# Evolving fuselage designs by incorporating SHM technologies

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## ABSTRACT

Research efforts at Bombardier Aerospace have investigated design constraints that need to be addressed when considering the design of a future unconventional fuselage concept. Using a composite design platform integrated with structural health monitoring (SHM) technologies, the design space is broadened and there are many more unknowns to investigate from our current knowledge of the subject to date. The principal idea is to identify structural zones and quantify stress levels in areas of concern, referred to as 'hot-spots', by integrating an SHM system at a conceptual design level. This new concept would require an assessment of benefits and detriments in order to evaluate the certification processes, impact on maintenance, operation, and ownership costs.

The integration of an SHM system using onboard sensors introduces many challenges, such as the requirement for multiple sensors in the structure and additional systems weight. The investigation shows how the aircraft structural design would be impacted and how design, stress, supply-chain, manufacturing, and the systems departments need to be harmonised in order to design a feasible and integrated SHM-structural fuselage concept.

## NOMENCLATURE

| | |
|---|---|
| AU | acousto-ultrasonic |
| BM | bending moments |
| BVID | barely visible impact damage |
| CVMTM | comparative vacuum monitoring |
| DM | damage monitoring |
| FBG | fiber Bragg gratings |
| FEA | finite element analysis |
| FO | fibre optic |
| IML | inner mould line |
| OM | operational monitoring |
| OML | outer mould line |
| SF | shear force |
| SHM | structural health monitoring |
| TRL | technology readiness level |

## 1.0 INTRODUCTION

Throughout the history of aviation the evolution of the wing has been well documented, however, this is not the case for the fuselage design process. The design of the civil aircraft fuselage has only changed slightly since the Comet, which was the first pressurized civil airliner[1]. The cylindrical pressure vessel is considered 'structurally, the most efficient form of pressure vessel[2]' for handling hoop and membrane stresses; which is the geometry traditionally used in Bombardier Aerospace's existing fleet (Fig. 1). The development of wings has evolved significantly by aerodynamic optimisation; increasing performance and efficiency, by reducing the drag, weight, and environmental impact. Few studies have been

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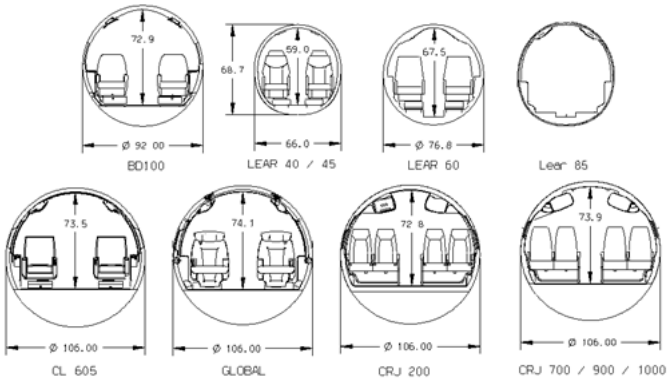



Figure 1. Bombardier portfolio fuselage cross-sections.

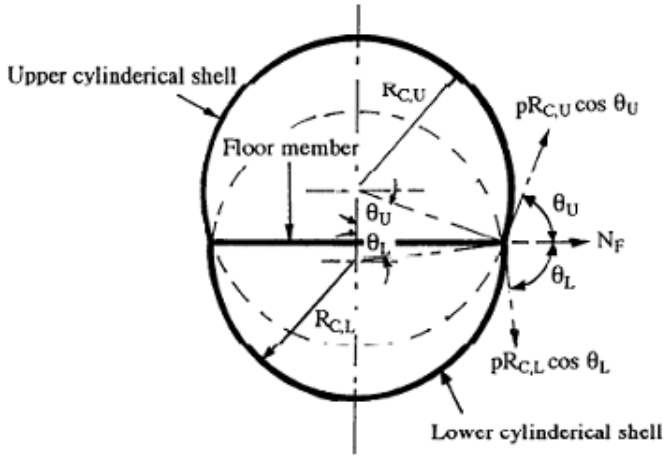



Figure 2. Double-bubble fuselage design 2.

documented on the development of alternate fuselage cross-sections and their impact on the design, stress, and testing of specified unconventional shapes. Passenger comfort has been a major driver in the development of aircraft through changing, cabin temperatures, seat pitch, and the cabin environment, but not through investigating the geometrical shape of the vehicle.

Larger widebody commercial aircraft typically use a double-bubble concept (Fig. 2) and these designs are proven to work well for higher capacity aircraft. The double-bubble concept is used to maximise both the passenger cabin and under-floor storage. This design concept has proven to work effectively for larger multi-level cabin designs of other airframe companies.

Looking towards future aircraft, there has been a lot of research into unconventional concepts and how they could provide benefits compared to existing aircraft. Many studies focus on the advantages in aerodynamic performance, reduced weight, higher efficiency, and the ever increasing challenge to make aviation 'greener'[3-6]. A lot of interest has been expressed in unconventional wing designs, but less focus has been directed towards the fuselage design. Researching the field of unconventional fuselages identifies an industry-wide focus on larger configurations[7,8], however there are a few studies looking at remodelling the conventional 'tube'[9,10]. The evolution of fuselage design is an important area for development in future aviation endeavours, and one which should not be forgotten.

This study investigates the feasibility of novel concepts and how they differ from a 'conventional' circular fuselage, referred to hereon as the baseline (Fig. 3). The intention is to identify variables in the design process and establish a way forward for the design, evaluation, and certification of a non-circular pressurised fuselage.

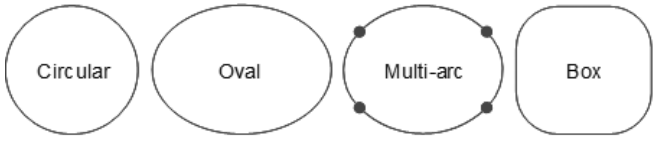



Figure 3. A few of many fuselage cross-section types.

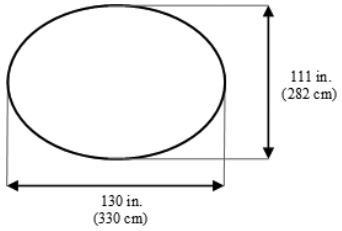



Figure 4. Oval fuselage cross-section geometry.

The design space was reduced to explore an oval fuselage cross-section so that knowledge from traditional approaches could be used. Figure 4 shows a single design point for the geometry. Further studies are required to identify the optimal width and height of an oval pressure vessel. Material selection, design layouts, and assumptions made in this investigation will be explained in more detail. The main concern with the unconventional geometry was to understand where traditional techniques no longer apply and where designs fall outside of the bounds of our design envelopes.

When investigating new non-circular fuselages, the impact on the design, safety aspects, and growth of the passenger cabin need to be considered. The main drivers impacting the passenger cabin design is to increase the comfort level whilst meeting all safety requirements. Aircraft level impacts, such as drag and vehicle performance, are not addressed in this paper.

A non-circular fuselage introduces questions as to how the structure will withstand in-flight bending and pressurisation effects. A compound SHM system was introduced to understand how SHM could assist at a conceptual level; with the design, stress, validation, manufacturing, and certification process of this new configuration. These results are highly dependent on vehicle geometry variations, in this particular case, fuselage length.

Many studies completed by airframe companies investigate larger and wider cabins to enhance the living space. The challenge is to investigate how the new design concept can be analysed using existing design processes, whether these are still applicable and if we need to create new tools to address knowledge gaps.

The focus of this study is to identify key drivers to incorporate SHM technologies into a conceptual design. Understanding methods to enhance and capture knowledge of non-circular pressure vessels is critical for the evolution of the fuselage. Fuselage cross-sections such as multi-arc and box sections (Fig. 3) represent another stage of the development which is not covered.

## 2.0 WHY AN OVAL SHAPED FUSELAGE?

The oval cross-section was viewed as a relatively small change in the cross-section compared to the baseline. Many aspects of the design would be similar, but cut-outs would require more investigation into their impact on the structure. Considerations such as lightning strike, hail impact, foreign object damage, etc now play a greater role due to the larger surface area of the crown (upper) and lower fuselage skins depending upon materials used. Zones of high stress, fatigue, buckling, and corrosion are now also viewed differently compared to the baseline.

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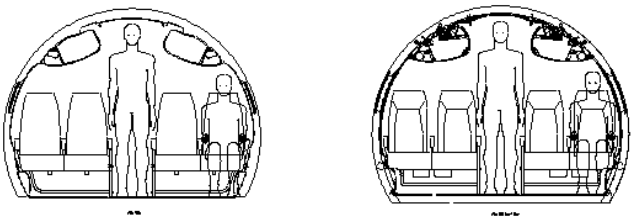


Figure 5. Bombardier CRJ-700 interior cross-section.



Figure 6. Bombardier standard CRJ-700 interior.

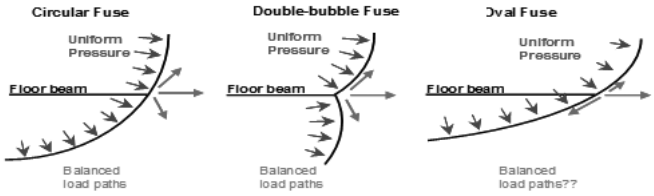



Figure 7. Comparison of: (a) circular, (b) double-bubble and (c) oval fuselage with pressure load.

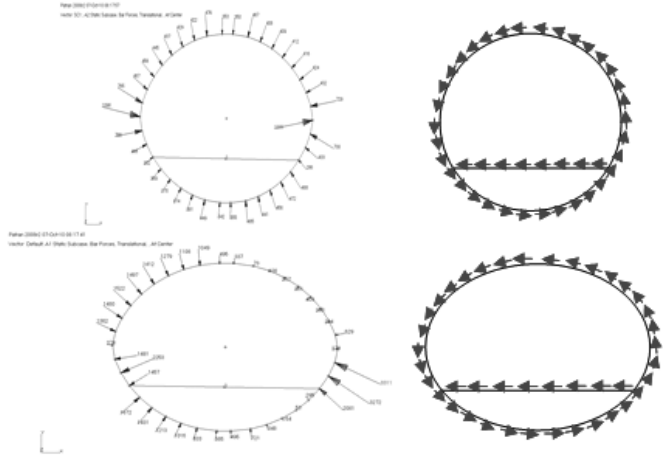


Figure 8. SF distribution comparison between a circular and oval fuselage section.

Changing from a circular to an oval cross-section also changes the cabin configuration. By increasing fuselage width, there are now two options to develop the cabin. The first is a wider cabin providing more comfort to passengers with an unchanged fuselage length relative to the baseline. The second option would be to increase the number of seats per row and to reduce the fuselage length. This would reduce fuselage bending loads fore and aft. The first option is generally not considered in the industry, since the idea is to maintain passenger numbers based on air traffic and customer demands, so the second option was selected to focus on for this study.

## 3.0 MAJOR CONSIDERATIONS FOR THE DEVELOPMENT OF AN OVAL FUSELAGE

There are many considerations that involve the transfer of knowledge and lessons learnt from different disciplines for the design of a fuselage, where here-on discussions are based on problems identified from a design and stress perspective. Additional considerations from manufacturing and maintenance are also factored into the discussions.

### 3.1 Cross section geometry

The fuselage cross-section has some of the most important design considerations. The traditional circular fuselage design is defined by passenger size, where maximum cabin height, usable volume, seated height and seating pitch are all considered, as shown by Fig. 5.

Many cabin design requirements are imposed on the airframe company at a very early stage of the design. One such requirement is seating capacity, and this ultimately is dependent on the aircraft carrier and their ideal seating capacity (Fig. 6). The capacity limits tend to be aircraft specific and are not relevant for this study.

At an early stage, a simple fuselage pressure load analysis is considered to be a linear problem. Analytical tools are used to predict fuselage behaviour under load. Simple analysis performed for unconventional sections should be followed by a non-linear analysis to fully understand what happens under load. The aim is to understand, first and foremost, how gradual changes in curvature affect the pressurisation of the fuselage.

A first step to understand the behaviour of these cross-sections is to investigate shear and bending moments. A simple cross-section case, Fig. 7, shows three different cross-section geometries. Cross-sections which are well understood are the circular (a) and double-bubble (b). Geometry (c) represents an oval fuselage, where the effect of the floor support beam needs further investigation.

Figure 8 was created using finite element analysis and a distributed load was applied to represent the pressure effect on the circular and oval fuselage concepts. The design space investigated here-on focuses on the circular and oval cross-sections so the double-bubble design will no longer be discussed. The shear force (SF) distribution observed for the two geometries (Fig. 8) show NASTRAN results on the left and a typical SF flow on the right. The SF flow diagrams for both sections are the same, but the main discrepancies are in the magnitude of the shear forces around the cross-sections.

The baseline SF has a relatively uniform distribution of shear above the floor level. The floor support beam acts as a restraint, increasing the stiffness, and prevents the expansion of the fuselage under pressure loads, and hence there is a lower SF within this region. The images do not show the vertical floor support members. The oval cross-section SF distribution is not at all uniform above or below the floor support. SF distribution is completely different to the baseline and requires further investigation.

Figure 9 shows the bending moment (BM) experienced by the two cross-sections under the same uniform pressure load. The left of the image represent NASTRAN results and the right shows the distribution of BM to provide a clearer representation of behaviour in the

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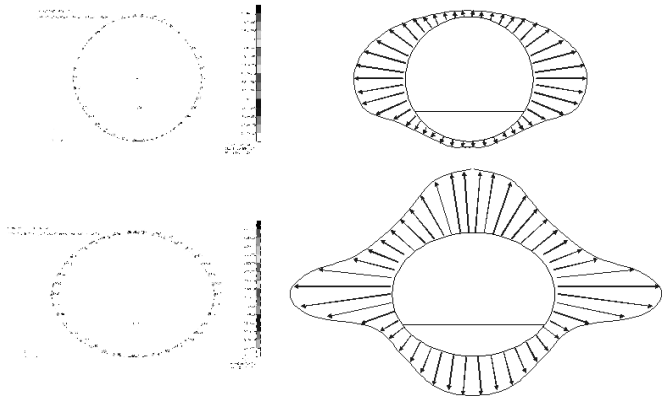


Figure 9. BM distribution comparison between a circular and oval fuselage section.



Figure 10. CRJ-700 assembly.

sections. The images provided are solely to illustrate the trend in BM distribution in a metallic frame and are not to scale.

The BM above the floor member in the baseline provides the maximum BM at either side of the cabin and a local minimum at the top. Below the floor member there is a change in gradient due to the horizontal floor support adding stiffness and preventing movement. If the floor member were not present, then this diagram would show an elliptical distribution.

When considering the oval cross section, the BM distribution is completely different to the baseline. Two similarities are present between the cross-sections, the first being the effect the floor has on reducing the local BM, and the second being that the maximum local BM is experienced at the cabin sides. The oval cross section results provide a much greater BM, and when comparing the maximum BM at the cabin sides, the oval fuselage experiences in excess of 3x103 times that of the baseline.

The simple analysis above provides an idea of how these two cross-sections compare when considering SF and BM. There are many design and stress considerations that should be factored into the design that are not mentioned above; such as the 'optimum' dimensions for the oval, composite material selection, number of cut-outs, varying thicknesses, manufacturing processes, etc., however, for a top-level analysis, these are not considered in such detail.

### 3.2 Barrel geometry

The cross-section is not the only variable for the design and we must consider the geometry of the barrel, where the 'barrel' is defined as the region of constant fuselage cross-section. This region was

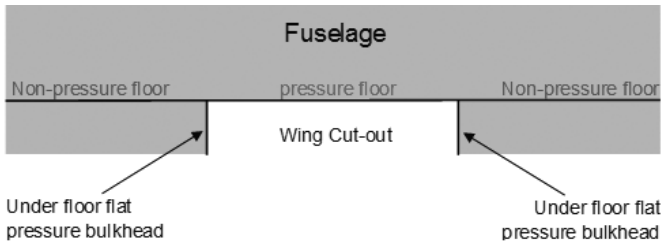



Figure 11. Simplified oval fuselage barrel section showing wing-box cut-out.

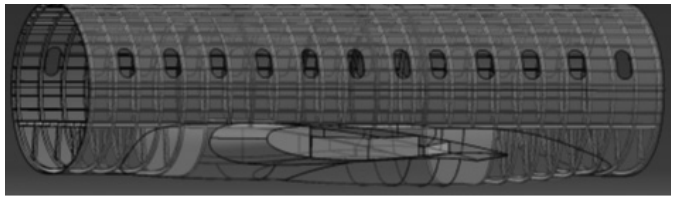


Figure 12. Oval fuselage design model using a 'black metal' approach.

selected to focus on a constant section and to remove any double curvature sections which would provide non-linear behaviour, i.e. at nose or tail, so that the properties of the oval cross-section could be fully understood using a linear analysis. Figure 10 represents the CRJ-700 on the assembly line, where it is important to note that the wing attachment is typically located in the constant barrel section. Therefore for this paper, the focus will be on the design of the centre-barrel section, which will include the wing-box cut-out, windows, but not the passenger doors.

A simplified view is shown in Fig. 11, where the cut-out for the wing is clear. The design uses a pressure floor above the wing box cut-out and the wing is assumed to be attached to the fuselage in the un-pressurised bay. The definition of attachments types will be described at a later stage.

This design has many flat pressure panels to consider. At either side of the wing box cut-out, there are lower floor pressure bulkheads, designed to contain the flight pressure loads. The floor is also a flat pressure panel and the challenge is that for the oval fuselage, the floor has a larger width relative to a circular fuselage, and this could provide additional concerns during the design phase. The large pressure floor area would require more stiffeners, greater thicknesses, and would impact structural weight.

An oval fuselage barrel was modelled using a 'black metal' approach which is shown in Fig. 12 and was used to look at the design from a metallic perspective; to identify how using skins, frames, and stringers could compare to a new fully composite sandwich panel design of the same cross-section. The black metal approach was used to identify areas of interest when considering design, stress, manufacturing, and maintenance constraints. The areas of interest are regions with design concerns and are known as high stress zones, which will be referred here-on as 'hot spots'.

Assessing the behaviour of a fully composite structure using finite element analysis (FEA) was not considered at this early stage. The initial status of the study introduced many knowledge gaps that need to be studied further before maturing the level of effort to include FEA.

There are many hot spots from a stress perspective, and these are:

- Window surrounds & cut-outs
- Door surrounds & cut-outs,
- Emergency exit surround & cut-outs,
- Fuselage crown,
- Junction between floor support members and frames/skins,
- Flat pressure bulkheads either side of the wing cut-out,
- Under floor pressurised baggage and systems bays.

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Figure 13. CRJ-900 representing a few of hot spot areas that are considered for the oval fuselage concept.

These are mainly critical structural components and in some cases, prone to crack initiation or delamination, due to impact damage or fatigue. Additional hot spots such as skin and barrel splices are areas of high importance that require monitoring at a more detailed design stage.

### 3.3 Design assumptions

The areas identified as hot spots are specific to the oval fuselage concept, where it is necessary to identify applicable materials for the structure as well as the locations of hot spot on the barrel. A few of the main hot spots are identified within Fig. 13.

#### *3.3.1 Materials*

There are fundamentally different design approaches when considering a composite or metallic design. A typical metallic design uses the assumption that 80% of the barrel weight is the skin and stringers, with the remaining 20%, being the frame weight. A metallic design would be driven more-so by the skin and stringer design to withstand pressure loads and fuselage bending effects; since the crown is generally acting in tension and the lower surface is under compression. Additional concerns for window and door cut-outs would also be factored into the design with local thickness increases.

Composite materials are known to have high specific strength and stiffness with high fatigue and corrosion resistance. Composite structures are susceptible to in-service impact damage, and manufacturing defects may lead to serious degradation of their structural integrity. As a result, many composite structures are over designed due to the requirements for safe operation with undetected damage. Many assumptions are made when considering material properties, for example, fibre types, resin types, and manufacturing processes. Considering the design for a composite barrel, a conservative approach would be to create a 'black metal' design; where assembly techniques applicable to metals are used with composites. This approach does not use the full potential of the composite properties and should be avoided.

A composite design solution for the barrel could use a sandwich panel skin, which reflects similar working characteristics as a metallic skin and stringer design, and may weigh less. This lighter weight is based on composites having fewer components and no fasteners. In using a sandwich panel skin there are no reasons why frames are required, and this not only reduces weight, enhances fatigue characteristics, but also provide more IML cabin space depending on the thickness of the composite construction used. The challenge is that there is now a thicker skin made up of an upper and lower series of composite plies with resin and a core in the centre. The total weight saving can only be speculated without a manufactured parts comparison, so further studies are required.

The oval fuselage design concept considers the following assumptions:

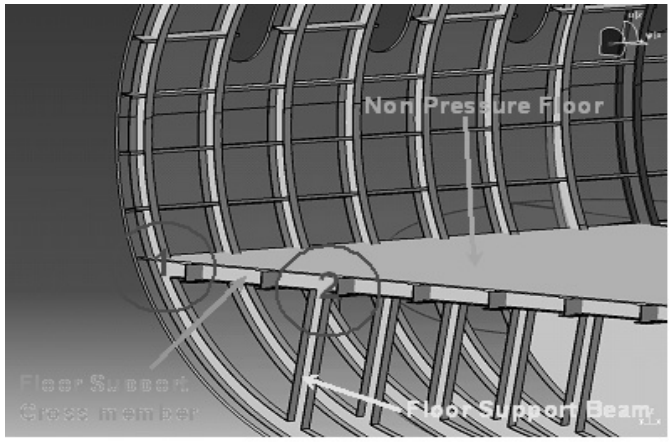



Figure 14. Oval fuselage 'black metal' design showing Region 1: interaction between floor support cross member and fuselage frame, and Region 2: interaction between floor support beam and floor support cross member.

- All fuselage components are composite
- All structural joints are bonded
- The fuselage skin has a sandwich panel construction with 0.5 inch thickness

#### *3.3.2 Wing to fuselage attachment*

The wing to fuselage attachment considers the transfer of aerodynamic loads on the front and rear spars into the fuselage structure and the transfer of landing load cases. The auxiliary spar is designed to assist the rear spar to transfer main landing gear loads and not flight loads. In the event of a gear failure, the auxiliary spar will shear off, ensuring that the rear spar and any neighbouring structure linked to fuel tanks are not damaged in order to minimise fuel spillage.

The wing is attached to the fuselage by a series of lugs and keel beams. This 'traditional' attachment approach was used because it is an established process and it reduces the number of unknowns so that more focus is placed on the fuselage design factors than on a new design connection between wing to fuselage.

#### *3.3.3 Window and doors surrounds & cut-outs*

Windows are important to monitor due to high stresses in the cut-outs and surrounds. Stress distribution surrounding the cut-outs is not uniform under pressure loading and is a primary hot spot. A similar approach to the windows should be taken for doors and emergency exits. As previously shown in Fig. 12, the model used does not extend towards the main door, so design factors for passenger doors are not considered here-on.

#### *3.3.4 Fuselage crown*

The crown of the fuselage, predominantly the skin, carries high stress and deformation under pressurisation loads; more-so when there is a longitudinal joint or splice. The crown is one of the areas prone to impact damage from hail and also moisture ingress, which are two of the critical drivers for composites at this location.

#### *3.3.5 Floor support members & skins*

The junction between the floor support members and the frames are considered areas of high stress. The floor support cross member carries a heavy tension load because of stress induced as the fuselage is loaded under pressure. The floor support member and frame interface is shown in Fig. 14, Region 1, where this is considered to

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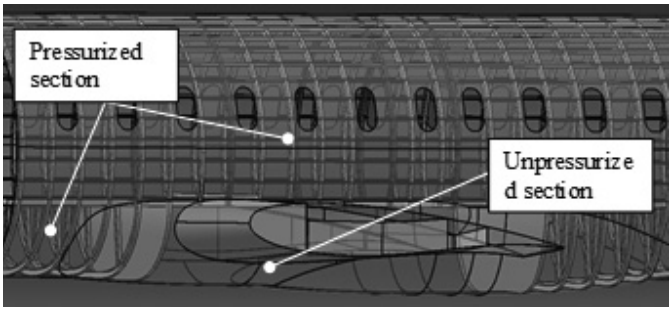



Figure 15. Centre fuselage section, where the two orange members represent the front and rear lower pressure panels.

be an area of high stress. Region 2 represents the interaction between the floor support beams and the floor support cross members. These increase the stiffness of the lower fuselage structure and induce a larger bending moment.

#### 3.3.6 Floor and lower pressure bulkheads

Selected frames located before and aft of the wing front and rear spar, are considered to have flat pressure bulkheads below the floor line; in order to create an un-pressurised zone where the wing would be attached as in Fig. 15. The lower floor pressure bulkheads are a direct result of having a wing attached via keel beams and lugs in an unpressurised bay. The floor directly above the wing-box is a flat pressure floor.

#### 3.3.7 Under-floor baggage compartments

The design of under-floor baggage storage is more specific to operators and maintenance crews; to ensure that baggage and systems located below the floor level can be accessed. Ergonomics are essential for designing these regions, especially when considering loading the baggage and removal of systems, but this is too detailed and is not essential to explore at a conceptual level.

Any cut-outs for passenger doors, emergency exits, baggage doors, maintenance hatches will use a similar principal as the main window surrounds. This approach ensures that the method used to assess cut-outs in composites is addressed. Details such as opening of doors, sealing, and hinge locations, are not considered here-on in the study.

## 4.0 WHAT IS SHM AND HOW CAN THIS HELP OUR CURRENT FUSELAGE DEVELOPMENT PROCESSES?

Structure health monitoring (SHM) is the process of evaluating the integrity of targeted structural elements using onboard systems. The main goal is to reduce direct operating, maintenance, and ownership costs. SHM is divided into two main aspects at Bombardier Aerospace, operational, and damage monitoring.

Operational monitoring (OM) regroups all indirect measurement methods that can contribute to the evaluation of structures utilisation or condition. OM parameters can be derived from the damage tolerance and fatigue evaluation of structure. The output of OM can be advisory indication or usage evaluation. This usage evaluation can lead to increased inspection intervals when margins of safety exceed the airworthiness requirements.

Damage monitoring (DM) regroups all direct measurement methods that allow the detection of damage in the structure. DM can also include damage localisation and damage sizing. Sensors are generally installed in targeted areas. DM can take the form of an alternate method of inspection. In this case, it implies that the

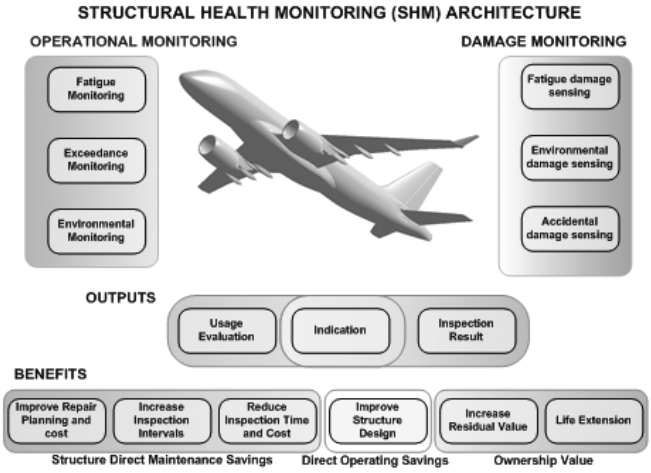



Figure 16. SHM architecture.

damage sensing method meets the inspection requirements and the output is an inspection result. If the inspection requirements cannot be met, DM could be complementary to the inspection program. In this later case, the output is an advisory indication that can initiate a maintenance action.

Damage likely to occur on composite structures and that could be monitored by SHM technologies are:

- Impact damage,
- Delaminations,
- Debonding,
- Water ingress.

### 4.1 SHM technologies

Three types of SHM technologies are investigated for this study and primarily for application to composites:

- *Fibre optic* for detecting impact, crack, delamination and debonding,
- *Acousto-ultrasonic* for detection of impact, crack, debonding and delamination,
- *Comparative vacuum monitoring* for detection of crack and debonding.

The SHM architecture shown in Fig. 16 presents the architecture at top level and the benefits for design validation and SHM applications.

#### 4.1.1 Fibre optic systems

Fibre optic (FO) technology with fiber Bragg gratings (FBG) has been considered for application to this research study.

The advantages of the optical fibres over conventional sensors include:

- light weight,
- low profile (to be embedded without significantly degrading strength of the structure),
- free from electromagnetic interference,
- resistant to electricity noise,
- require low power,
- multiplexed (many sensors can be accessed via a single optical fibre).

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Multiple advantages of the fibre optics are promising for integration of this technology as a load monitoring and damage detection system for aerospace structures.

FO sensors can be used to monitor the strain in aircraft structures under operational loading. FO can be considered as an alternative method for damage detection through processing of strain/stress distribution along with a good knowledge of expected strain/stress distribution.

Different scenarios are considered for implementation of this technology including surface mounted on the IML or OML and embedded into the composite plies or into the resin-rich interfacial region between the ply layers. The latter case can help to avoid turning point issues.

#### *4.1.2 Acousto-ultrasonic systems*

Acousto-ultrasonic (AU) systems use onboard transducers to generate ultrasonic stress waves by an actuator at one point, and sense by the same/another sensor at the same/different position in a structure. A change in the material local behaviour (damage for example), will cause variation in the travelling wave to experience a variation in the acoustic impedance, causing wave reflection, scattering, refraction and possibly wave mode conversion. It is a highly sophisticated and advanced method using digital signal processing and pattern recognition algorithms, which is superior to other conventional ultrasonic methods.

Typically transducers used for this application are piezoelectric elements whose shape and size are highly customisable. Although surface mounting is the most common method of transducer installation, embedding in composites is also possible.

A series of integration assumptions were deduced prior to considering the use of AU systems on the oval fuselage concept:

1. AU transducers are suitable to be embedded in the resin region between the ply layers without any significant degradation of the host structure,
2. The spacing between two layers are variable with respect to the material properties for detecting a minimum of one inch crack, delamination and disbond including location and size for composite and metallic materials,
3. The minimum pitch for the transducers are 2 inches,
4. Acoustic waves can propagate through thin to thick sheets.

#### *4.1.3 Comparative vacuum monitoring systems*

CVM™ has been developed on the principle that a small volume maintained at a low vacuum is extremely sensitive to any ingress of air and is thus sensitive to any leakage. A series of assumptions were made prior to considering the use of CVM on the oval fuselage concept:

1. CVM galleries are suitable to be surface bonded or embedded in the adhesive layer through bonded structures without any significant degradation of the host structure,
1. The spacing of the galleries dictates the sensitivity of the sensors. Consider a minimum detectable crack, delamination and disbond size of 0·02 inches.

### 4.2 How can SHM help the oval fuselage?

SHM has the ability to validate a structural design when a new concept is being introduced in-service to the market. Design and stress engineers are constantly looking forward for ways to confirm their analyses, and this could be achieved though using SHM. SHM can be incorporated into a fuselage composite structure and this has two potential benefits for operation and damage detection principals.

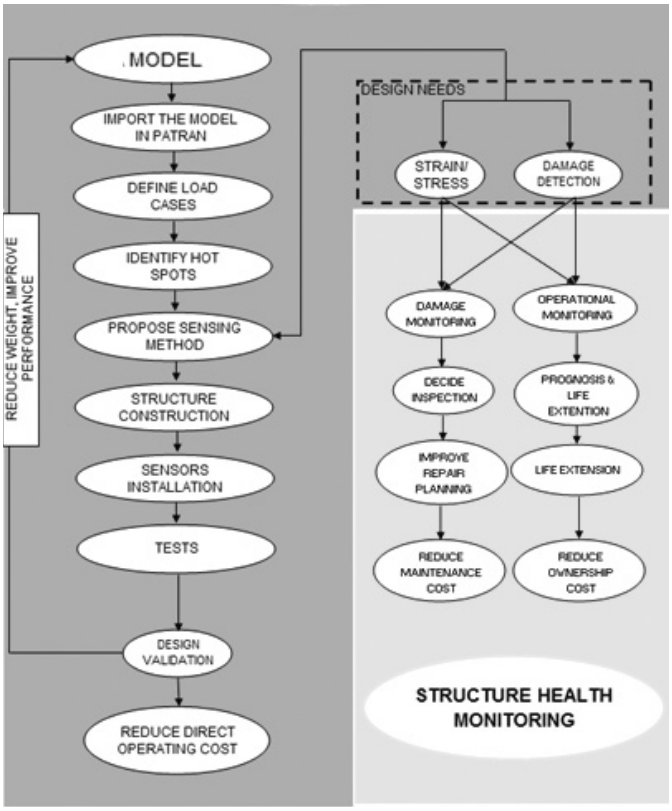



Figure 17. Design methodology incorporated with SHM.

A benefit of having the SHM sensors integrated into the structure would be that sensors could be left on the aircraft, if embedded and/or surface bonded, so that during flight operations, the sensors could be used to inspect areas which are generally difficult to access. The use of these types of sensor would be beneficial to maintenance crews because there would be a reduced requirement for large access panels and this would also save weight. One potential disadvantage could be the weight impact.

The SHM requirement for the oval fuselage is more focussed on using the technology for damage detection and validation purposes on the geometry.

## 5.0 IMPLEMENTATION OF SHM AT THE CONCEPTUAL LEVEL

In order to understand how to implement SHM into a conceptual design process, it is necessary to understand where this concept could fit into an existing methodology. Figure 17 represents an adapted methodology for a new design concept integrated with SHM.

The methodology identifies the key steps that are required to integrate SHM at an early design phase of a program. Design validation would be relatively simple, since NASTRAN models can be compared with measurements from the final model. The main challenge would be the number of sensors used, amount of data extracted, man-power, and computing power required in data processing.

Using design methodologies developed within Bombardier Aerospace, an SHM concept for the oval fuselage cross-section was developed. This study has been summarised into a discussion of the key hot spot regions which were previously identified.

### 5.1 Wing to fuselage attachment

Identifying the internal loads on the fuselage can be achieved through using the strain results from a FO system. Considering a

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**Table 1**
**Damage types and scenarios for the wing to fuselage attachment**

| Location & considerations | Potential damage types and scenarios |
|---|---|
| Attachment between spars (front, rear and auxiliary) and heavy frames: | External crack (crack due to delamination), internal delamination or disbond between: |
| Hot spot | Spars and joining method |
| Difficulty of access | Frames and joining method |
| High probability of damage occurrence | Frames and floor panel |
| Critical structure | |

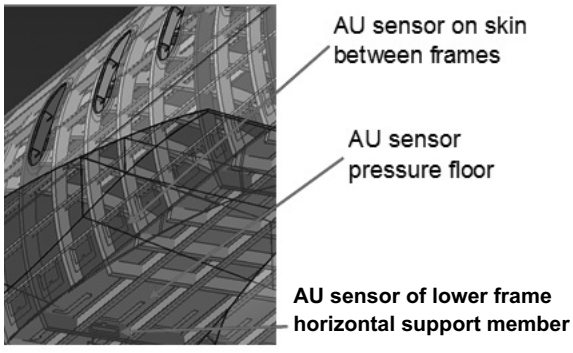



Figure 18. Design concept selected for the wing to fuselage attachment using AU transducers.

fuselage is fully composite, the internal loads in each ply won't be the same. Therefore it is possible to obtain a load distribution in each layer based on the strain distribution.

Damage in the form of matrix delamination or debonding could occur within the wing-to-fuselage attachment because of the variation of loads transferred from the wings. Adhesive bondline and the surrounding area around the joint is a potential area of interest for damage detection. The potential types of damage and scenarios are represented within Table 1.

Comparing each of the three sensors to this specific region provided interesting design options. Acousto-ultrasonic sensors were selected for this area, because of their ability to monitor the structure surface and interior without being embedded

The design concept is shown in Fig. 18, which shows the AU systems concept applied to the black metal design. The challenge with this concept is that if the design were made from composite sandwich panel, there would be no need to break the smart layer AU sensors into small units and there could be a single long strip placed on the inner skin, and this would also be the case for the pressure floor and the horizontal support members. Therefore using AU on a composite sandwich panel would significantly reduce the SHM parts count compared with a black metal design.

## 5.2 Window surround

Windows have always been an important area to monitor due to high stresses in the cut-out of the windows and surrounds. Stress distribution surrounding the cut-outs is not uniform under pressure loading.

The presence of stiffeners on the inner skin causes a significant installation issues for a 'black metal' design because sensors have to pass over stringers, and cannot pass over the frames, as illustrated within Fig. 19. A composite optimised solution could involve a complete sandwich panel fuselage for which frames or stringers are no-longer required, in which case this problem is no longer an issue, and sensors can be mounted freely on the inner skins.

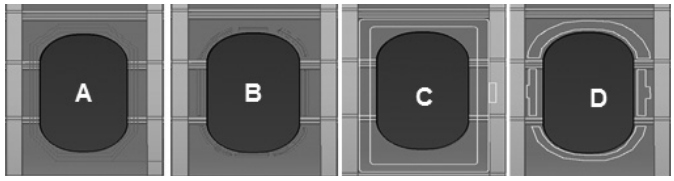



Figure 19. Window surround concepts for A- FO, B- CVM, C- AU option 1, and D- AU option 2.

**Table 2**
**Damage types and scenarios for the window surround**

| Location and considerations | Potential damage types and scenarios |
|---|---|
| Windows surround: | External crack in corners (crack due to delamination) |
| Hot spot | Internal delamination or disbond |
| High probability of damage occurrence | |

**Table 3**
**Damage types and scenarios for the fuselage crown**

| Location and considerations | Potential damage types and scenarios |
|---|---|
| Fuselage crown: | External crack (IML and OML) could be also crack due to delamination |
| Highly stressed | Internal delamination or disbond |
| Difficulty of access | Hail impact |

Using the barely visible impact damage criteria is considered a guideline for this area. Table 2 provides a summary of potential damage types and scenarios using the BVID criteria and also a few assumptions regarding the use of composites.

When considering the design options shown in Figure 19, the installation selected for the study was AU option 2, installed on the inner fuselage skin. The advantage of this configuration is that there is no interference with the surrounding stiffeners, and that we are able to monitor the OML and inside the composite skin layers. The disadvantage is that it requires numerous single layers which require many interrogators or even multiplexors.

If considering a sandwich panel composite construction for a design solution the design would be a completely different. The options for implementing SHM technologies lean towards the FO or AU options, because the systems could be placed around the window surround, using a single sensor. A single continuous sensor loop would significantly reduce the number of sensor and interrogators used compared to the solutions shown above.

## 5.3 Fuselage crown

This region is also susceptible to hail impact and is considered a key area to monitor for SHM because of difficulty for inspection. Stresses and strain levels observed on the OML are considered greater than on the inner skin surface.

Once again BVID criteria were considered and Table 3 provides a summary of the potential damage types and scenarios for the crown of the fuselage.

A CVM solution for SHM at this location has been disregarded because there is a broad area to cover, as illustrated in Fig. 20, and CVM is more suitable for local monitoring.

When considering OF, the pitch between fibres should be determined by the stress department and the damage behaviour in the

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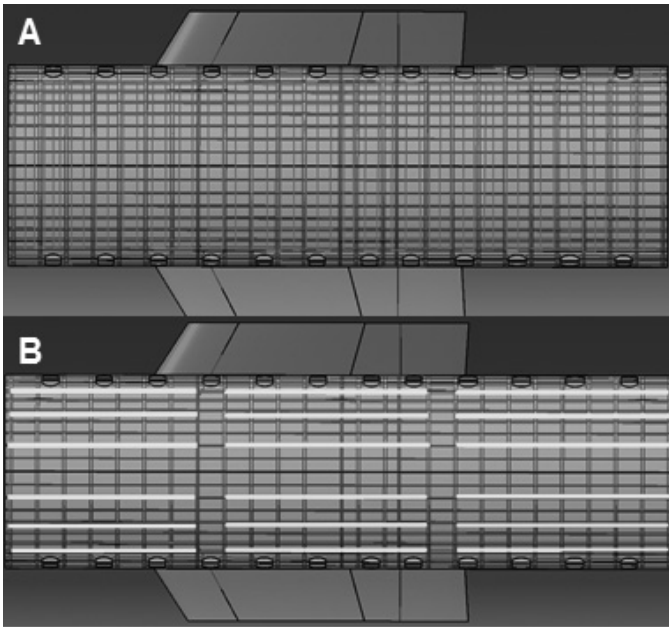



Figure 20. Two options for SHM at the crown, (A) FO and (B) AU transducers.

**Table 4**
**Damage types and scenarios for the wing-to-fuselage pressure bulkheads**

| Location & considerations | Potential damage types and scenarios |
|---|---|
| Pressure bulkhead surround: | External fatigue crack or internal delamination or disbond between: |
| Highly stressed | Bulkhead and floor supports |
| Difficult to access | Bulkhead and lower skin |
| | Floor supports and pressure floor panel |

structure. Selecting a very small pitch between fibres suggests a long single fibre installation and this increases the challenge of maintaining integrity of the fibres in service. Aerodynamic considerations have to be taken into account for FO systems, because these sensors would have to be mounted externally to avoid the internal structural components. This shouldn't be an issue due to the fibre size. The sandwich panel solution does not have the same restrictions for AU, but this would require a large number of sensors, and could impact the system weight.

The chosen design solution for the fuselage crown was the FO solution. This is because there is a larger area to cover in this region, and the aerodynamic impact of the AU system would be greater than the FO system. The main uncertainty here would be the weight of the AU compared to the FO solution.

### 5.4 Wing-to-fuselage pressure bulkheads

As pressurisation is a cyclic loading we expect that fatigue to be the main driver for the two bulkheads and pressure floor, in which case using composites would be an advantage over a metallic design.

Since there is limited public knowledge on the damage and inspection of the composites, once again the BVID criteria for metallic structures were used. Table 4 provides a summary of potential damage types and scenarios.

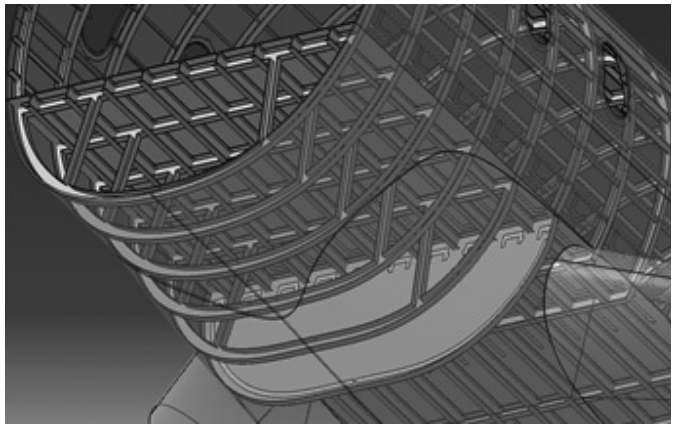


Figure 21. AU transducer design installed between the wing-to-fuselage pressure bulkheads.

**Table 5**
**Damage types and scenarios for attachment between floor support members and barrel**

| Location & considerations and scenarios | Potential damage types |
|---|---|
| Attachment between light frames, skin and floor panel: | External crack or internal delamination or disbond between: |
| Hot spot | Frames and skin surrounding the floor panel |
| Difficulty of access | Frames and skin surrounding the floor vertical beam |

CVM patches can only be installed on one side i.e. in the intersection between floor panel and pressure bulkheads, so should ideally be installed on both sides, increasing the number of sensors and systems weight. AU transducers can be installed on the interface between floor members, pressure bulkheads, and the inner skin of the OML because these are areas of fatigue concern. Investigating the limit curves for the installation of FO sensors showed limitations in their application in this region. AU systems were selected because of the simplicity of installation and sensing through both sides of the pressure walls with the same sensor as presented in Fig. 21.

### 5.5 Attachment between floor support members and barrel

A traditional metallic design has an integrated horizontal floor support member with the frame which is stiffened by vertical or near vertical supports. This design is deemed 'traditional' because it is used by many airframe companies. When considering a composite design, a 'black metal' approach would be similar to the metallic design, but could have reduced number of sections to construct the frame structure.

Alternatively a new composite solution could see the design of a sandwich panel skin without frames, and then the design of the floor support members could be bonded onto the inner skins, but would this be effective?

The area between the horizontal floor supports and frames is highly loaded in tension due to the cross-section pressurisation effects. Damage occurrence is a greater concern in this region, and this is where the SHM sensors would be beneficial. FO sensors could be installed on the inner OML skin but this depends on the type of design. Metallic designs propose a challenge with the use of FO because of the location and pitch of stringers. CVM patches could be placed either on the inner fuselage skin or embedded and

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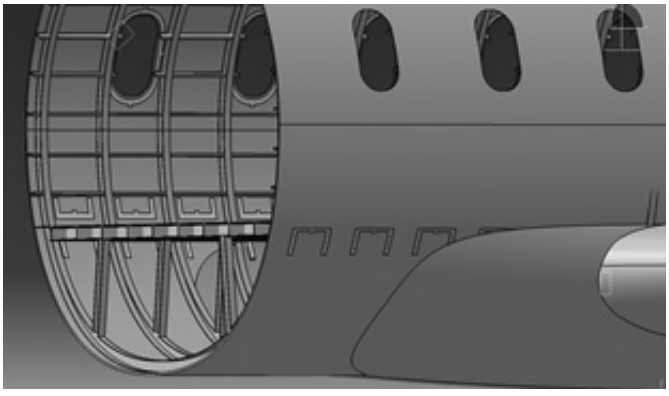


Figure 22. AU transducers design on a metallic design for interaction between the horizontal floor support beams and barrel skins.

would be used to monitor damage occurrence. AU sensors are also proposed as an alternative because they boast the capability to monitor inside the composites without being embedded. Table 5 provides a summary of potential damage types and scenarios using the BVID criteria.

AU systems were considered optimal for this zone because they monitor a greater depth of structure without the need to be embedded as shown in Fig. 22.

A fully composite sandwich panel solution would have a bonded solution for the floor supports, and may not necessarily have the same geometry as the metallic design. There are many different solutions for this region and therefore a general comment about the design can not be made at this early stage. Further investigation is required into developing composite solutions for the lower floor support members.

## 6.0 WHAT CAN WE DO TO ENHANCE THE WAY WE LOOK TO THE FUTURE?

There are many unknowns and concerns about the design of the composite barrel especially when changing the cross-section to an oval design. However, without an in-depth investigation into the design, development, manufacture, and test of such a vehicle, speculation is our only means to progress with this study.

The principles behind the fuselage development have been discussed as well as an introduction to the SHM systems that are currently available. When using a traditional design approach as a baseline, it is clear to say that with the multiple parts associated for a metallic fuselage, using CVM and FO systems has its restrictions because of the number of members that intersect one another. AU systems were considered a more promising solution for the design of a 'black metal' fuselage based on the hot spot identified. However, this statement is not valid for alternate composite design solutions where other sensor types would show more promise.

Composite design solutions do not conform to the traditional metallic design conventions, and the design space is broadened. Designing a composite non-circular fuselage enables design and stress engineers alike to explore multiple solutions, for example:

- Fully bonded black metal design,
- Sandwich panel skin only, no frames,
- Sandwich panel skins and bonded heavy frames,
- Sandwich panel skin & bonded floor support members,

These are a few of the solutions available and there are many more either being developed or are in the process of being tested by the aviation industry.

The main challenge is to see where the aviation industry should be aiming at in order to maximise the full potential of materials and systems that are available. Using an SHM integrated into a composite design solution could enable a new era of aviation where active monitoring during flight can provide real-time estimates of the structure under extreme load cases. The SHM system would be used to identify non-visual damage, crack growth, impacts, debonding, and as a result could extend the life of the vehicle and reduce the number of ground checks required. Reducing the maintenance down-time of the aircraft is not only a cost saver to the customer or operator, but is beneficial for the airline because this promotes more reliable aircraft, and helps push aviation to more reliable products.

Alternatively from an experimental perspective, SHM could assist with the design validation process. As an example, SHM integrated with the oval fuselage concept, would assist with validating the barrel during the pressurisation tests; enabling design and stress engineers to monitor results across the cabin cycles. This would provide key indicators of the fuselage behaviour and identify regions of poor design and also crack initiation, delamination, and debonding of structures during the tests, and more importantly, at what stages of the aircraft life they would develop.

The challenge in implementing SHM technologies into a new platform is with the current TRLs of the systems. A major concern of implementing SHM systems would be the weight, because SHM sensors produce a significant amount of data, which needs to be captured. The memory required to record the data from the sensors depends on whether the sensors are continuously operating in flight (online-monitoring), or on ground between cycles (offline-monitoring), and also depends on how many sensors are installed.

The SHM interaction with a composite fuselage has been introduced for an oval cross-section. These design principles are not applicable to alternate cross-sections. Further research is required to investigate the possibility of expanding knowledge on creating multi-curvature cross-sections, so that we can evolve the shape of aircraft to explore new levels of efficiency.

## 7.0 CONCLUDING REMARKS

This research introduces a new approach in the integration of SHM in the design process. A methodology has been proposed to implement this new architecture on a future aircraft platform. The system boasts the potential to assist validation and certification processes for new designs. An additional benefit is the potential to reduce life-cycle costs and increase the reliability of aviation products.

Research into the fuselage design process has introduced many more uncertainties in the design, mainly due to the selection of composites. Many applications for SHM systems have been discussed for composite design solutions. The difficulty in selecting SHM systems is with the current way of thinking for designing 'black metal' fuselages and as such AU systems are seen as a more promising option along-side the use of FO sensors. CVM is not considered practical for most of the barrel applications, but this is design specific and will change when considering alternate composite solutions.

More design research is required to understand and select composite designs, a few of which have been mentioned above. Through comparison of these designs to a metallic concept, we can understand and identify potential weight savings be able to install sensors efficiently on the structure. This installation at a conceptual level will enable more investigations into the systems weight and resources required to create either an operational or damage monitoring system. The development of such a system will assist with the future design and development of unconventional fuselage geometries.

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