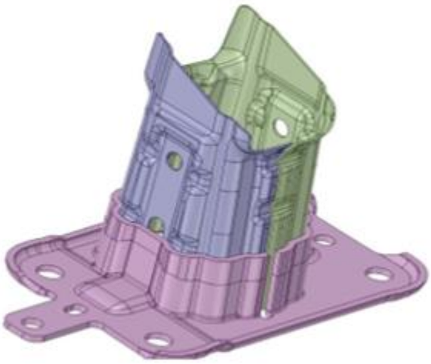
MULTIM

Challenges using mixed materials

Open report



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MULTIM – a project within sustainable production

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1 Sammanfattning

Det finns flera anledningar till varför det är tekniskt svårt att minska vikt och även utsläpp. I dag är det därför ett stort fokus på alternativa material för användning i fordonskonstruktion, i den s.k. Body in White (BiW). Det har fullständigt exploderat med forskning som har resulterat i olika nya lätta material med olika nischer, såsom sandwichstrukturer, avancerade kompositer och metaller med låg densitet. Även mer traditionella material som höghållfasta stål, produktionsvänliga aluminiumlegeringar och magnesiumlegeringar är tillgängliga för designern.

Dagens brist på kostnadseffektiva och pålitliga fogningslösningar begränsar användningen av multimaterialkonstruktion. De nya materialen måste kunna kombineras med de mer traditionella materialen för att kunna användas optimalt i en konstruktion. Material med olika fysikaliska och kemiska egenskaper ger en mer problematisk situation än mer likartade material. Termisk expansion, galvanisk korrosion och dålig löslighet av legeringselement i varandra är några exempel på fenomen som kan göra situationen svår. Andra tillhörande processer förutom fogning, såsom ytbehandling, skärning och finishing av olika slag, är också komplicerade för multimaterial.

Projektets syfte var att utveckla nya metoder för konstruktion med artolika material. Typfogar togs fram som senare skulle användas vid konstruktion av en komponent. Typfogarna var centrala i studien och var gemensam nämnare i de flesta arbetspaket och case. Unikt med denna studie var att befintlig teknik från tidigare projekt utnyttjades för att optimera en fog med avseende på ett antal aspekter som representerar de kompletta kraven på fogen.

Från lärdomar inom de fyra casen så extraherades rekommendationer för multimaterialkonstruktion som kan användas generiskt för en mängd konstruktionsproblem. Rekommendationerna innehåller allt från sammanställningar av olika mekaniska fogningstekniker, till limguide, till hur man ska tänka vid kombination av lim och punktsvetsning. Projektet har reducerat tröskeln för industrin för att i större utsträckning använda sig av multimaterialkonstruktion industriellt. Resultaten från projektet kommer från industrierna fordon, flyg, och handhållna verktyg, men kan appliceras betydligt bredare än så.

Projektet har tagit upp ett högt prioriterat och nödvändigt område för alla deltagande organisationer. Att kunna möjliggöra multimaterialkonstruktion anses vara avgörande för att kunna behålla och utveckla nuvarande marknadspositioner. Det är uppenbart att bilindustrin måste uppnå lättvikt. Vid start av projektet MULTIM saknades möjligheten att utnyttja den fulla potentialen som finns i de olika materialen. Att kunna utveckla ett fungerande sätt att konstruera fogarna så att konstruktion med olika material blir möjligt ger en stark konkurrensfördel.

Projektet hade sex olika arbetspaket (WP) där varje arbetspaket har definierat leveranser och ansvar. Projektet hade också fyra specifika fall, med olika utmaningar, som behöll branschrelevant fokus inom varje arbetspaket.

Projektets viktigaste slutleveranser listas nedan.

- Riktlinjer för konstruktion av olika typer av fogar som kan användas i olika branscher
- Sammanställning av befintliga industrirelevanta processer som kan användas i multimaterialkonstruktion
- En grund för modelleringsmetodik av konceptstudier inom multimaterialkonstruktion
- Tillverkning av demonstratorer med hjälp av multimaterialkonstruktion
- Flera workshopar för att sprida de lärdomar som byggts upp i projektet
- Stärkt forskning och utbildning inom de deltagande instituten och industrierna
- Utbildningsmaterial som kan användas för kompetensspridning t.ex. IWE och annan teknisk utbildning

Upplägg och arbetssätt som använts i MULTIM anses vara framgångsrikt. Att kunna arbeta med den fullständiga kravssituationen för en produkt/komponent ger möjlighet att kunna lösa de faktiska problemen som uppstår, istället för att suboptimera. Tillvägagångssättet utnyttjar också befintlig kompetens/teknik på ett bra sätt, vilket resulterar i en lättare implementeringsfas.

2 Executive summary

There are several technical reasons why it is difficult to reduce weight and emissions. Today, therefore, there is great focus on alternative materials for use in the vehicle body, also known as Body in White (BiW). It has completely exploded with research that has ended up in various new lightweight materials with different niches such as sandwich structures, advanced composites and low-density metal structures. Even more traditional materials such as very high strength steels, production-friendly aluminum alloys and magnesium alloys are available to the designer.

Today's lack of cost-effective and reliable joining processes limits the use of multi-material design. The new materials must be able to be combined with the more traditional materials in order to be used optimal in a design. Materials with different physical and chemical properties give a more problematic situation than more similar materials. Thermal expansion, galvanic corrosion and poor mixing of alloying elements in each other are some examples of phenomena that can make the situation difficult. Other related processes besides joining, such as surface treatment, cutting and finishing of various kinds, are also complicated for multi-material.

The project purpose was to develop new methods for design including dissimilar materials. Type joints was designed which can later be used in the design of a component. The type joints were considered central in the study and was the common denominator that was addressed in most work packages and cases. The uniqueness of this study was that existing technology from previous projects was utilized to optimize a joint with regard to a number of aspects that represent the complete requirements of the joint.

From lessons learned in the four cases, recommendations for multi-material design were extracted that can be used generically for a variety of design problems. The recommendations include everything from compilations of various mechanical joining techniques, to adhesive bonding guide, to how to think when combining adhesives and spot welding. The project has reduced the threshold for the industry to make more use of multi-material design in industrial applications. The results from the project have been generated within the industries of vehicles, aircrafts, and hand-held tools, but can be applied much broader than that.

The project has addressed a high prioritized and necessary area for all participating organizations. Being able to enable multi-material design is considered crucial in order to be able to maintain and develop current market positions. It is obvious that the automotive industry must achieve light weight. When starting the project MULTIM, the solutions, however, lacked the opportunity to utilize the full lightweight potential that exists in the materials. Being able to develop a functioning way of designing the joints so that design with dissimilar materials becomes possible gives a strong competitive advantage. Throughout the participating companies' strategies, achieving the prevailing environmental goals is with lighter and more environmentally friendly components, especially within the transport industry.

The project had six different work packages (WP) where every work package has defined deliveries and responsibilities. The project also had four specific cases, with different challenges, which kept a industry relevant focus within each work package.

The project's most important final deliveries are listed below.

- Guidelines for the design of different type joints that can be used in different industries
- Compilation of existing industrial processes that can be used in multi-material design
- Groundwork for modelling methodology for concept studies within multi-material design
- Manufacturing of demonstrators using multi-material design
- Several workshops to disseminate the learnings that has been built up in the project
- Strengthened research and education within the participating institutes and industry
- Educational material that can be used for competence dissemination e.g. IWE and other engineering education

The approach of MULTIM is considered successful. To be able to work with the complete requirement situation for a product/component gives the opportunity to be able to solve the actual issues occurring, instead of sub optimizing.

The approach also makes use of the existing competence/techniques in a good way, which results in an easier longer perspective in the implementation phase.

3 Background

In the future, the automotive and transport industries will be forced to drastically reduce their emissions due to the EU's demand for average CO_2 emissions to fall from 130 g/km to 95 g/km for a vehicle fleet. This in turn means that many of the car manufacturers are forced to use hard-to-produce and expensive materials. In the future, this is not about profitability and how much profit the companies show, but in this case it is about survival. There are several technical reasons why it is difficult to reduce weight and emissions. Today, therefore, there is great focus on alternative materials for use in the vehicle body, also known as Body in White (BiW). It has completely exploded with research that has ended up in various new lightweight materials with different niches such as sandwich structures, advanced composites and low-density metal structures. Even more traditional materials such as very high strength steels, production-friendly aluminum alloys and magnesium alloys are available to the designer. Polymer-based carbon fiber composites are probably one of the most interesting areas for today's automotive industry. These materials will only be used on a large scale when there are cost-effective methods for high volume production.

The weight of the vehicle accounts for a quarter of the CO_2 emissions and investments in lightweight have been a major priority for many vehicle manufacturers in recent years. For example, Germany has made major investments in building expertise and infrastructure for innovative lightweight technology in collaboration between industry and institutes/academia. Open Hybrid LABfactor and Aachen Center for Integrative Lightweight Production (AZL) were formed in 2012 with a focus on combining material science with production technology to be able to develop future production processes for vehicle components of composites and multi-materials.

Already in 1994, Audi launched its space frame in aluminum for serial production and in recent years BMW has invested heavily in volume production of cars in multi-material where the 7-series is one of the latest example with a weight reduction of a total of 130 kg for BiW. Swedish manufacturers have also given priority to lightweight e.g. through increased use of high-strength steels, for example, the structure of Volvo's latest XC90 contains up to as much as 40% hot formed boron steel.

What one should not forget when studying the subject of multi-material design is cost. Already today there are solutions that could be used which in practice could achieve desired functions (at least partly), but the price for this is high. Technology that is currently used for multi-material in components within F1 cars or aircraft is not viable for production in the passenger car industry.

State-of-the-art for the manufacturing of vehicle components in multi-material means high costs (material cost) and low productivity (cycle time), which means that multi-material design is primarily used for the manufacturing of premium cars in small series. There are also major challenges regarding quality assurance and recycling.

Today's lack of cost-effective and reliable joining processes limits the use of multi-material design. The new materials must be able to be combined with the more traditional materials in order to be used optimal in a design. Materials with different physical and chemical properties give a more problematic situation than more similar materials. Thermal expansion, galvanic corrosion and poor mixing of alloying elements in each other are some examples of phenomena that can make the situation difficult. Other related processes besides joining, such as surface treatment, cutting and finishing of various kinds, are also complicated for multi-material.

The actual design of products in multi-material can still be considered as something of a competence gap within research and industry. One can work with research within joining methods to develop the technology, but if one never takes product-specific requirements into consideration and includes this when choosing the joining method, the industrial benefit is very low. The MULTIM project has addressed the design of joints between two widely different materials where the industry's total requirements for the product are taken into account, not just light weight. The design has been based on a number of generic joint types typical for joining multi-materials. Instead of driving the research around a certain joining method, the choice was to create a smart design that was adapted for already existing technology. The hypothesis was that by attacking the problem from above (design) instead of from below (technology), one can more easily benefit from already existing competence and technology.

4 Purpose, research questions and methodology

The project purpose was to develop new methods for design including dissimilar materials. Type joints was designed which can later be used in the design of a component. The type joints were considered central in the study and was the common denominator that was addressed in most work packages and cases. The uniqueness of this study was that existing technology from previous projects was utilized to optimize a joint with regard to a number of aspects that represent the complete requirements of the joint. The requirements were based on the environment and loading situation that have been identified. The research was thus to design a joint between two dissimilar materials, not to develop a joining process that has been the focus of most previous projects in the literature. This is considered a great advantage and no similar previous studies have been found nationally. Even at international level, implementation is lacking since the costs have become too high. As mentioned in the background, there have previously been projects that focused on a similar issue, but these projects have not addressed the problem from a holistic perspective to enable design with multi-material, but to develop a special technique. Thus, those projects do not consider the complete perspective, which only contributes to partial solutions.

A project that generates design solutions for dissimilar materials provides completely new opportunities for optimized design with respect to light weight and production of light weight structures.

Hence, the technical questions to be answered by the project was:

- How can a product be designed to enable advanced design in multi-materials with existing joining methods?
- How should a joint be formed between two materials in order to be optimized for multi-material design?
- Which joining methods should be used to meet the requirements of a joint?

Thus, this project will focus on technically attractive joining techniques that contribute to achieving a cost-effective solution.

The project had six different work packages (WP) where every work package has defined deliveries and responsibilities. The project also had four specific cases, with different challenges, which kept a industry relevant focus within each work package.

- WP1: Demands and criterions for chosen type joints, and compilation of existing solutions
- WP2: Design of joints between two dissimilar materials, choice of joining method
- WP3: Joining, process optimization and physical evaluation of properties
- WP4: Modelling of performance of joints
- WP5: Development of demonstrators and preparation of future production
- WP6: Project management and dissemination

The four cases that were in focus throughout the project was:

- Spare wheel housing (owned by Volvo Cars)
- Chain saw guide bar (owned by Husqvarna)
- Outlet guide vane (owned by GKN Aerospace)
- Crash box and back plate (owned by Gestamp)

5 Incentive

The project has addressed a high prioritized and necessary area for all participating organizations. Being able to enable multi-material design is considered crucial in order to be able to maintain and develop current market positions. It is obvious that the automotive industry must achieve light weight. When starting the project MULTIM, the solutions, however, lacked the opportunity to utilize the full lightweight potential that exists in the materials. Being able to develop a functioning way of designing the joints so that design with dissimilar materials becomes possible gives a strong competitive advantage. Throughout the participating companies' strategies, achieving the prevailing environmental goals is with lighter and more environmentally friendly components, especially within the transport industry.

5.1 Case 1: Spare wheel housing – the Volvo Cars case

Volvo cars have identified the need for implementation of a mixture of materials in their car bodies to further facilitate light weighting of their products. Today the majority of their car bodies are made of steel, with occasional addition of aluminium in either cast or extruded form. Larger sheets of aluminum have not yet been implemented in a bigger scale in serial production. The challenges to implement larger aluminum panels are many and consist of choosing suitable joining methods for these joints, handling geometrical changes due to differences in thermal expansion between aluminium-steel and building up the necessary competence and experience to design suitable joint configurations for these, for Volvo, new material combinations and scenarios. In a traditional car manufacturing process, the BiW will pass through an electrocoat curing oven reaching up to about 185°C. Therefore, in the Volvo case a main task was to study how thermal changes may cause deformation and distortions in the product.

In this project we have chosen to focus the research on a specific component from Volvo that possess several generic challenges and the findings and potential solutions from this research can thus be implemented much wider, both within Volvo and for other companies within the MULTIM project and possibly also within Sweden in general. The chosen component was the spare wheel housing, which is one of the larger floor panels of the rear floor structure in the car. In Figure 1 and Figure 2 one can see the rear floor structure and the detached spare wheel housing panel.

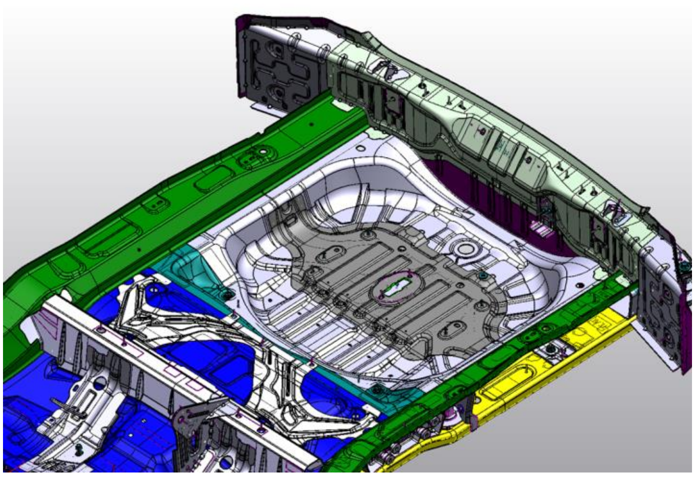

Figure 1 – Rear floor of Volvo V90

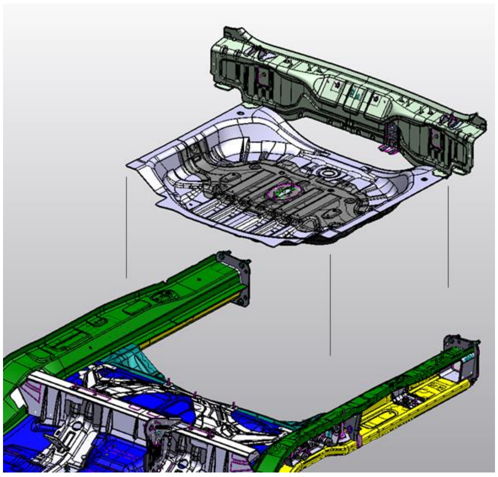

Figure 2 – Spare wheel housing detached from the rear floor

The size of the spare wheel housing makes this component ideal for generic evaluation of the challenges associated with implementing larger aluminium panels in an otherwise steel dominated surrounding structure.

The more detailed research questions that was studied in this case was:

- What joining methods are most suitable for joining overlap joints in mixed material situations between aluminum and high strength steel, with adhesive present between the sheets?
- Will the mismatch in thermal expansion between the aluminium panel and the surrounding steel structure be an issue during production and cause too large deviations in the final geometry? Can this be modeled virtually?

    - How does the thermal mismatch affect the integrity of the joint?
- What solutions are there to handle thermal mismatch between materials?
- Can simple design guide lines be created to aid designers when implementing mixed material parts the car body?

The approach to answer these research questions was a combined experimental and modelling approach where the applicability of the joining method was studied in parallel with the issue of mismatch in thermal expansion coefficient between aluminum and steel. Several ideas on how to limit the geometrical deviations caused by the mismatch in thermal expansion have been tested both experimentally and modeled virtually. The virtual models are also intended to be used to extract easy to use design guidelines.
Several advanced analysis techniques were needed to e.g. measure the resulting geometrical changes due to thermal expansion mismatch. In this case 3D-scanning technologies have been applied and that data have been used to validate the simulation models developed.

5.2 Case 2: Guide bar – the Husqvarna case

In the Husqvarna case the focus has been bonded guide bars. The objective from Husqvarna has been to find designs for low weight products. The aim in MULTIM was to focus on the bonding technology suitable for overlap joints (with large areas) and to assure the bonding quality of a steel - aluminium - steel connections.

Already in the project plan it was decided not to make any public/open demonstrator in this case. The results of generic character are presented in a separate guideline, where the results related to the specific design of guide bars is omitted.

The goal has been to find out best practice in joining of multi-material guide bars, to be concluded and added into the lightweight guide bar specification at Husqvarna. A large part of the work has been on refinement of designs combining steel and aluminium, but also other alternative materials for the mid-plate has been investigated.

5.3 Case 3: Outlet guide vane – the GKN Aerospace case

Today it is a trend in the aeronautics industry to make the jet engines more efficient by increasing the by-pass ratio. To achieve this the fan diameter and by-pass duct in engines must increase in size. One drawback is however the increased weight and significant efforts are being made today to introduce weight saving technologies.

One possibility to reduce weight is to replace metal components with composites. This however often increase the cost (more expensive materials and manufacturing). Another aspect is that metal-composite joining is a common design and manufacturing challenge in composite structures. One product that is interesting for a composite solution is outlet guide vanes which structurally connects an intermediate case to the back of the fan case (see Figure 3)

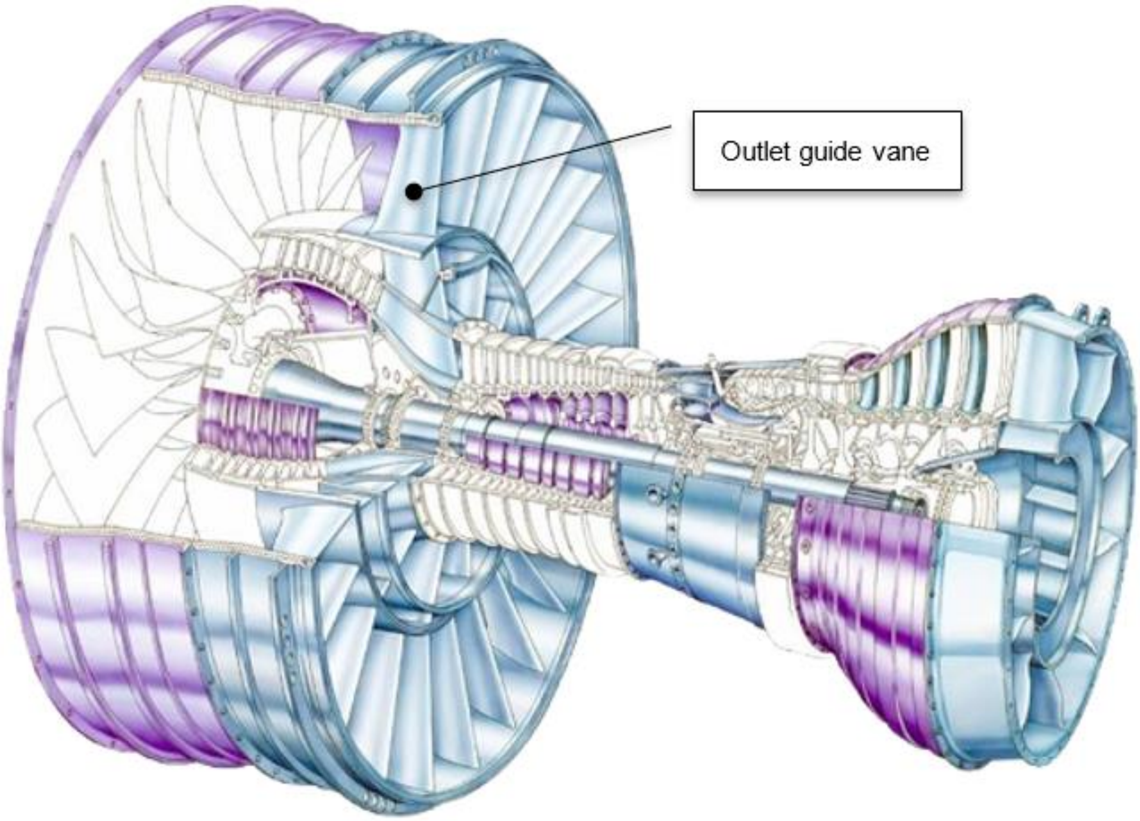

Figure 3 - *Outlet guide vanes in an aeroengine*

The guide vanes have the purpose of guiding the swirling airflow from the fan to an axial flow. Guide vanes can operate in temperatures between -55°C and 120°C and should fulfil certain structural requirements (fatigue, loads, impact).

Today are many guide vanes manufactured using aluminium and/or titanium. However, some modern designs use composite materials, i.e. the LEAP engine. One composite concept is to first manufacture the composite airfoil and then in a separate manufacturing step bond the airfoil to titanium brackets at each end of the vane. The titanium brackets are then bolted to the intermediate case. The joint between the composite vane and the titanium brackets can be a combination of adhesive and mechanical fasteners. The adhesive joint between the composite and metallic structure is difficult to inspect, especially if it enclose the airfoil profile on both sides as for a pocket joint.

Prepreg material are often considered as a first choice due to excellent material properties and well-defined manufacturing processes. Another concept is to manufacture the composite vane in an RTM-process. In this process, dry carbon fiber reinforcements are inserted in a closed mould and epoxy resin is infused to impregnate the fibers, However, a separate manufacturing step to bond the vane to the brackets is still needed. A very interesting concept is therefore to mount a dry preform in the brackets (together with an adhesive film) before everything is placed in a tool and the infusion takes place. During the curing step the vane and brackets are thus bonded and no additional manufacturing step for bonding is needed. This co-bonding/co-curing RTM-concept is very promising when it comes to cost and quality. There are however many technical uncertainties and questions that need to be cleared for this concept.

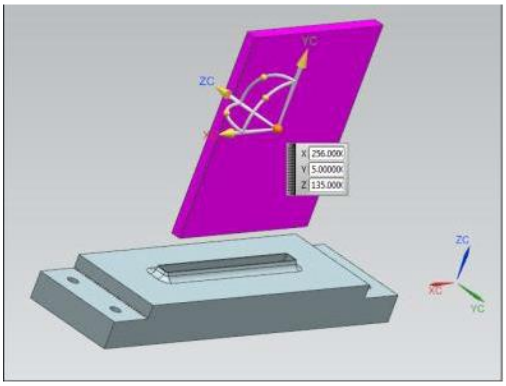

Figure 4 - The composite vane is bonded to the titanium bracket by a pocket joint

The project has addressed the following research questions:

- Design solution: How to design a pocket joint for joining a composite to a metal during RTM-process (co-curing/co-bonding)? This includes design of both the preform and bracket as well as the RTM-tool. What materials (adhesive, resin, reinforcement, primer) are suitable to use and what are the properties of the resulting joint? Innovative solutions in the design will also be investigated.
- Manufacturing approach: What are the best methods for applying primer in a pocket joint? Is it possible to compact the preform enough (with sufficient fiber volume fraction) so it can be mounted inside the pocket with adhesive film? Will process be suited for high volume production?
- Quality issues: Will the infusion process destroy the adhesive film? Since high temperatures and pressures is used during infusion there is a risk that the adhesive film will move away from the bond area or that it will be completely dissolved into the resin. Another problem may be a lack of pressure of the adhesive film during curing. Normally a certain pressure is needed on a bond during the curing of the adhesive to ensure bond quality. In theory the preform will spring-back during infusion and put pressure on the adhesive film, but will this be enough?

To answer the questions and to achieve a proof of concept theoretical studies, simulations, manufacturing trials and testing has been performed.

5.4 Case 4: Crash box and back plate – the Gestamp case

Today, Gestamp cold form crash boxes and back plates in high strength steels. These parts are then joined together by welding. Figure 5 shows an illustration of a car front and the locations of back plate and crash box. The purpose of the crash box is to absorb energy during a crash, and it is important that the joint between back plate and crash box can stand that impact. Another demand on the joint is to sustain unbroken after a varying static load to ensure the parts to stay non-defect after towing. These parts are often dynamic (crash) and tensile tested (tow) in accordance to e.g. General Motor (GM) standards. The purpose in the Gestamp case was to investigate if it is possible to design and create a multi material crash box with reduced weight and sustained mechanical properties.

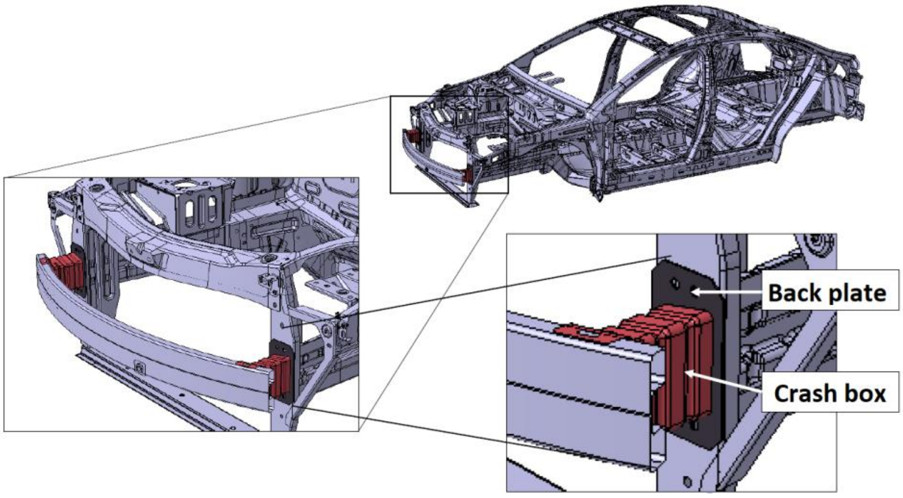

Figure 5 – Illustration of crash box and back plate in steel

The multi material design developed in this case includes a back plate in carbon fibre reinforced plastic (CFRP) and a crash box in hot formed high strength steel, see Figure 6. These two parts were joined together with an overlap joint using epoxy-based adhesive. The target was to design the back plate and joint to withstand the same test loads as a conventional crash box in steel.

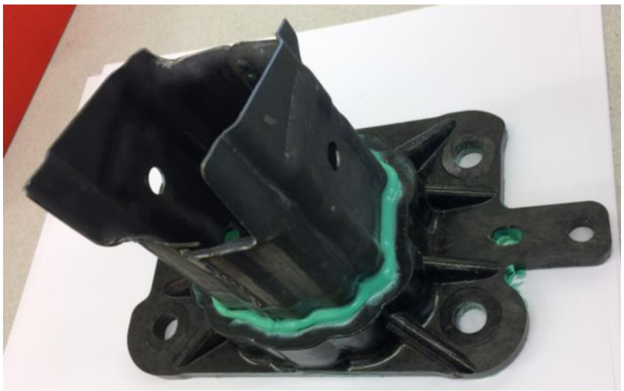

Figure 6 – The crash box and back plate produced with the final design

Design of CFRP back plate and adhesive joint

The design approach was divided into 5 steps, see *Figure 7*. Each step has an individual purpose in the iteration process, and the final design have to achieve set mechanical properties and be suitable for the manufacturing procedures (moulding and joining with adhesive).

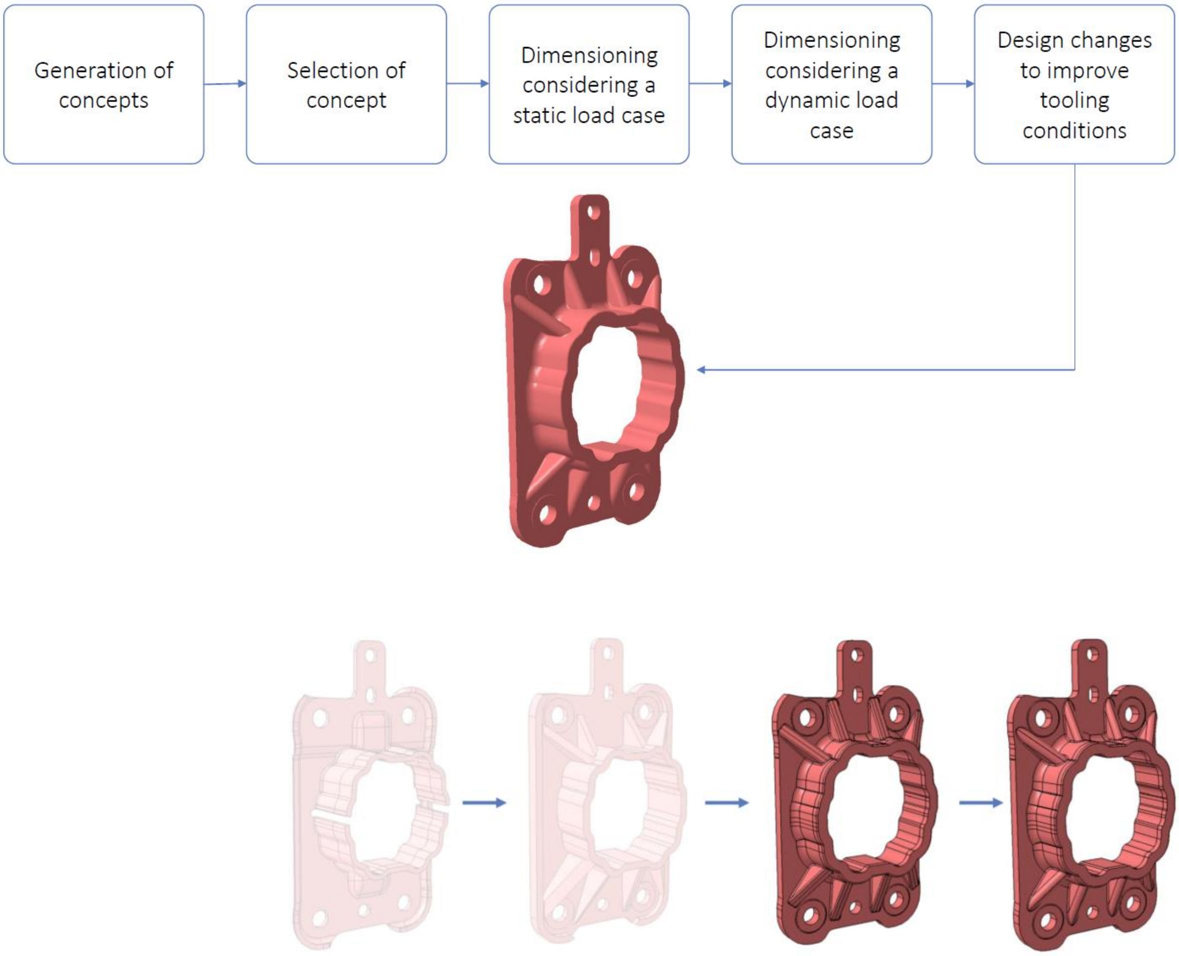

Figure 7 - Design Procedure Overview – note that the back plate geometry changes for each iteration step.

Generation of Concepts

Many different joining concepts were discussed including design of adhesive joints, and hybrid solutions using mechanical and adhesive joining together.

Selection of concept

A concept was chosen with adhesive in-between the crash box and back plate with flanges. This improves the joint as it increases the area where adhesive was applied, which is almost parallel to the load direction. The adhesive joint is designed to be exposed to shear force.

Dimensioning considering a static load case

One of the customer requirements for the bumper serving as a base design in this project is the Test of Towing Device. It consists of different test loads in different directions applied to the tow eye, see Figure 8. The last test is pulling with 25 kN to ensure that the bumper will withstand higher loads than the towing equipment [3]. This 25 kN towing was evaluated both in simulations and testing in this project. The target in this test is to be able to keep the 25 kN load for 10 s. A FEM simulation was used to calculate the back plate dimensions required to manage load tests mentioned above.

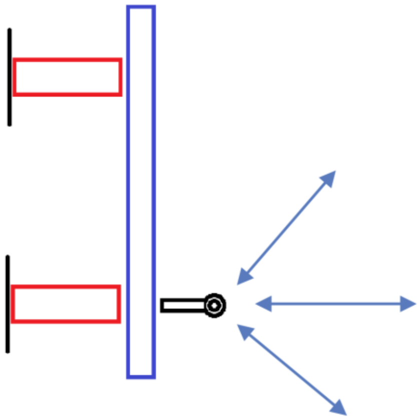

Figure 8 - Test of Towing Device

Dimensioning Considering a Dynamic Load Case
One of the insurance requirements is typically the RCAR structural test. For a front bumper it is performed as described in Figure 9. The Car is driving into a rigid barrier with a speed of 15 km/h. The barrier has an overlap of 40% of the width of the car [1]. This test can be simplified to component (CMS) level during development. A simplified simulation model was used in this project to evaluate the performance. The typical target in this test is to stay below a given force and intrusion level. The dimensioning of joint and back plate in CFRP was designed according to this dynamic load case.

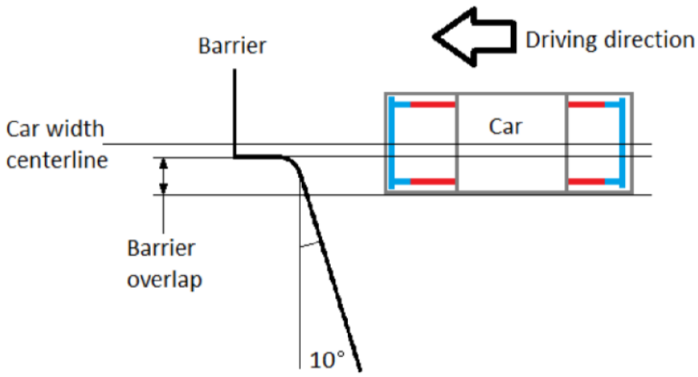

Figure 9 – RCAR Structural Test Setup [1,2]

Design changes to improved tooling condition.
A final adjustment of the design geometry was performed to fit for the mould, this included changed radius of the edges etc. The final design was implemented and manufactured.

Manufacturing back plate in CRFP
A press moulding tool was designed and used for manufacturing the back plates, see Figure 10. The design was based on calculations from the design step. The calculation did not include fibre placement or voids in the material, which could have a major influence on the results.

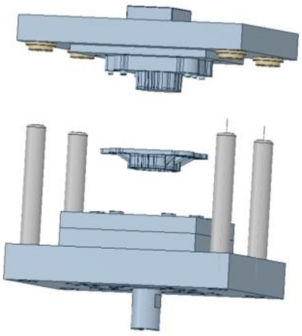 

Figure 10 – Design of tool for moulding back plate in CFRP(left), and the molded back plate results(right).

Adhesion test

An introducing test was performed with focus on how the release agent on the base material (CFRP) influences the adhesive joint. Steel test dollies were joined to cleaned CFRP and CFRP with release agents on the surface, using Sika POWER 533 MBX. The adhesion stresses were compared between these cases and there were no clear difference seen.

Before joining the CFRP crash boxes to the back plates, a 3D printed scale 1:1 model was used in a primary joining test, see Figure 11. This facilitated the design of fixture and joining procedure. It was discovered that the crash box could not fit in the back plate mounting it from the top side but only from the back. This was crucial in the fixture design step.

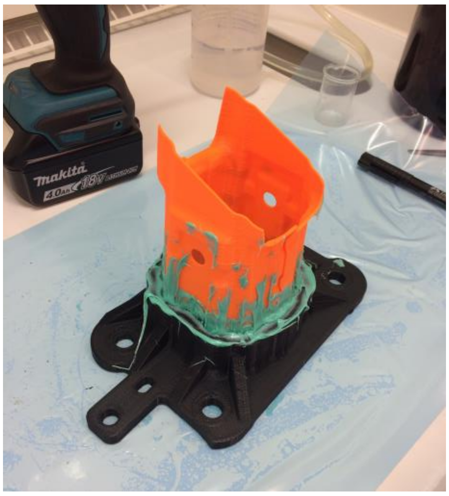

Figure 11 – 3D printed back plate and crash box.

The crash boxes were press hardened and welded. Then they were joined to the CFRP back plates using Sika POWER 533 MBX in an overlap joint. An advanced fixture design was required to achieve good fit and ensure even distribution of adhesive.

Adhesion procedure:

The back plate was first mounted with screws in a solid aluminium base plate. Then the crash box was adjusted to the center position (even gap in between back plate and crash box). When the center position was found the crash box was also strapped with a screw to the base plate, see Figure 12 Distances in fluorine plastic was used to keep a 3,1 mm distance between back plate and crash box. When the crash box´s position was set the back plate is detached and the fixture was ready for applying the adhesive.

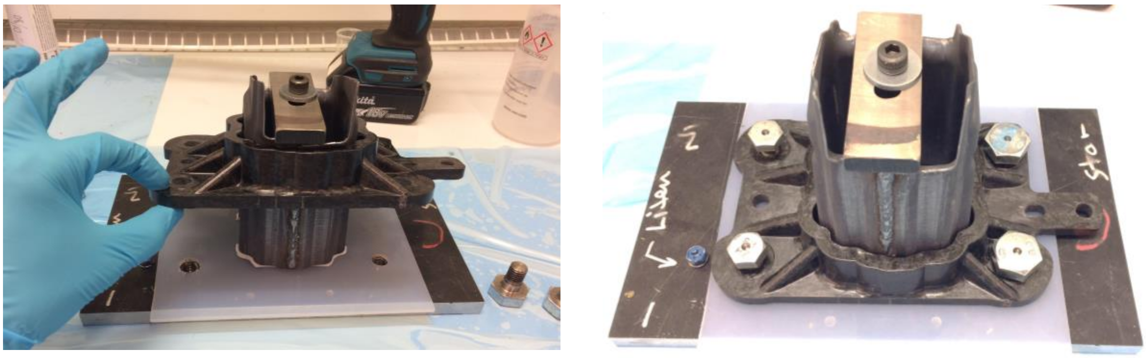

Figure 12 – Fixture used to fix the gap where the adhesive was later applied.

The adhesive is heated to 60 °C, and the fixture plus component to 75 °C before application of the adhesive. The adhesive was applied to roughly half the height of the joint interface, as the picture shows. Applied thickness of the adhesive on half the joint area, see Figure 13.

Figure 13 – Procedure used to apply adhesive.

The back plate was slowly pushed towards the fixture base plate and excessive adhesive was removed. Then the back plate was screwed to the base plate into position. The fixture and component were placed in a furnace for curing. When the thermocouple showed 175 °C the 20 min count down started. The final product was then taken out from the furnace, see Figure 14.

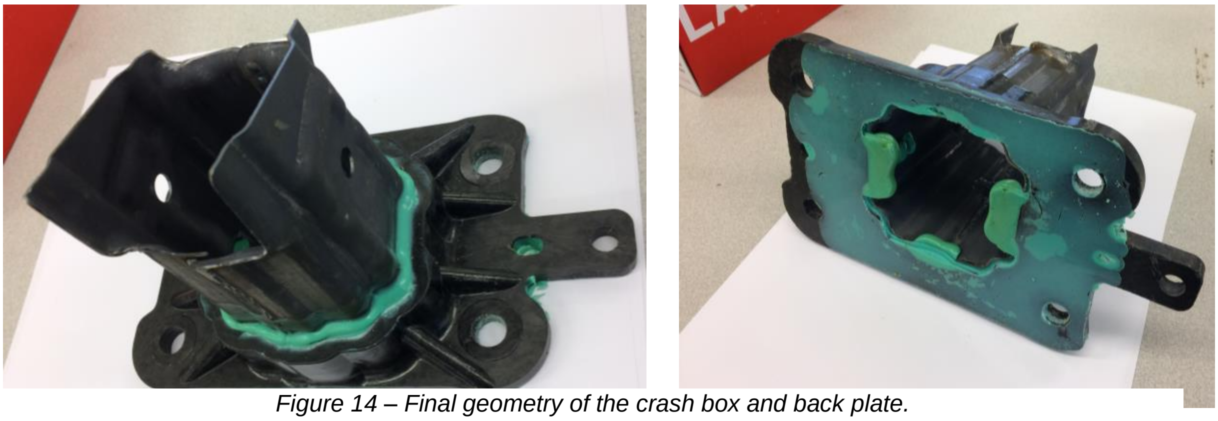

Figure 14 – Final geometry of the crash box and back plate.

References

[1] Research Council for Automobile Repairs “RCAR Low-Speed structural crash test protocol”, Issue 2.2, 2011.

[2] D. Gustafsson “Method for Optimization of Crash Management Systems considering Multiple Load Cases”, Luleå University of Technology, Luleå, 2014.

[3] General Motors Worldwide (GMW) “GMW14289 Test of Disabled Vehicle Attachment Point, Towing Device”, 2011

6 Project goals

The project goals formulated in the initial stage of the project was:

- Increased process control and reduced lead times: In comparison with the manufacturing of multi-material components today that are only suitable (regarding cost and lead times) for expensive vehicles, the project should contribute with finding more efficient products and manufacturing solutions for high-volume components
- Increased competitiveness: Products with improved performance that create attractiveness within Swedish industry. Products in multi-materials are necessary in future vehicles to meet present and upcoming environmental requirements
- Improved quality and reduced weight: Reliable joints in desirable materials provide the opportunity to implement advanced components and new light weight materials to a greater extent
- Cost savings and reduced environmental impact: New design possibilities that enable light weight, more efficient production of advanced components, differentiated requirements and the use of environmentally friendly materials

From these project goals, and in discussion with participating companies, a number of deliverables was decided:

- Guidelines for design of different type joints that can be used in different industries
- Compilation of existing industrial processes that can be used in multi-material design
- Simulation and modelling methodology for concept studies and design
- Manufacturing of demonstrators using multi-material design
- Workshops to disseminate the expertise that has been built up in the project
- Strengthened research and education within the participating academia and industry.

Within each case, several minor goals where determined. These are in line with the above mentioned goals and can be found in each case report.

7 Results and achievements

The project has developed design solutions where existing/modified joining methods has been used for joining lightweight materials to more traditional materials. On a high level, the project results primarily address the overall FFI target for increased competitiveness in the automotive industry by enabling superior products in multi-material. The project involved several industry collaborations, but also collaboration between suppliers and OEMs and between institutes and industry. The project was also directed towards the goals of new products since this project will enable new functions linked to new (for the product) materials.
Within the FFI HP roadmap there is great focus and an overall goal to create competitiveness for Sweden's automotive industry. Similar objectives are found within the various strategic innovation programs (SIP), where parts of the issue from this project could also be addressed within, for example, SIP Lightweight. The reason why this project was aimed at FFI HP is that lightweight and cost-effective multi-material solutions are largely driven by the automotive industry. The project nevertheless focuses on the joint's total requirement situation including, for example, strength, surface finish, productivity and geometry requirements, not just light weight.

The project has addressed a number of key technologies for selected joint types originating from industry requirements, through a cross-functional approach. The requirement situation for each joint type was in turn derived from typical applications for the participating industry. By developing the chosen key technologies from today's TRL level to a more mature level, there was the opportunity for the industry to assess the potential of the joint types for future applications. Figure 15 shows an example of a number of identified areas where the arrows represent the need for development in each area. Each of the areas requires a different amount of work.

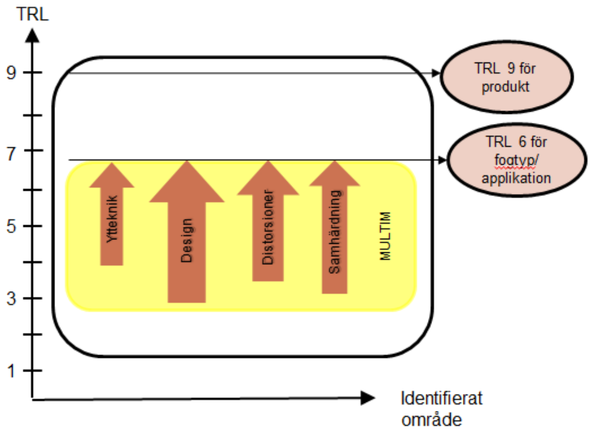

Figure 15 - Example of areas for chosen joint type and application

The methodology of the project was to look at different joint types, which are represented by the different cases. The project has delivered design solutions for joints containing dissimilar materials. Materials that have been involved are high strength steel, aluminium, titanium and carbon fibre reinforced composite. The material solutions that was studied for each individual joint type was determined by the project participants and was thus relevant material combinations for future components. The benefit from this approach is that the result from MULTIM will be easy to implement directly on components. The design solutions that was developed in the project consist of various joining techniques that has been adapted to series production. Something that has not been in enough focus during the project work, but what has been in parallel focus by the participating companies, is the cost perspective of the included solutions. No advanced calculations of life cycle costs have been done.

From lessons learned in the four cases, recommendations for multi-material design were extracted that can be used generically for a variety of design problems. The recommendations include everything from compilations of various mechanical joining techniques, to adhesive bonding guide, to how to think when combining adhesives and spot welding. The project has reduced the threshold for the industry to make more use of multi-material design in industrial applications. The results from the project have been generated within the industries of vehicles, aircrafts, and hand-held tools, but can be applied much broader than that.

In connection to what was stated in the initial plan of the project, the long-term perspective of the results is expected to lead to:

- Lighter designs by using new material combinations
- A simpler procedure for implementing new materials
- Increased knowledge of multi-material design that can result in new innovative design solutions
- Lighter vehicles and products in the Swedish industry that provide a great competitive advantage over competitors

The project's most important final deliveries are listed below.

- Guidelines for the design of different type joints that can be used in different industries
- Compilation of existing industrial processes that can be used in multi-material design
- Groundwork for modelling methodology for concept studies within multi-material design
- Manufacturing of demonstrators using multi-material design
- Several workshops to disseminate the learnings that has been built up in the project
- Strengthened research and education within the participating institutes and industry
- Educational material that can be used for competence dissemination e.g. IWE and other engineering education

7.1 Case 1: Spare wheel housing – the Volvo Cars case

As an introduction to the joining challenges of mixed materials and their differences in thermal expansion a presentation was made in how BMW has managed this kind of joinings in the 700 series model based on material gathered at the Automotive circle conference – Joining in Carbody Engineering - BMW insight edition. BMW has replaced many of their steel parts with carbon fiber reinforced polymer and aluminium.

The choice of joining method and configuration of the joint itself as well as the parts will be very important for the outcome. A guide for choice of mechanical joining method for different applications and material mixes has been developed. In this project the joining method Friction Element Welding was chosen due to its superior performance in mixed material joints between aluminum and very high strength steels.

If two flat panels are joined to each other they will just bend like a bi-metal when heated. To be relevant the steel part and/or the aluminum part must have some stiffness by their own. In a real structure, parts are constrained to other parts and the shapes of each individual part is often more complex than two individual sheets. We decided to use box beams as a test specimens for this study as shown in Figure 16.

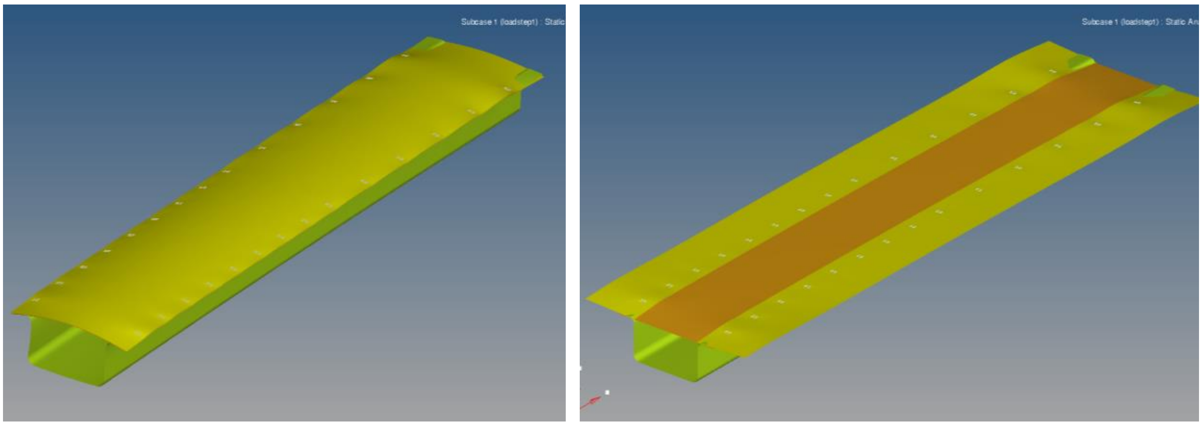

Figure 16 – Examples of simplified geometry used to evaluate deformations due to differences in thermal expansion coefficient.

Before performing tests with the most suitable joining technology some pre-trials were made where self-piercing rivetnuts was used to join the aluminum to steel. At that moment this was the only joining method we had access

to. The main purpose of these pre-trials was to evaluate a new method to track dimensional changes during hardening of adhesive in multi material structures using 3D-scanning.
The joined beam was scanned before the oven, in the oven at 190°C and after the oven. Scanning in the oven was done through a glass window. The results are presented in colored plots of dimensional change in comparison with original shape. Most of the deformation occurring in the evaluated structures are shown to be elastic deformation but since the adhesive is cured when the structure is in a distorted state, the distortions will still remain once cooled to room temperature.

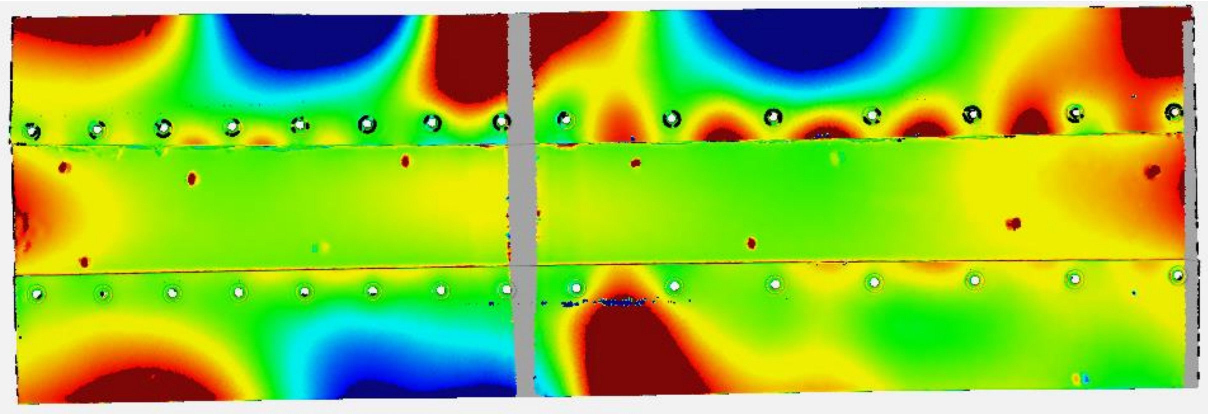

Figure 17 – Comparison of geometries before and after adhesive curing (both at room temperature). Color map of distortions relative to the original shape prior to adhesive curing, green = same shape as before. The lower joint was without adhesive and show less distortion.

The method worked fine. It shows how the shape of the beam bends and twists at heat exposure and confirms that distortions can be permanent if the adhesive is cured in the distorted state or if plastic deformation occurs. The movements between sheets can obviously have a large impact on joint filling and the sealing properties of the joint.
DSC measurements on four different epoxy adhesives were measured in order to understand when in the cure cycle the adhesive sets and lose the ability to flow. For these epoxies almost all the crosslinking reaction seems to happen already during the temperature raise in the span 150 -170°C in a typical Electrocoat curing line, and the goal is to achieve an object temperature of 180°C for 30 minutes.

Several trials on the influence of adhesive thickness on mechanical properties of the adhesive joint were also carried out. The motivation for these studies was that it is well known that a thicker adhesive joint than normal is often necessary in multi material joints to reduce stresses on the adhesive joint due to deformations caused by a mismatch in thermal expansion coefficients between e.g. aluminum and steel. Results show that a thicker adhesive joint give slightly lower shear strength compared to a thinner, however this is most likely due to that the distribution of load changes as the adhesive becomes thicker i.e. it is not pure shear load any more. The results also confirmed that a thicker adhesive joint can withstand larger elongations, which is why a thicker adhesive joint is necessary in multi material mixes with different thermal expansion coefficients.

A plan for a large test series with different material and joint configurations was made. Experimental work was initiated based on this test matrix and in total 23 specimens were made. Several variants of box beam configuration, pitch distance between joining points, jogglings, cutouts, adhesives, adhesive thicknesses and joining elements were tested and scanned using a 3D-scanner. Afterwards the beams were taken apart and inspected.
The scanning results revealed a lot in how different beam configurations behave both in global deformation and local deformation in-between joining points. There will be global modes of buckling depending of the geometry of the test specimen. Also built in stresses and deformations from clamping, fixturing and the spot joining process will affect how these modes of buckling behave at additional stresses from induced temperature changes. In addition the global deformation depends on how constrained the part is in a structure.

In a temperature cycle, a simple non constrained test structure may deform a lot but most of the deformation is reversible when the temperature returns back to normal. A constrained structure will deform less but stresses and local deformation will be higher and larger. If both parts in a joint are made stiffer, e.g. a sheet with a flange, the deformations decrease, but stresses increase in the assembly. The positioning and pitch between spot joining can be used to suppress deformations. If the spot joining is made by predrilled holes, screws and nut there are some possibility for slip in the joint, which make the global and local deformation very random.
If an adhesive cure when the structure is in a distorted state, there will be remaining distortions when the temperature returns to normal. If large deformations occur in between spot joining the quality of the bonded joint can be ruined and the sealing properties of the joint quickly deteriorate. The adhesive cannot follow large changes in the joint volume. The result can be under filled unsealed joints or joints where the adhesive lack adhesion. The adhesive cure starts already at the ramping of temperature up to the final oven temperature. It seems like the partial cured adhesive loose adhesion in this state if movements in the joints are too large.

Based on the experimental trials, several joining scenarios were extracted and simulated to better understand the limits of where distortions can be handled with parameters such as pitch distance, material type, material thickness etc. The aim of these simulations was to form a base for easy to use guide lines for design engineers. A parameter study was performed using a 2D simulation model where the following parameters were investigated:

- Aluminium sheet thickness: 0.7 mm → 4.0 mm
- Steel sheet thickness: 0.5 mm → 3.0 mm
- Distance between joining points (pitch): 40 mm → 73 mm
- Distance between sheets: 0.1 mm → 1.0 mm

Figure 18 shows the 2D-model setup with an arrow indicating the measure of maximum distortion. *Figure 19* shows one way of illustrating the complete result of the parameter study. It can be seen that for large enough thickness rations, deformations due to mismatch of thermal expansion coefficient is not an issue. For low thickness rations however, the pitch distance needs to be adjusted to minimize the influence of distortions during the adhesive curing cycle.

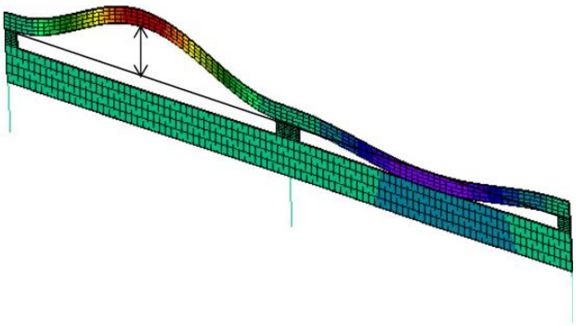

Figure 18 – Example of 2D simulation of maximum distortion for heating cycles from 20 → 180C.

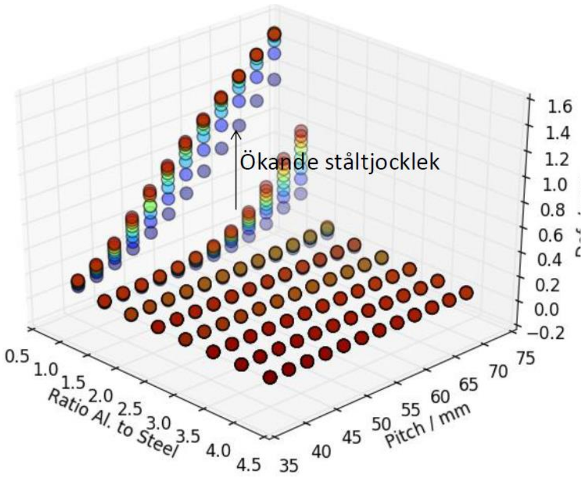

Figure 19 – Resulting maximum distortion as a function of sheet thickness ratio and pitch distance

The 2D-simulation model above does not include adhesive and only determine the maximum deflection of the metal sheets during the paint bake cycle. This approach has some flaws, one being that we cannot account for any stresses that might buildup in the adhesive layer at large thickness ratios. Although no deformations of the metal sheets seems to occur, the adhesive layer might still transfer a lot of stresses between the metal sheets. For a design guide line to be useful, this effect needed to be considered.
The simulation model was later improved to also include adhesive in between sheets and includes the possibility to determine stresses in the adhesive during the paint bake cycle. The new model was made in 3D to include geometrical aspects of the sheets to be joined i.e. flange length, global geometry etc.

A numerical investigation (FEM) regarding a 3D case (*Figure 20*) has also been conducted. In this case efforts were made to include the adhesive behavior. The adhesive was assumed to behave as a visco-elastic material. The mechanical response of such a material may be described by a so called Prony series. In the case of this project the coefficients the Prony series were determined using a DMA machine on monolithic specimens of fully cured adhesive.

Also in the 3D case parameters were varied.

- Aluminium sheet thickness: 0.3 mm → 1.0 mm
- Steel sheet thickness: 0.3 mm → 2.0 mm
- Distance between joining points (pitch): 20 mm → 80 mm
- Distance between sheets: 0.1 mm → 0.5 mm
- Adhesive thickness under the fastener: 0.01 mm → 0.5 mm
- Heat cycle duration: 1 min → 10 h

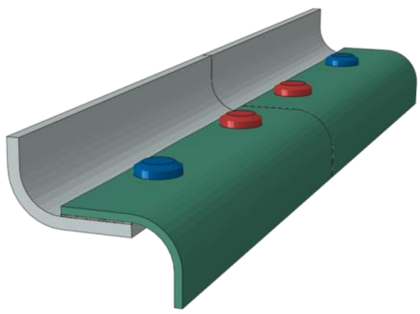

Figure 20 - 3D model of Al-Fe joint including an adhesive.

To facilitate the analysis of the numerical results a neural network (NN) was trained to predict distortions of the sheets at curing and the strain in adhesive. With this NN it was possible to investigate the influence of the different parameters and construct guidelines. Using the maps in *Figure 22* and *Figure 21* it is possible either to determine the deformation and strain response in a given joint or the determine for instance the necessary pitch knowing the acceptable deformations and strains.

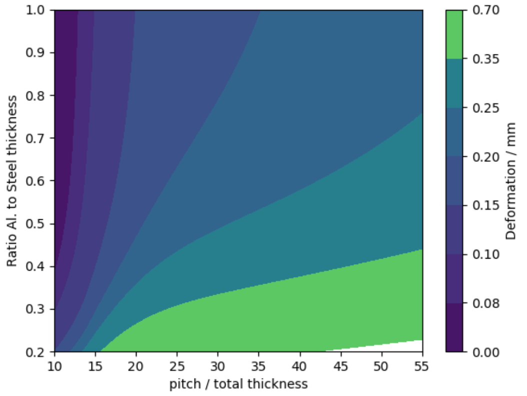

Figure 21 - Guidelines in the form of a map of deformations of the joint at curing.

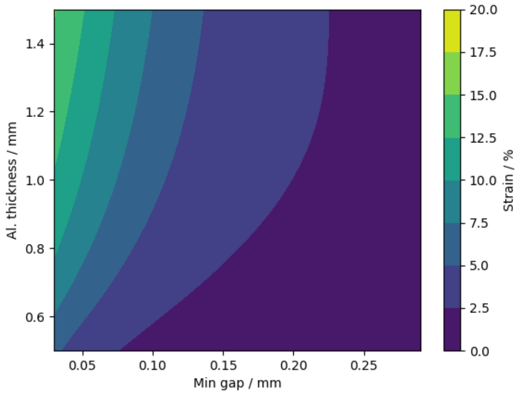

Figure 22 - Guidelines in the form of a map of maximum strain of the adhesive after cooling.

The methodology used within the case can be summarized:

- 3D scanning is a powerful tool to evaluate deformation behaviour in multilateral joints
- FEM simulations capture the trends of the Δα-challenge very well. Absolute values need to be confirmed.
- Global geometry play an important role in local deformation behaviour
- Relatively simple design guidelines have been developed for multilateral joints focused on the Δα-challenge

7.2 Case 2: Guide bar – the Husqvarna case

The work within the project was focused on conceptual design of guide bars. This has included, choice of materials, choice of joining system, adhesives and middle plate configuration.

At project start an initial specification of product requirements was made and during the project it has been refined. Also, a simple failure analysis on early bonded guide bars was done.

In total have 67 guide bars been manufactured. Five different adhesives were evaluated and tested. The manufacturing method has been developed continuously to improve quality. Issues like adhesive blistering, adhesive filling, tolerances and geometrical issues and residual stresses in joints have been addressed. Midplates made in composite materials did cause other quality concerns. The bending stiffness of the bars is dependent of the thickness in third power. For twisting thickness affects in the second power. Thickness deviations were measured with scanning and the testing results were normalized to nominal thickness in the comparation with simulations. The last batch of guide bars the adhesive was applied with a robot to achieve proper amounts for correct joint filling.

For guide bars with different joint and multi-material configurations, bending and twist stiffness calculations has been performed and compared with real tests. Initially a linear elastic model was used and later this was changed to a linear plastic model for the adhesive and also for the midplates in composite materials. The metal midplate design was refined with topology optimization in order to reduce the weight. The linear plastic model shows in comparison with linear elastic model, a large reduction of the stress levels both in the adhesive and in the midplate. Adhesives with different plastic behaviour and yield stress were compared. Despite a large reduction in adhesive stiffness, 70 %, the loss in stiffness for the bars were rather small i.e. less than 10 %.
These stiffness simulation results have been compared with the results from tested bars. The correlation is rather good.

A first insight in relation to initial assumption is that the difference in thermal expansion is a more demanding challenge than bonding each substrate with good adhesion.

Next step was simulation of the residual stresses after curing taken the thermo-viscoelastic behavior of adhesives during the curing process into account.

The model includes:

- Viscoelastic adhesive behavior (DMTA data WLF shift parameters for time- temperature superposition mastercurve)
- Curing process based on Kamal model (Cure rate is proportional to heat release rate in DSC measurements, best fit of scan and isothermal curing)
- Mechanical strain from linear model (metal)
- Thermal expansion and chemical shrinkage as a function of the degree of cure
- Shear and bulk modulus as a function of degree of cure
- The actual cure cycles.

Large efforts were directed in collecting and refine adhesive modeling data. Testing of key properties of adhesive system were made with DMTA and DSC (together with the Volvo-case). Data was also collected from literature, software developers and adhesive suppliers. The results show that the prediction of residual stresses and panel distortions is possible. Validation of the numerical simulations with experiments is necessary. Literature data for chemical shrinkage and thermal expansion must be improved by test data. Plastic strains have not been considered in this material model.

In the thermal elongation analysis, the stress estimation from the linear elastic calculation did propose a stress level exceeding the yield stress for the aluminium midplate. The linear plastic model gave stress levels around and below the yield limit of aluminium depending on the adhesive stiffness while the curing model gave somewhat below.
The aluminium in-between two steel sheets are elastically stretched in this sandwich type of joint after being fully cured. These bars were fully bonded over the whole surface. Practical tests with underfilled joints, too small bonded area, succeeded to provoke bonding failure in the adhesive joint. After curing and cooling light bending caused a noise of cracking. High residual stresses in the joint will jeopardize both the remaining load capacity and durability resistance.

Husqvarna have made bend and twist stiffness measurement of the different guide bar configurations. These measurements have been compared with both the simulation results and the all steel reference bar.
Husqvarna is also running fatigue tests on six selected configurations. Tests at Husqvarna show that we can get high enough twist and bending stiffness of the steel and aluminum laminate joint with adhesives, but fatigue tests show delamination between laminates. The underlying reason is that since curing temperature of adhesive is high, there will be large stresses in the joint at room temperature due to different thermal expansion between steel and aluminum. Design of mixed materials having different thermal expansion set large demands on the joint. Joining materials that has large difference in thermal expansion combined with adhesives that has high curing temperatures will induce large stress in the product already at room temperature without external load. Husqvarna has increased the knowledge within adhesives and joining technology with performed tests and is better equipped to develop products joint with adhesives in future products.

A general guiding presentation for the procedure of selecting an adhesive system was made and presented for the MULTIM participants.

Guiding on suitable surface pretreatments for adhesive bonding on different materials has been made. A short guide has been written.Focus is on surface pretreatment, but it is also a help to establish a technical specification for bonding applications.

The general knowledge learnt from this case of multi-material bonding in large overlap joints has been compiled in a presentation.

7.3 Case 3: Outlet guide vane – the GKN Aerospace case

When designing a pocket joint different designs can be used to improve mechanical properties. For example, if the pocket is cone shaped instead of straight it can provide different mechanical advantages. Especially if some type of wedge is inserted in the composite part (see *Figure 23*).

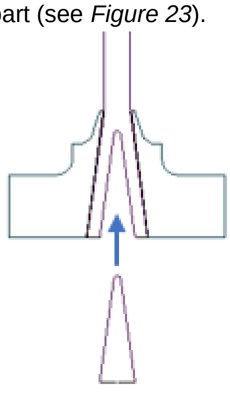

Figure 23 - Cone shaped pocket with a wedge in the composite vane will act as a mechanical locking

Different types of innovative solutions, with different advantages and disadvantages have been presented. However, simple manufacturing is also important and different shapes of the pocket makes can affect how easy it is to mount the adhesive film and preform in the pocket. Manufacturing trials that investigate these issues are summarized in a closed report. The main conclusion was that it is possible to mount the adhesive film and a preform (with close to 60% fiber volume fraction) in a bracket.

The exact load cases for the joint in a real-world application is not specified in the project but FE-simulations were performed with different joint designs to increase the understanding, identify the problem areas in the joint and to see if an adhesive bond feasible or if some mechanical joining method must be included in the design.

The materials are crucial for the manufacturing process and after investigations and discussions with suppliers a toughened epoxy resin was selected as infusion resin together with a toughened adhesive film. Characterization of the materials, including rheology measurements to determine viscosity profiles of the infusion resin and thermoanalytical measurements (DSC) has been performed.

One problem with a pocket joint is that it can be difficult to achieve a pressure on the adhesive when it cures, which may result in a weaker bond. The preform that is mounted in the pocket will however sping-back during infusion and put some pressure on the adhesive film. To investigate if this spring-back is enough and to analyze the strength of the bond created by co-curing some manufacturing and testing was performed on coupon level. The results shows that the co-curing process creates a strong bond.

An important task was also to evaluate and build knowledge about adhesive bonding, priming and surface treatment of this type of components (titanium brackets). A main task was to examine the topography of titanium surfaces with and without primer and the aging behaviour of one adhesive on these various surfaces using the Boeing wedge test ASTM D3762-03. Both the test method itself and different surfaces has been evaluated. Some work has also been made to pretreat and put primer on brackets. Since the pocket makes it less then ideal to apply the primer with spraying or brushing a dipping method was tested.

Regarding the resin there are some challenges during infusion that are connected to preheating. In the RTM-process the resin is infused from a pressure pot into the preform in a closed tool. Normally the temperature in the pot and in the tool can be the same. In this case however, the resin is toughened with thermoplastic particles and needs to be heated to >150 °C to melt the particles, otherwise they will be filtered in the preform and the impregnation of the preform will be problematic. Since the pot life will be extremely short (the time before the viscosity is too high due to curing) if the pot temperature is kept at 150 °C the temperature in the pot needs to be lower (manufacturer recommends that the pot temperature is set to 80 °C). This means that the resin needs to be continuously heated between the pot and the tool (with a decent flow rate). Therefore, a preheating method was developed and tested.

For manufacturing trials an RTM-tool was constructed in the project and one steel bracket was manufactured. The steel bracket was treated with release agent before manufacturing, so the joint could be disassembled, and the bracket reused in several trials. For the final manufacturing of demonstrators several titanium brackets were manufactured with additive manufacturing. *Figure 24* shows one of the demonstrators manufactured in the project.

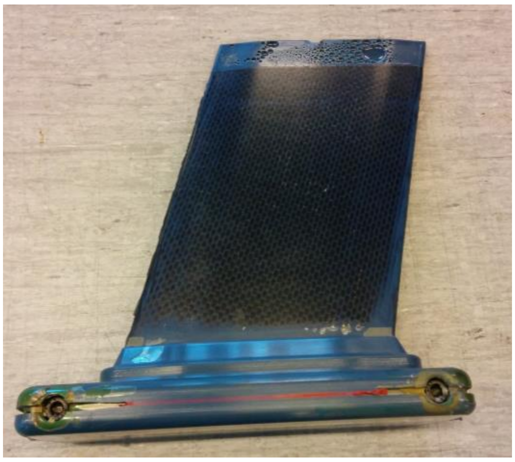

Figure 24 - Titanium bracket and composite vane manufactured and bonded by co-curing.

7.4 Case 4: Crash box and back plate – the Gestamp case

Mechanical testing and cross sections

The evaluation of the final properties in the crash box was performed with tensile – tow hook test and cross section analysis.

Tensile – tow hook test

The target in the design step was to achieve an adhesive joint and a back plate that could hold more than 25 kN, according to a GM standard. Three tensile tests were performed on the final products and all showed successful results with forces between 26.05kN and 30.78kN. All fractured surfaces were in the CFRP back plate and not in the adhesive joint, see Figure 25. To further improved the mechanical properties, it is suggested to improve the strength of the back plate. One option is to use a combination of different fibre lengths in different regions of the mould, to optimize the final mechanical properties.

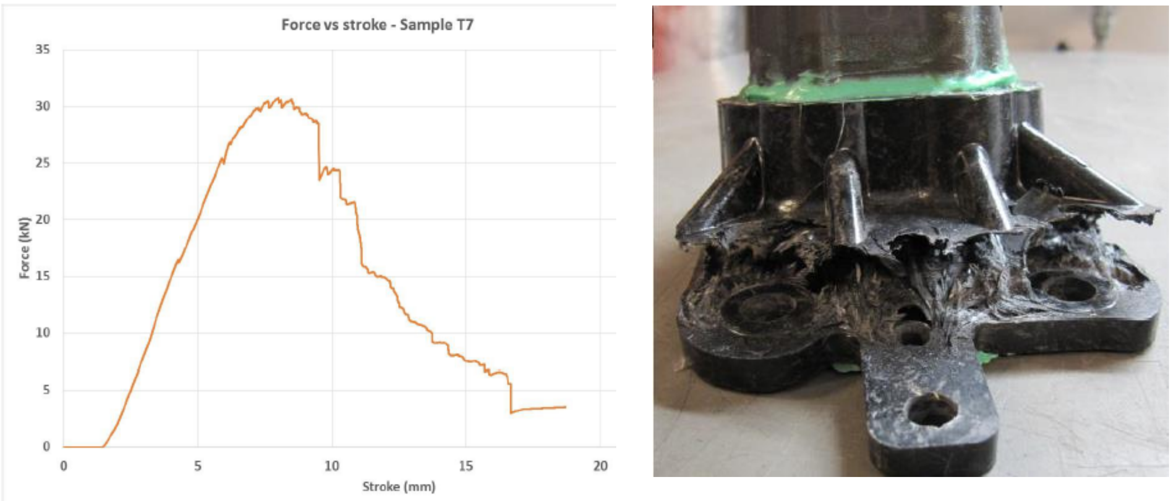

Figure 25 – Curve from mechanical testing (left) and failed component (right)

Cross section analysis after tensile test

Cross section analysis were performed after the tensile tests to investigate in there were imperfections visible. Three (3) sections through the adhesive joint have been investigated by visual study with a stereo microscope, see Figure 26. Imperfections can be seen in the joint between the rear plate and the crash box in cross section A and B. No imperfections are visible in cross section C. Cracks are present in the rear plate. It's not possible to determine whether some of them have been formed during the fabrication of the back plate or during the test.

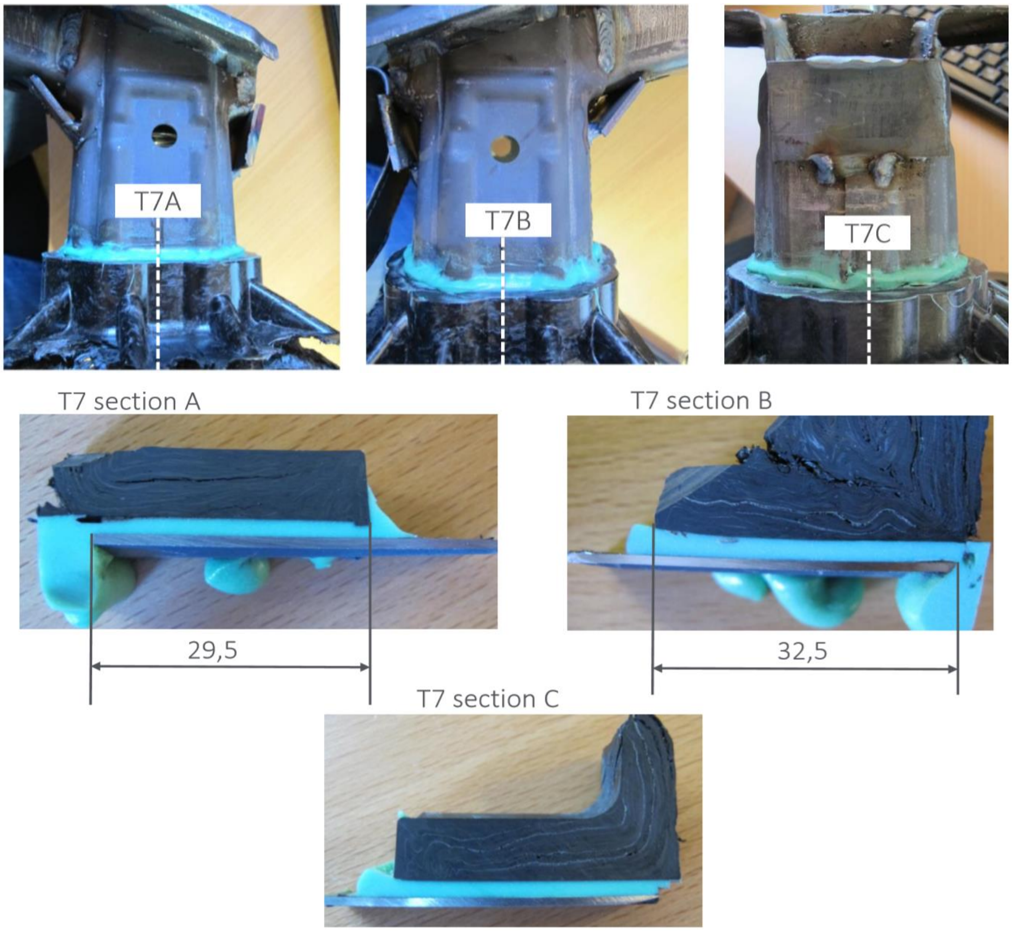

Figure 26 – Three cross sections of a tensile tested crash box

A closer look at sample T7 A show a 13,2 mm long imperfection (lack of adhesion towards the rear plate) detected in section A. 13,2 mm corresponds to approximately 45 % of the joint length. See figure below.

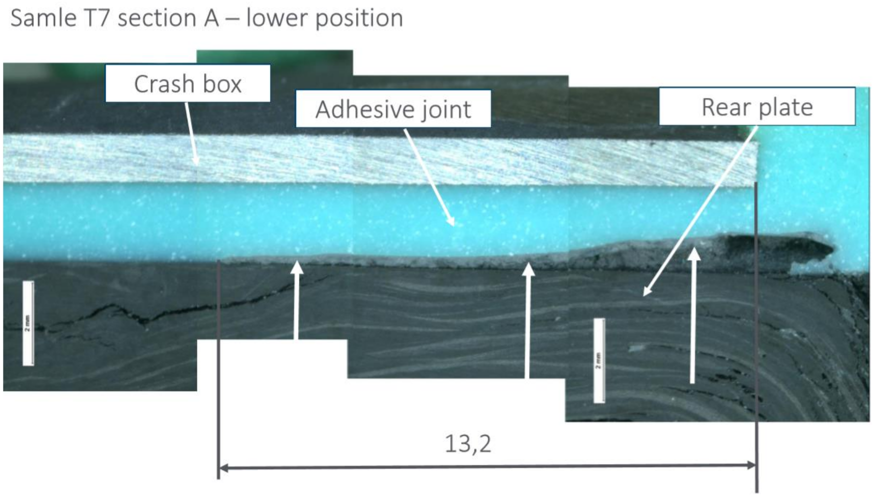

Figure 27 – Voids and crack like imperfections in the CFRP

Three short imperfections (cavity inside the adhesive and lack of adhesion between the adhesive and the crash box and between the adhesive and the rear plate) detected in section B, see Figure 28.

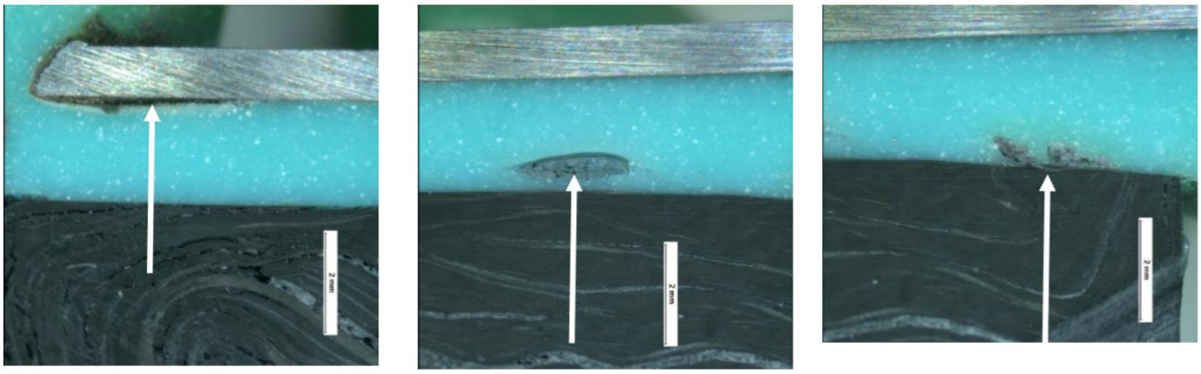

Figure 28 – Imperfections in a tensile tested crash box

Dynamic load testing

RCAR structural crash tests were planned to be performed on the crash box products, but it was not possible within the timeframe of the project. The test procedure is detailed presented in the design step in Chapter 5.4.

The adhesive joints were designed to stand the high shear force expected in a crash test, and the simulations were based on a load case where the force/crash direction is parallel to the joint interface surface.

Summary

- The maximum tensile force that has been reached is approximately 31 kN
- Fracture occurred in the back plate only and not in the weld joints that join the crash box to the bumper system cross member beam during the test.
- No fracture has been detected in the adhesive joint between the crash box and the back plate.
- A somewhat more comprehensive study of the adhesive joint has been made in three positions.
- There are imperfections in two of the studied cross sections. The length of the imperfection in cross section A is approximately 50 % of the length of the entire adhesive joint.

8 Dissemination

This project focuses on designing the joint and the joints from a holistic perspective so that existing joining methods can be used. Ultimately, this will lead to lighter and more optimized structures adapted to industry requirements.

Through the project, participating partners has increased their knowledge about how design can be applied to their specific products and processes and what opportunities and limitations that exist. The partners also have got a unique opportunity to exchange experiences across industries, even though the focus has been heavily on the automotive industry.

The project results will help the automotive industry, as well as hand-held tools and aerospace industry, and its subcontractors to design and produce new and innovative components with lower environmental impact in the form of reduced weight. The project has resulted in expanded design freedom for designs that provide additional weight savings. One objective was to implement results from the project before 2020. The demonstrators produced within the project is relevant and can be used as for demonstrate techniques that can be used for today's production.

Informative documentation has been developed within the project which should be used for seminars with project partners and for disseminating information within each participating company and for educational purposes at higher education institutions. The project has been presented at conferences and published in technical journals.

In general, key competence for several individual techniques exists, but what is missing is that the links between the necessary competencies I limited, since the area of multi-material design is enormous. Subcontractors knows their products, end manufacturers know theirs, and institutes and universities are often specialized in a particular area. What this project has brought is an interdisciplinary approach to a specific problem. For a specific identified topic MULTIM has connected expert competencies within, for example, steel, composite, joining and design.

The project's consortium includes several industries but also companies of different size and position along the value chain. The results from the project are considered to have great potential for use in other industries, which was confirmed by the participants in the project. An important part was also that the research resources that are intended for use in the project included the various building blocks that were needed. A collaboration between the various members of the innovation and supply chain constituted a great project committee for the MULTIM project.

8.1 Dissemination of competence and results

Hur har/planeras projektresultatet att användas och spridas?	Markera med X	Kommentar
Öka kunskapen inom området	X	Education package has been created within the project which can/should be used for internal and external purposes
Föras vidare till andra avancerade tekniska utvecklingsprojekt	X	A continuation of MULTIM are being planned
Föras vidare till produktutvecklingsprojekt	X	The results from MULTIM will be used by the participating industry for internal product development projects
Introduceras på marknaden		
Användas i utredningar/regelverk/ tillståndsärenden/ politiska beslut		

9 Conclusions and future work

The approach of MULTIM is considered successful. To be able to work with the complete requirement situation for a product/component gives the opportunity to be able to solve the actual issues occurring, instead of sub optimizing. The approach also makes use of the existing competence/techniques in a good way, which results in an easier longer perspective in the implementation phase.

What was an issue of concern in the initial phase of the project was that the different participating industries did not have that much in common regarding multi-material design. However, during discussions at the project meetings and seminars all companies have been active and contributed to all cases.

The deliveries from the MULTIM project are in line with what was decided in the initial state of the project. The different specific results have varying significance for different industries, depending on the maturity level of the industry regarding multi-material design and that specific topic.

For all cases, proof-of-concept has been achieved. There are several topics in each case that could be subject to future work; adaption for series production (tolerances, cycle times etc), quality assurance of the joint, etc.

Some specific proposed future work activities:

- Detailed description of adhesive mechanical properties
- Further evolve the FEM model that also include failure prediction
- Improve the adhesive material models to better capture the curing behaviour (shrinkage etc)
- Verify absolute deformation values with relevant experiments
- Challenges related to transferring the model concept to larger, more complex geometries

10 Participating partners and contact persons

Since the area of multi-material requires a multidisciplinary approach, participating partners was crucial for the project's ability to succeed. The three institutes that participated have different angles of approach, whereby the results in the project did considered not only the joining but also areas such as design (design), constituent materials, surface properties, strength, modeling, surface treatment, geometry, etc.

The project's results and opportunities with multi-material construction will be discussed during workshops with the project's participants. The results of the project will also be used in welding engineering at KTH with the aim of increasing knowledge about multimaterial construction and disseminating knowledge about the possibilities of combining different materials.

Partner	Contact persons
Volvo Cars	○ Marcus Schmidt ○ Oscar Andersson ○ Per Lindahl ○ Paul Jonason ○ Austen Clark ○ Alexander Govik ○ Jonas Horkeby ○ Håkan Karlsson ○ Per-Arne Käck ○ Sandeep Shetty ○ Jonas Wessung ○ Jonas Öman
Gestamp	○ Håkan Andersson ○ Richard Östlund ○ David Gustafsson ○ Ricardo Molina ○ Pedro Rubio Sanchez ○ Nils Hagström ○ Waseem Tahir ○ Ester Rayo ○ Mireia Illana
SSAB	○ Egemen Erdogan ○ Thomas Müller
GKN Aerospace	○ Dennis Rikemanson ○ Fredrik Edgren ○ Spyros Tsampas
Husqvarna	○ Niklas Sarius ○ Christian Liliegård
Swerim	○ Karl Fahlström ○ Paul Janiak ○ Christof Schneider ○ Alexander Lundstjälk ○ Fredrik Wredenberg ○ Etienne Bonnaud
RISE SICOMP	○ Jonas Engström ○ Rolf Lundström ○ Magnus Edin
RISE IVF	○ Tomas Luksepp ○ Per-Johan Wahlborg ○ Fredrik Wandebäck