Composite suspension arm for an armoured fighting vehicle

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SUMMARY

There is a requirement to improve the performance of armoured vehicles by developing lighter structures. The paper describes a programme that has been undertaken to design and manufacture a lighter weight suspension arm using fibre braiding and resin infusion, capable of withstanding the loads exerted by a 20 tonne vehicle.

Keywords: Armoured vehicles, suspension, braiding

SUSPENSION ARM PROGRAMME

Armoured vehicles while weighing between 5 to 70 tonnes still require the development of lighter systems to allow improvements in survivability and mobility to be achieved. Previous work has looked at developing a composite hull to reduce the weight of these vehicles since the hull provides a major portion of a vehicles weight budget as shown in Figure 1 below.

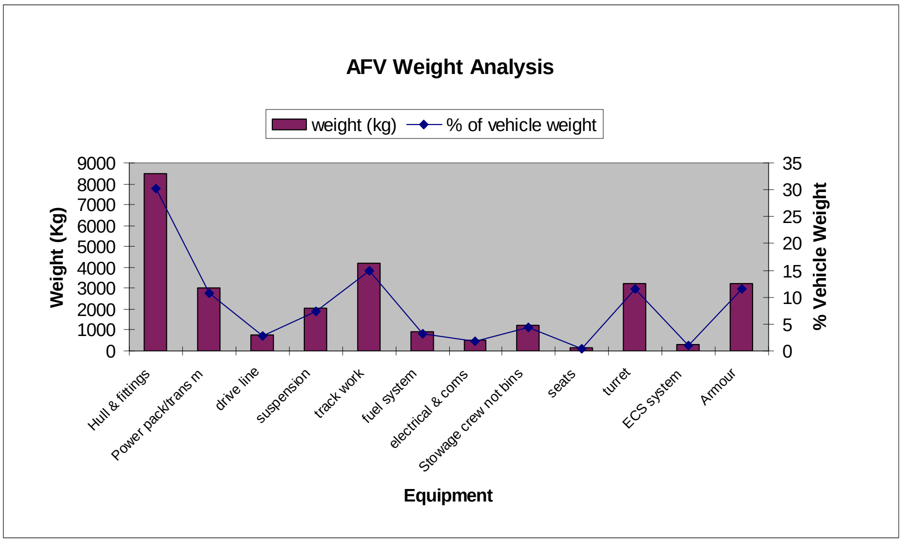

Figure 1 AFV component weight analysis

A second area which makes a large contribution to a vehicles weight is the running gear consisting of the wheels and suspension elements including trailing arms and torsion bars. Consequently, the aim of the suspension arm programme was to demonstrate that a lighter composite suspension arm could be manufactured and that the mechanical properties of the arm could meet those required for satisfactory vehicle running. This required the selection of a manufacturing process coupled to the development of finite element models to accurately identify the loading and define the required composite design performance. The primary goals for this program were to show a:

- Significant weight reduction (50%) while maintaining the same cost;

- Clear design approach for composite suspension for existing and future vehicles;

- Identification of the advantages and disadvantages of manufacturing techniques for composite suspension arms including associated costs;

- Identification of structural loading requirements and validation of chosen design by testing.

DEMONSTRATOR SUSPENSION ARM MANUFACTURING SELECTION

A suspension arm currently produced in steel was selected as the design case, see Figure 2, thus allowing a direct measure of the potential weight saving for the composite arm versus the existing metal arm.

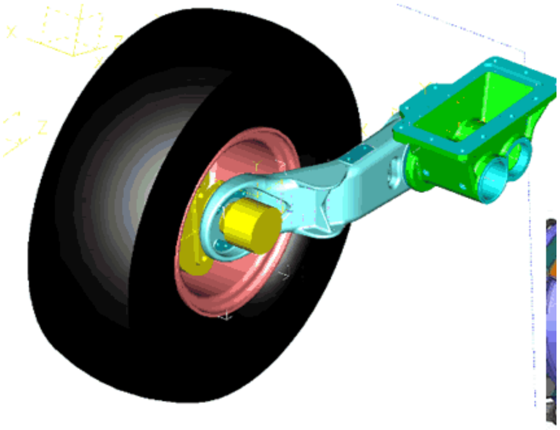

Figure 2 Baseline metallic design

The baseline trailing arm is designed to fit a 20 tonne 6 x 6 wheeled vehicle and weighs approximately 60 kilograms. A complete set of design requirements against which an alternative composite component could be optimised, was generated together with design considerations such as integration with existing systems and the definition of space envelopes within which the new designs must be contained.

The baseline arm measures approximately 0.75m long x100mm deep x 80mm thick and has a joggle halfway along its length designed to accommodate the offset between the suspension torsion bars mounted at the hull and wheel bearing attachment at the wheel hub. A flat platform approximately 100mm diameter is provided midway along the upper surface of the arm near the knee of the joggle which impacts a resilient bump stop mounted on the hull. The trailing arm is connected to the torsion bar mounted in the hull via a splined sleeve which is bolted to the arm structure. The wheel hub assembly is mounted on a spigoted flange which is bolted to the other end of the trailing arm. Shear loads are carried between the two components through a combination of bearing load at the spigot and friction between the two bolted faces.

Materials and process requirements for the composite arm

Selection of materials and manufacturing processes are key factors for the success of the finished components, as these factors drive both structural performance and cost. The merits of alternative manufacturing processes were reviewed some of which were geared towards large production batches with high initial tooling costs while others were more labour intensive but more suited to the production of one off components. The key technical drivers in the design of a novel suspension arm included,

Lightweight
- Use of materials with high specific properties, e.g. composites

High stiffness
- Use of carbon fibres or carbon based hybrid materials
- Novel arm design

High strength
- Use of glass fibre and carbon fibre
- Novel design and fibre architecture

High through thickness mechanical properties
- 3D fibre architecture, braiding or fabrics with stitching or tufting

Impact resistance and damage tolerant
- Toughen resin systems
- 3D fibre architecture

Simple and rapid manufacturability
- Simple design
- Development of a fibre preform
- Short fibre compression moulding

Low cost
- Low cost materials & tooling
- Short cycle time & low temperature process

Manufacturing Solutions - Process and material cost study

After a down selection process using FEA to predict likely weights for various designs, two baseline design options, these being a solid arm and hollow shell arm, were explored in more detail to identify the influence of potential manufacturing routes on cost and mechanical properties, Figure 3. The component could be manufactured by a range of processes using a range of possible lightweight composite materials. The most appropriate process and materials will be dependent on a number of factors that include:

- Fibre architecture
- Material deposit rate
- Material cost
- Material thickness
- Fibre volume fraction
- Through thickness performance

- Tooling cost
- Production volume
- Production rate

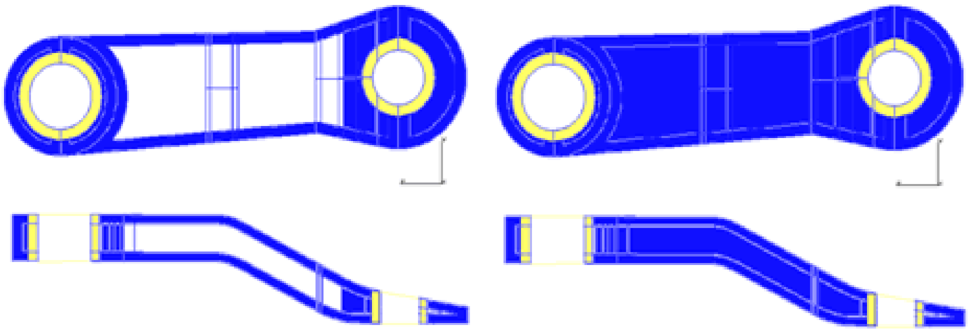

Figure 3 Shell and solid baseline designs

Because the cost of the existing arm was relatively low, efforts to identify the most cost effective route were assessed and influenced the selection to the same degree as for the need for optimised mechanical performance resulting in reduced weight. Most of the processing routes available for manufacturing the composite arm require the production of a dry fibre perform, and this is a significant cost in the total component cost. Most dry fibre performs will be processed by liquid resin infusion, such as Resin Infusion under Flexible Tooling (RIFT) or Resin Transfer moulding (RTM), and therefore this would be a fixed cost that would be independent of the way the perform was manufacture.

Manufacturing implications for a solid arm

A simple solid arm solution offers the lowest weight saving, but would be the simplest to manufacture. The main structural loads in the component are a combination of bending and torsion; therefore to efficiently carry these loads requires a fibre architecture as a first order that is a combination of 45 degree and axial fibres, relative to the axis of the component. The solid arm could be manufacture in two ways, firstly with a flat fibre architecture and secondly with a wound architecture.

One major issue in manufacturing a component in this manner is the loads through the bearing surfaces and the large hole in the structure would not give an optimised solution. The simplest method of producing a flat architecture is to use layers of fibre reinforcement, which could be cut from prepreg, woven, non-crimp fabrics or short fibre bulk moulding compound. These would be laid up on a flat tool, consolidated and cured if it was a prepreg material, or infused with resin if a dry fibre perform has been produced. The high cost of prepreg materials, combined with the lower deposit rate and the high level of de-bulking required during the assembly of the preform would result in a high component cost compared to a dry fibre route.

The relatively poor mechanical properties from long fibre bulk moulding compound, compared to continuous reinforcement, and the difficulty in achieving a truly random fibre distribution and orientation would result in the component being significantly heavier than using continuous fibre. The use of dry fabrics would increase the fibre deposit rate and reduce cost and level of debulking, thus resulting in a lower cost preform compared to a prepreg solution. The manufacturing of a composite component that is potentially a 100mm thick will lead to challenging problems with regard to such issues as residual stress, resin shrinkage, resin exothermic and prolonged cure cycle. It would be possible to optimise the process to minimise these effects, but the cure would still be very drawn out. This solution would have relatively poor through thickness properties, and therefore this design would have to be produced with this in mind. However, where through thickness performance needs to be improved in localised areas the fibre stack could be stitched, tufted or Z-pinned. Z-pins are very expensive and can only be inserted up to a few 10's of mm. Therefore, stitching or tufting, inserting reinforcing fibre through the thickness, could be used and would be very cost effective. In both these techniques there is a limit to which the fabric stack that can be penetrated, which is around 30 to 40mm.

A solid arm could be manufactured with circular fibre architecture, such as winding fabric tightly around a small central core or by an over-braiding or dry filament winding process. Such a process would give a significant improvement in the through thickness properties due to the curved fibre architecture. However, in terms of fibre deposit rate the winding of fabric around a small core would be considerable quicker, but the material cost would be rough double that of a braided solution. Also, to be able to wind fabric in this manner would require the design of the component to be truly axis-symmetric. Against this as with the flat fibre stacking manufacturing route there would be the same problems with the curing of such a thick components.

Manufacturing implications for a shell structure

The main potential benefits of a shell structure are two fold, firstly a hollow beam is more weight efficient in bending than a solid beam since the inner material carries considerably less load than the outer material, and secondly the thicker shell structure may allow more efficient ways of transferring the loads from the bearings to the arm to be engineered into the design. The generation of a closed shell structure could be achieved by manually wrapping fabric around a central core, but the complex fibre architecture and 3D shape would mean that the process would be very slow and there would be significant difference between components. Therefore, components manufactured by fully automated processes, such as tow placement, filament winding and braiding, offer the most attractive and cost efficient process that can deliver a quality component. One major benefit of all these three processes it that each process can cope with non-axisymetrical components.

The braiding process has some similarities with tow placement and filament winding, but with main difference being that fibre rovings are place around the complete perimeter simultaneously. The mechanism that the rovings are placed and simultaneously interwoven means that there is excellent control of the fibre architecture but care needs to be taken in critical region of the arm end closures, since the fibre becomes in effect unidirectional which can lead to splitting issues. In a large braiding machine there can be up to 144 creels, compared to 8 or 16 in the other process. This results in the fibre deposit rate being very high, compared to that of the other process. The braiding process is very flexible so that braiding angles from 15 to 85 degrees can be achieved. One other benefit of the braiding process is that a proportion of axial fibres can be introduced into the fibre architecture, thus increasing the bending stiffness and strength. Manufacture using tow placement using pre-impregnated fibre tows in a computer controlled process, but the high material and equipment cost coupled with the low deposit rate would lead to a very expensive unit cost. This process could be used to give a very well controlled and elegant solution to the end closure issue. This process typically deposits a fibre band up to 100mm wide with a band thickness of 0.25mm, but the band width is totally dependent on the component geometry and for this application would considerable small that the maximum figure. Filament winding is a similar process to tow placement, but uses a much low cost material with the capital equipment cost being rough one tenth of tow placement. The process can be conducted with both dry or wet fibres, and uses fibres in their lowest cost form, i.e. rovings. However, to prevent fibre slippage at the ends of the component the fibre path has to follow a geodesic path, which can make it very difficult and complex to programme especially for thick walled components.

Fibre selection

The structural requirement of the arm is driven by axial strength and stiffness, in both the tensile and compressive directions. Also, the design requires a reasonable level of torsional stiffness and strength. Therefore, the component could be manufactured from either glass or carbon fibre or even a combination of the two fibres as a hybrid material. A structural arm manufactured from carbon fibre would result in a high stiffness and strength, but the material cost would also be considerable higher than for glass.

Matrix selection

The standard matrix system for infusing fibre performs would typically be a thermoset solution, such as a slow curing epoxy and vinyl ester due to the thickness of the component. The use of these resin systems provide good in plane properties, but have fairly poor through thickness properties. The through thickness properties can be increased by the use of toughen matrixes, but these do increase the material cost and can be more difficult to infuse into a thick structure. Due to impact and damage tolerance requirements thermoplastic matrixes would seem to be an ideal material. However, due to the high viscosity of the melted resin these materials can be very difficult to infuse. Tooling and resin costs appear to rule out the use thermoplastic prepregs.

Design solutions that use prepreg materials either in the form of tow or fabric are dominated by the cost of the material, which results in a very high perform cost. Since the solid arm design uses significantly more material than the shell design, the solid solution is likely to be more expensive. The use of woven or NCF materials reduces the predicted cost of the perform. However, it is clear that the lowest cost process options rely on the use of rovings, such as filament winding and braiding. The benefits of the braiding process outweigh the attraction of the filament winding process. A braided glass fibre structure offers a very attractive cost over a carbon fibre structure, but this will come at a weight penalty.

Conclusions for the selection of the manufacture process for the trailing arm

- Material cost plays a major role in the unit cost of an arm;
- Non axis-symmetrical arm profiles can be manufacture by a number of routes;
- Shell design is more weight efficient than the solid, and manufacturing is of a comparable complexity and cost;
- 2D braiding appears to be the best manufacturing process;

- Metal fittings could be included into the design to help transfer the load from the bearings;
- Improved through thickness properties including bearing can be achieved by localise through thickness stitching or tufting.

Because of the drive to reduce weight the shell design was selected based on a over braiding process. Due the time and funding available to the programme it was decided to use a RIFT manufacturing route which would not require tooling and would simplify the preform manufacture. However it was recognised if the programme was successful and went to production, a closed tool infusion process would be required in order to maintain the external dimensions of the arm to the required level.

MECHANICAL DESIGN

Load case data defining six limit and one ultimate load conditions was supplied by Timoney. The limit load conditions represent the worst cases that may regularly be expected to occur in service, the trailing arm structure must be capable of withstanding limit loads without experiencing permanent deformation (yielding) or fatigue failure. The ultimate load condition represents the worst case one off event which the structure must survive without failing, although some permanent deformation (damage) of the structure may result.

Structural analysis of the baseline metallic design was performed to identify the design envelope. This predicted that stresses would not exceed the ultimate strength of the iron material when subjected to the ultimate 5G bump load condition. This ultimate 5g bump condition is equivalent to applying an upward load of 13 tons, approximately half full vehicle weight, at the centre of the contact patch between the tire and the road. This load is reacted by a combination of torque at the torsion bar and a load of approximately 11 tons at the bump stop position. As the bump stop is located mid way along the arm this bump stop load must be carried by the arm structure to the wheel hub. This information used to provide design guidance for the generation of the initial designs and for optimising the selected shell design, which indicated wall thicknesses in excess of 30mm were required.

The main design challenges facing development of a composite trailing arm were producing a design that will fit within the available space envelope with sufficient strength and stiffness and able to integrate with existing equipment. One of the main constraints in effectively producing a 100 x 80 x 750mm long composite box section with a wall thickness of around 30mm is needed for an internal radius along all edges. This radius allows fabric to wrap around the corners and ensures an even pressure through the fabric during the curing process.

Of the allowable design parameter values for the arm, the out-of-plane loading, had the lowest safety margin identified in the previous study. Stress analysis of the component found that the combination of small internal radii and large wall thickness resulted in the generation of relatively high through-thickness tensile stresses in very localised areas, reaching 38MPa under the 1g bump / 0.6g scrub limit load condition. This combination of bending and torsion of the arm structure generates through thickness tensile stresses which attempt to pull the layers of the composite apart. In the absence of any through thickness reinforcement, these stresses are resisted only by the strength of the matrix material, which is relatively weak compared to in-plane performance.

To a large degree, the ability of a composite material to resist this load condition is related to the resin strength and fibre-matrix resin strength, consequently, since all the fibres being investigated were either carbon or glass combined with epoxy resin the allowable design parameters for the different materials were quite similar. Component testing undertaken in support of the ACAVP programme [1] found that the ultimate through thickness tensile strength of the chosen non crimp E-Glass / Epoxy material employed in the hull of ACAVP was around 40 MPa. This value was found to vary slightly depending on the resin specification, fabric material or manufacturing process. Because the arms are being produced by fibre braiding rather than fibre fabric, the 40 MPa cannot be relied on to accurately predict an allowable strength for the material used in the arm. A programme looking at composite pipes had used a lower ultimate through thickness tensile strength, and of equal concern was a more conservative definition and calculation of the limit load to be used in the analysis. The limit load is the load at which no damage should occur in the laminate and is particularly relevant when looking at fatigue damage. In ACAVP the limit load = ultimate load divided by 1.5. The pipe programme suggested using a much more conservative approach of using the limit load = ultimate load divided by 3.5, resulting in the allowable through thickness material strength being reduced from the original limit load of 27MPa to just 11MPa for suggested limit load conditions. As structural analysis results predicted values in excess of this new definition of allowable value, it was decided that the programme should as a priority focus on investigating the out of plane loading by a review of the design to investigate ways of reducing the magnitude of stresses generated in the local areas.

The use of S2 glass as the reinforcing fibre was investigated as this fibre has considerably higher strength than E-glass, though its stiffness is only 10% higher. The study found that neither going to S2 glass, nor increasing the wall thickness was a weight effective method for reducing through thickness stress, since stress is dominated by the resin's performance and concentrated at the internal corner and increasing wall thickness does not reduce this stress intensification. The following Figure 3 illustrates how the sharp radii in the original design concentrated through thickness stress into a small area of high value, while a larger radii distributes the stress over a larger area when subjected to the same load. The change in radius reduces the maximum stress from 40MPa down to 17MPa.

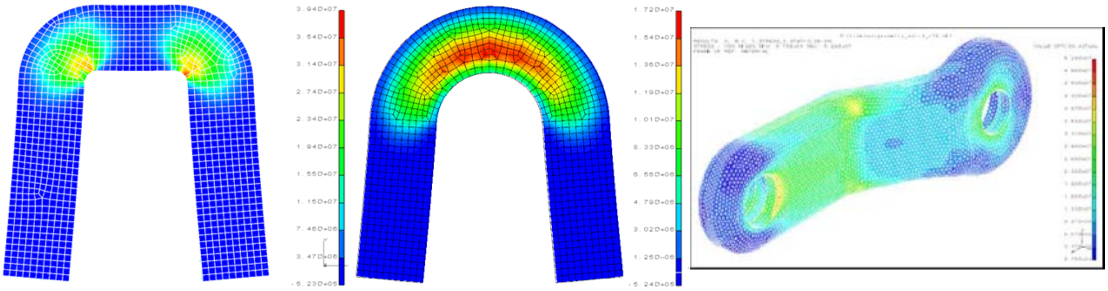

Figure 3 FEA model showing influence of internal radii

From the above analysis the shell concept required a 30mm thick quasi isotropic carbon composite shell with a reinforced bump platform bonded on after manufacture of the primary structure this being the most weight efficient solution compared to an E-glass or S2 solution. Further analysis using dynamic modelling will be conducted [2].

MANUFACTURING AND TESTING TRIALS

A supplier of braided components (Eurocarbon) was used to braid arms over a machine foam core to provide a fibre preform for subsequent infusion. A simple hollow straight arm structure was manufactured and mechanically tested first to assess the ability to infuse both glass and carbon fibre preforms. This was successful and glass and carbon preforms incorporating the more complex "dog-leg" were manufactured to meet the design illustrated in Figure 4.

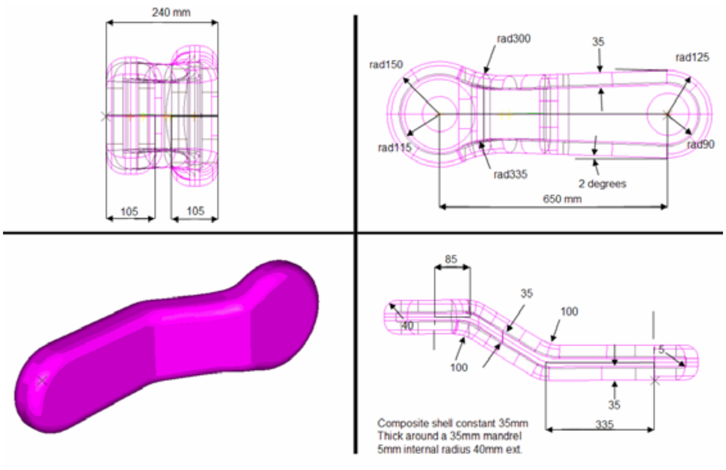

Figure 4 Carbon fibre shell design

The tested arms, Figure 5, matched the mechanical properties predicted from the FEA modelling and met the performance requirements of the existing metallic component, while demonstrating weights of 26 kg for the carbon arm and 30 kg for the glass arm, compared to the original metallic arm weighing 64 kg.

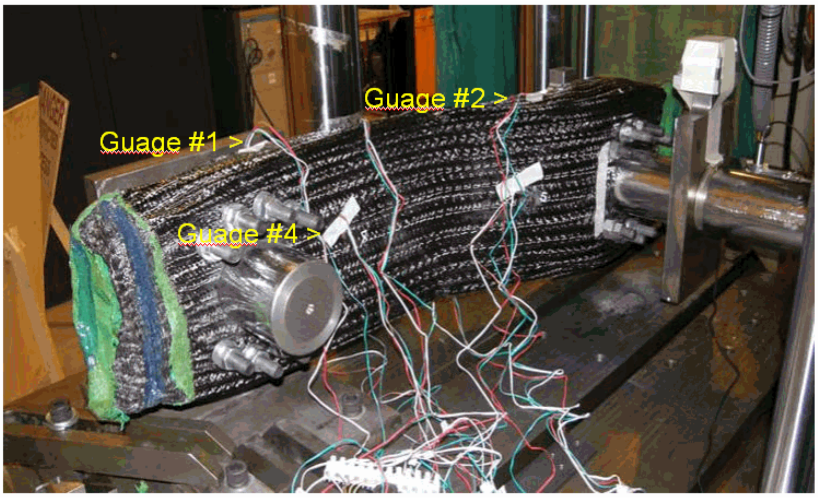

Figure 5 Strain gauge locations on carbon trailing arm undergoing mechanical loading

CONCLUSIONS

Following a review of the available manufacturing routes and their influence on the component's design, a manufacturing route based on a hollow shell design with fibre over braided around a foam core was selected combined with a resin infusion process. A carbon fibre solution provided the best weight reduction achieving the target 50%reduction in arm weight. The results of the programme have provided confidence on how well a composite suspension arm of an armoured vehicle would perform in service based on ultimate strength and deflection requirements.

Following the success of the project a number of potential applications for this technology are being explored for both insertion into existing vehicles and for new vehicles. Trials will then assess issues such as fatigue, ballistic impact and environmental degradation particularly from in-service impacts and abrasion.

ACKNOWLEDGEMENTS

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