid-pad	Standard A	5,11
Maximum Acceleration	Standard A	2,66
Maximum Braking	Standard A	4,88
Crossbeam	70% of GVM	2,72
Hump	70% of GVM	5,40
Drain	70% of GVM	3,87

3. Hybrid evo arm design

Based on the original stamped steel swing arm a multi-material arm made of a steel plate incorporated between two CFRP covers have been developed. As already mentioned, the main difference between the design approach applied in this study and the one applied in **[20]** is that the hybrid evo arm features a complete component redesign and a novel optimization methodology, allowing to deepen and completely understand the potential of multi-material applications.

Three constraints were set to obtain a hybrid LCA replaceable with the original component:

- the integration of the original bushing sleeves;
- the position of the hard points;
- the maximum packaging volume (to avoid any interference in the vehicle subframe).

First, during the hand-sketching phase, various ideas have been collected and evaluated. In this early design stage the proposed solutions were based on research work carried out at the beginning of the study, in the field of lightweight suspensions, and were inspired by existing components such as the optimized steel arm described in [9] and the full carbon fiber arm described in [12]. Among these designs it was selected the one with the best development chances considering both mechanical performance and feasible production methods. The CFRP covers can be pre-formed in dedicated molds to obtain a central embossment meanwhile the steel plate with a reduced thickness can be laser-cut and then welded to the X-bushing supports and to the X and Z bushing sleeves. Thanks to the know-how contained in **[20,22],** it was possible to integrate into the laminate an innovative solution provided by Kraibon, which consists of a thin calibrated non-crosslinked rubber film whose viscoelastic properties are specifically tuned to enhance NVH, impact and chipping behavior, increasing the damage tolerance capabilities of the component. This material (named HVV) has been placed as first layer of both CFRP covers to provide a distributed damping effect throughout the component. The final assembly can be obtained keeping the metal core and the two covers in position with a template during the curing phase. Metal and laminates can bond thanks to the presence of the HVV material which is compatible with this manufacturing process and provides a direct connection without additional bonding agents.

Finally, starting from the hand-sketches a CAD geometry has been designed (Figure 1).

[Insert Figure 1. Hybrid evo arm CAD geometry]

At this stage of design, the covers have been assigned a fictitious thickness value because the tailored stacking sequence will only be defined after the optimization phase.

The targets that the final hybrid LCA design must met are:

- Achieve a mass reduction of more than 25%.
- Ensure the same longitudinal and lateral stiffness as baseline.
- Meet special and misuse events requirements in terms of stress distribution.
- Ensure production feasibility.

4. FEM Models description

The metal core was modelled by using the same material as the original stamped steel component (S420MC). Concerning the covers, their mission is to assure the required stiffness and strength to the final hybrid arm assembly. In this context carbon fibers represent the best trade-off between performance and mass reduction. They can be classified as high modulus (HM) or high strength (HS) based on their tensile modulus and their tensile strength. For the hybrid evo arm design two different kind of fiber reinforcements have been selected:

- Unidirectional layers **(UD)**
- Fabric layers

As far as unidirectional fibers are considered it has been decided to compare the behaviour of the UD M46J and the UD STS. The M46J was already used in the hybrid arm described in **[20].** Additionally:

- The UD STS is made of high strength fibers and its price is about a third of the one of UD M46J allowing a cost saving of ≈ 70% for the same material quantity
- The UD M46J is more expensive but significantly more performing as it is made of high modulus fibers.

Regarding the composite fabric it has been chosen the twill fabric GG430T. It has been used throughout the laminate as structural layer to homogenize the stress distribution along the arm surface thanks to its strength properties which are the same at 0°/90°. Additionally, used as last layer, this material will provide the typical carbon-look to the final component. All materials used in the model are summarized in Table 2.

Table 2 Materials defined in the model for each component

NAME	Weave	Component
T700 GG430T	Twill 2x2	CFRP covers
UD M46J 150 g/m^3	Unidirectional	CFRP covers
UD STS 300 g/m^3	Unidirectional	CFRP covers
S420MC	-	Arm plate, X bushing supports
FE510	-	Bushings

Even though the benefits of composite materials such as carbon fibers are well known to carmakers, their use continues to be limited due to the significant differences with metals from the standpoint of design, mechanical behaviour, manufacturing process and, last but not least, cost. For this reason, material choice played a fundamental role in the early stage of the design phase, because, when dealing with composites, feasible means also cost-effective. In the next steps advanced computational tools and customized material cards have been used to model and predict component performance. The CAD geometry has been clean-up and meshed using ANSA BETACAE (Figure 2).

[Insert Figure 2. Model clean-up and mesh]

Regarding the mesh, upper and lower covers as well as the arm plate and the X bushing supports have been meshed using CQUAD4 shell elements while X and Z bushing sleeves are made of solid CHEXA elements. The maximum LCA dimensions are about 372mm x 360mm x 60mm and the average mesh size used is 2 mm (total number of elements 46171).

To simulate the conditions of installation of the control arm three boundary conditions have been included in the FEM model. Instead of lower ball joint and X and Z rubber bushings three rigid bodies (RBE2 elements) were created. They replace these three components by introducing less complexity into the model and, if properly constrained, allow to replicate the actual mounting conditions. All the simulations have been performed using Altair OptiStruct solver. Figure 3 displays the complete model configuration in Altair HyperMesh including the boundary conditions. **Under the conventional symbol of constraint the degrees of freedom fixed have been reported as numbers from 1 to 6 where 1, 2 and 3 represent the translations along X, Y and Z axes respectively while 4, 5 and 6 represent the rotations around X,Y and Z axes respectively.**

[Insert Figure 3. Hybrid evo swing arm FEM model]

The workflow followed to obtain the final optimized hybrid LCA is explained in Figure 4.

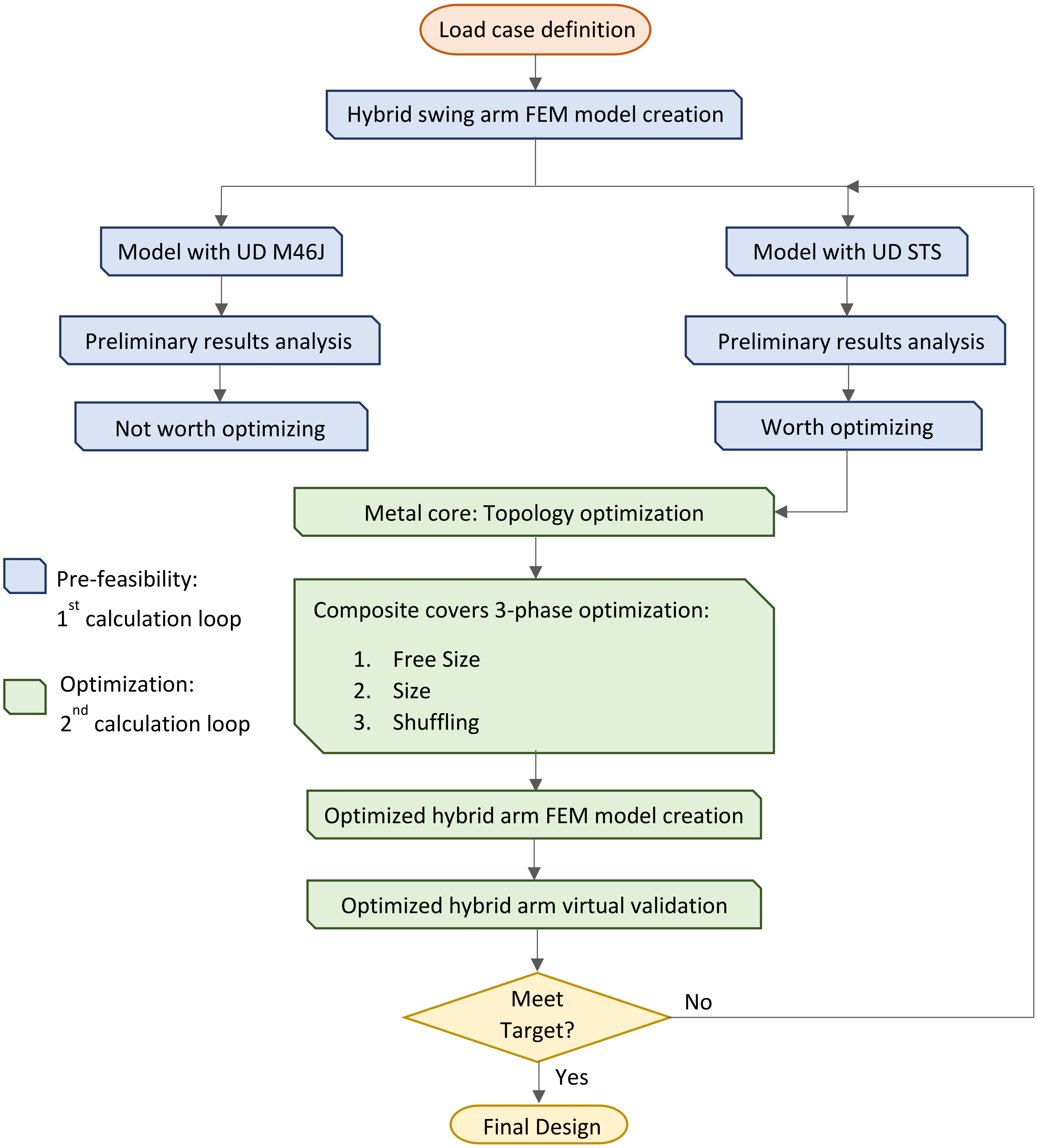

Figure 4 Methodology flow chart

The process diagram shows that, before the optimization, a first calculation loop has been included. In this phase, thanks to the knowledge developed in the previous experiences of multi-material design and modelling **[20,22],** two different hybrid evo LCA solutions have been created. **One using UD STS and one using UD M46J as main CFRP reinforcements with the aim of ensuring robustness to the material selection.** The results obtained after this calculation loop, which can be considered a pre-feasibility study, demonstrated that both the UD STS and the UD M46J are suitable for this application. However, analysing the values reported in Table 3, it has been decided to proceed with the optimization of the multi-material arm in which the UD STS has been used to get a more cost-effective component.

Table 3 Pre-feasibility study results

Component	Mass Reduction [%]	Longitudinal Stiffness [kN/mm]	Delta Longitudinal Stiffness [%]	Lateral Stiffness [kN/mm]	Delta Lateral Stiffness [%]
Swing Arm: Baseline	-	6,9	-	27,20	-
Swing Arm: Hybrid evo with UD M46J	18	7,70	+11	74,62	+174
Swing Arm: Hybrid evo with UD STS	17	7,10	+2	67,56	+146

Even before the optimization, this new hybrid arm design obtained a mass reduction close to 20% and met all stiffness targets. The amount of CFRP needed to obtain the UD M46J version is slightly lower but seems not to justify the decision to use it instead of the UD STS considering their 3:1 cost ratio. Additionally, the UD STS being made of high strength fibers has higher maximum strength limits which should guarantee a better behavior in terms of durability. The optimization phase will be fundamental to find out the best trade-off between performance, cost, and mass reduction.

5. New Optimization Methodology

The new methodology presented features a combined optimization of metal and composite. Considering that the CFRP covers are responsible for the performance of the arm while the metal core guarantees the steel-composite integration it was necessary to create an *ad hoc* procedure that would allow to minimize the mass on both sub-components and yet not having negative effects on stiffness and stress distribution.

To implement this approach the first step has been defining the influence of the single components of the hybrid arm assembly on the stiffness results. To obtain this information, the FEM model has been modified deleting the CFRP covers and leaving only the steel core. Thereby, running again the longitudinal and lateral stiffness simulations, the role played by the metal core only has been evaluated. As expected, the overwhelming majority of the total stiffness contribution (more than 90%) is given by the covers. The steel plate works as a base for the CFRP covers and as a link between the non-design areas such as bushing sleeves and ball joint housing that would be difficult to integrate into a full composite monolith. This makes the optimization of plate and CFRP covers even more important to achieve a final hybrid arm which fully exploits hybridization lightweight potential with a perfect steel-CFRP integration.

5.1 Metal Optimization phase

The type of optimization used is referred to as "topology optimization". OptiStruct solves topological optimization problems using the density method, also known as the SIMP method **[26]**. The density of each element is directly used as design variable. The DRCO **(Design Variables-Responses-Constraints-Objective)** approach has been used. The design variables are the parameters, properties, features which can be changed in a model. They define the optimization type. The optimization responses are usually measurement of output characteristics of the system while the constraints are the limits applied to the model responses which must be satisfied for a feasible design. Finally, the objective is linked to one of the model responses and represents the ultimate goal of the optimization. In this case:

- The design variable (DTPL card) is the PSHELL property assigned to the design area.
- The responses are three: a volume fraction response (needed to define the objective) a static x-displacement response and a static y-displacement response at the master node of the rigid element representing the ball joint.
- The constraints have been defined so to guarantee that the hybrid arm has at least the same stiffness as the baseline.
- The objective of the optimization is to minimize the volume fraction response.

The main output of topology optimization is the density distribution of the elements within the original component geometry. Elements that, after the optimization, have a density equal to 1 are highly stressed and thus necessary to reach the targets imposed at the beginning of the optimization phase. On the other hand, elements with a density close to 0 are redundant and can be removed. Clearly this density is not related to the physical density of the materials but rather to the behavior of the elements according to component load paths. The cut-off value (usually 0,5) is imposed by the user and must be a trade-off

between being conservative and achieving the targets in mass. Optimization results have been plotted in HyperView in terms of element density and are shown in Figure 5.

[Insert Figure 5. Topology optimization results]

These results have been exported as CAD file and modified manually following the topology optimization indications to obtain a feasible shape. Finally, the new plate design has been virtually verified repeating the stiffness calculation.

At the end of this optimization phase the metal core achieved 7% of mass reduction with respect to the first layout. It is a good result considering the limited design space. Additionally, even if the mass has been reduced, the uniform plate thickness increased from 1,5 mm to 2 mm. This means that thanks to the optimization also the welding interfaces between plate and bushing sleeves have been improved.

5.2 Composite Optimization phase

At this stage, the hybrid arm assembly featuring the newly optimized metal core has been FEM modelled and the optimization of the CFRP covers have been set. The approach adopted can be summarized in three steps:

1. *Free Size*: it is a concept-level optimization that works by modifying the thickness of each composite layer. The results of the "free-size " optimization are extremely useful in understanding how the total thickness of the element should be distributed over the topography of the laminate as shown in Figure 6.

   [Insert Figure 6. Free size optimization results]

   Free size results are the starting point for understanding how, where, and even which material and orientation is best suited to achieve the finest trade-off between structural performance and mass reduction. However, interpreting the "free-size" optimization to obtain meaningful and manufacturable ply shapes is challenging and requires experience and engineering expertise.

2. *Size:* it is a finetuning level optimization. The starting point of the size optimization is the output file of the Free-size phase (Figure 7-a). OptiStruct generated 96 plies, but most of them must be deleted or modified due to:

   - Not manufacturable shape (many patches were made of less than 10 elements).
   - Not manufacturable thickness (many plies had a thickness lower than 0,1 mm).
   - Ply overlaps issues.

   Also, in this phase, the self-generated elements sets were manually modified to obtain ply-shapes and reinforcements conforming to the manufacturing process (Figure 7-b).

[Insert Figure 7. Free size optimization output (a) Reinforcement's regions (b)]

3. *Shuffling:* it is a composite-specific optimization that rearrange the plies stacking sequence to obtain the optimal plybook for the optimized composite structure. It takes into a count some detailed manufacturing constraint such as the maximum number of successive plies with the same orientation, which is a very important parameter to avoid delamination issues. The optimization reached a feasible design after three iterations, the optimized ply-book is equal for both upper and lower laminates.

The ultimate design step has been the adjustment of ply shapes to be compliant with the plies drop-off constraints imposed by manufacturing. The final layout allows to avoid abrupt thickness changes and cavities in which the excess resin can accumulate, otherwise there may be discontinuity in structural performance.

Finally, the optimized hybrid evo arm model (Figure 8) has a mass of about 1,56 kg so it provides a 28% mass savings over the standard steel version. The total number of plies for each CFRP cover is 20, the composite mass added is 0,84 kg while 1,43 kg of steel have been saved from the starting arm geometry.

[Insert Figure 8. Final optimized hybrid evo LCA model]

6. Structural and Modal Results

Subsequently, the hybrid evo LCA performances have been FEM tested to validate this new hybridization approach. The arm stiffness has been evaluated with the same simulation set up used for the baseline. The displacement results have been plotted in HyperView for both longitudinal and lateral case with focus on the deflection of the MASTER node of the rigid element representing the lower ball joint (Figure 9).

[Insert Figure 9. Displacement results in [mm]: longitudinal (left) and lateral (right) case]

The point load of 10 kN applied both along x and y-axis results in a deflection of 1,426 mm for the longitudinal and 0,170 mm for the lateral case. The longitudinal stiffness K_x obtained is equal to 7 kN/mm while the lateral stiffness K_y is 58,5 kN/mm which means respectively 1,5% and 115% increase with respect to the original arm. **This result highlights that the most critical target in the design of the new component is the longitudinal stiffness. This target influenced the optimization results by constraining the maximum mass reduction outcome.**

To complete the study the optimized component has been virtually tested according to the set of simulations defined for the baseline swing arm. It has been used Von Mises criterion for the stress distribution analysis of the metal core while for composite covers it has been evaluated the maximum stress in the principal direction σ_1. Additionally, the Hashin criterion **[27]** has been adopted to estimate the composite failure index, which must be lower than 1 to avoid cracks. As far as special events are considered, the most critical case is maximum braking. In this analysis, the steel core reaches a maximum stress of 227 MPa as reported in Figure 10-a. Composite covers maximum principal stress σ_1 is equal to 63 MPa and it is registered on layer 5 of the upper cover made of UD STS as shown in Figure 10-b. The maximum Hashin registered on the composite covers is 0,008 (Figure 11-0).

[Insert Figure 10. Stress results for maximum braking: metal core (a) composite covers (b) and failure index (c)]

Between the misuse condition the hump is the most critical. In this simulation the steel part reaches a maximum stress of 202 MPa (Figure 11-a) while the composite covers have a maximum principal stress σ_1 of

51 MPa (Figure 11-b) which has been recorded on ply 5 (upper), made of UD STS. Also for misuse events the failure index has been evaluated and it is reported in Figure 11-c, the maximum value reached is 0,006. As can be noticed from the figures the threshold values have never been exceeded.

[Insert Figure 11. Stress results for hump: metal core (a) composite covers (b) and failure index (c)]

The overall stress distribution of the hybrid arm under each load case is lower than the baseline's, thus the arm seems over-sized compared to its characteristic workloads. This is the consequence of the stiffness-oriented design applied to the component. Probably the material utilization could have been improved by choosing a stress-oriented design and by making additional considerations during the definition of the design constraints. An example could be increasing the allowable stress considering material parameters instead of baseline arm results, as proposed by [28]. However, a stiffness-oriented design is considered to be more failsafe especially if durability issues are taken into account.

Moreover, to evaluate the effect of the HVV material, a virtual FRF **(Frequency Response Function)** analysis has been performed. The frequency response simulation has been set in Altair OptiStruct so to replicate as much as possible the test and simulation set up described and validated in **[22].** The same methodology and damping parameters have been used. The model also reproduces the accelerometers map and the load cell position according to **[22].** To add accelerometer's mass on each specific node, concentrated mass elements (CONM2) have been used. Figure 12 shows both, the model used in **[22]** (Figure 12-a), and the one with the new evolution of hybrid LCA (Figure 12-b).

[Insert Figure 12. FRF model: previous version of hybrid LCA (a) hybrid LCA evo (b)]

The procedure followed, starting from an already validated model, allowed to obtain reliable virtual results. As it can be noticed in Figure 13 the peaks corresponding to the arm's normal modes are damped in a comparable way to that obtained on the previous hybrid arm. The plot represents the sum of each single inertance amplitude in dB in the frequency range of interest, between 100 and 1000 Hz.

[Insert Figure 13. FRF sum of previous hybrid LCA and hybrid LCA evo]

Compared to the 6 modes of the previous hybrid arm version, only 3 normal modes have been found within 1000 Hz. Even if the design space and the positions of the hard points are the same several parameters to which the modal analysis is very sensitive have changed:

- the geometry of the component due to the redesign (of both the metal part and the CFRP covers).
- stiffness performances.
- the overall mass.

This mode shifting is probably due to a combination of this factors.

The FRF analysis proofs that the HVV material integration increases the damping of the structure. However, HVV's mass is not negligible (about 2% of the overall mass), hence further improvement of the actual concept could be achieved by focusing on active solutions such as the one described in [23].

Tables 4 summarizes the results of the redesigned and optimized hybrid swing arm geometry (Hybrid LCA EVO) and compares it with the baseline and with the previous version described in **[20]** (Hybrid LCA). It can be noticed that the hybrid evo arm has widely guaranteed and even exceeded the intended targets with a final mass of 1,56 kg. Also, the difference with the non-redesigned component is noticeable, meaning that being able to re-think and redesign the component and the optimization methodology provides with no doubt great benefits when the manufacturing process is changed.

Table 4 Hybrid arms comparison: with and without component redesign

Component	Mass Reduction [%]	Longitudinal Stiffness [kN/mm]	Delta Longitudinal Stiffness [%]	Lateral Stiffness [kN/mm]	Delta Lateral Stiffness [%]
Baseline LCA	-	6,90	-	27,20	-
Hybrid LCA	23	6,30	-9	25,30	-7
Hybrid LCA EVO	28	7,00	+1,5	58,50	+115

7. Conclusions

This paper evaluates the lightweight of multi-material design developing structural automotive components under stiffness, mass, and stress state constraints. A comprehensive workflow and optimization methodology specifically developed for multi-material applications is also presented.

Starting from targets and constraints imposed by the baseline arm geometry a new hybrid version of swing arm has been hand-sketched, CAD designed and finally FEM modelled. The design developed includes a metal core and two CFRP covers assumed to be bonded together by the excess of epoxy resin of the prepreg composite laminates. The HVV material has been successfully included into the laminate to improve the damping properties of the component. Also, some preliminary cost considerations have been introduced and influenced material choice to obtain a cost-efficient part. The final hybrid arm release has been obtained thanks to a careful optimization process combining the optimization of the metal core with that of the composite covers. This has enabled to understand the far-reaching possibilities of hybridization obtaining a mass reduction of 28% not only maintaining the original component performances but rather improving them. This result has a positive impact both on fuel consumption and therefore on pollutants emissions and on handling performance.

More important than one single outcome is the methodology developed from concept to final part. The process steps which have been followed to achieve the results shown in this paper can be adopted in the design of any other hybrid structural component, thus becoming a standard multi-material design approach.

With respect to [20-22], the optimization procedure presented, started with the component re-design thereby the potential for weight reduction was not limited by the geometry of the baseline. The layout has been adapted for the hybrid technology and the manufacturing process has been simplified. The steel plate can be laser-cut and welded to the X-bushing supports and to the X and Z bushing sleeves avoiding the expensive sheet metal stamping process. However, the integration of X-bushing supports could end up being the structure's weakest point, due to the relevant stress concentration in that area.

In this perspective a durability evaluation and the production of a prototype for experimental testing, are under investigation to prove hybrid LCA’s reliability and correlate physical/virtual analyses. Particular attention should be devoted to delamination and debonding issues. Further improvements to the process include also a deeper cost analysis, maybe involving potential manufactures. But this work provides also new hints for future solutions as for example the application of this methodology to different chassis components and material combinations (e.g. aluminium and CFRP).

Acknowledgments

The authors would like to thank Altair Engineering Italia and BETA CAE Systems for the support and software tools provided for FEM analysis.

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NOMENCLATURE

CAD Computer Aided Design

CFRP Carbon Fiber Reinforced Plastic

DRCO Design variable, Responses, Constraints, Objective

EV Electric Vehicle

FEA Finite Element Analysis

FEM Finite Element Model

FRF Frequency Response Function

GVM Gross Vehicle Mass

HM High Modulus

HS High Strength

ICE Internal Combustion Engine

LCA Lower Control Arm

NVH Noise Vibration Harshness

OEM Original Equipment Manufacturer