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Impact of additive manufacturing on structural integrity methodologies for aerospace components

CUSTOMER: Netherlands Aerospace Centre

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EXECUTIVE SUMMARY
UNCLASSIFIED

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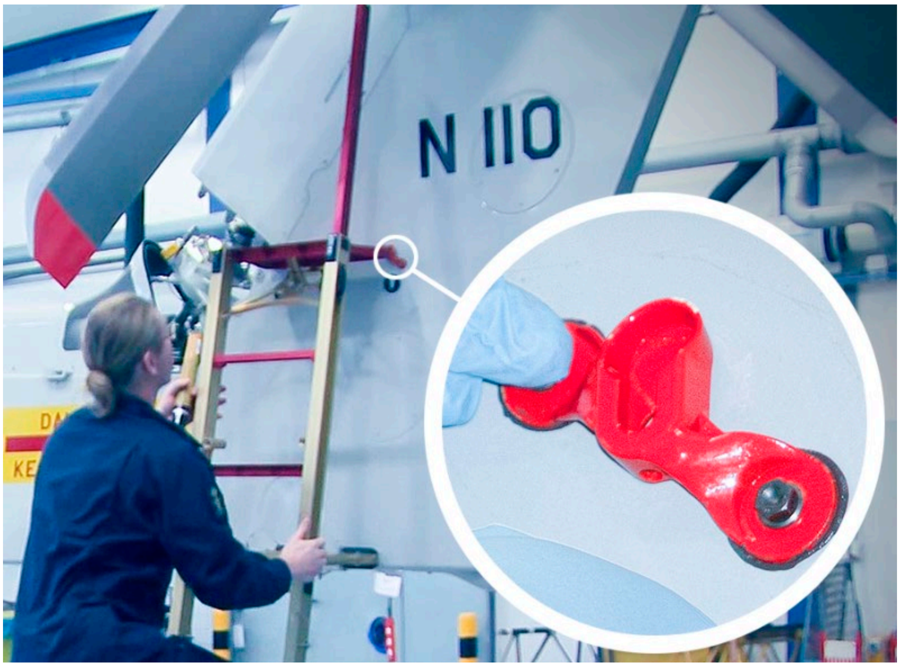

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KNOWLEDGE AREA(S)
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Problem area

Within the aerospace environment, structural integrity is ensured by satisfying specific requirements. Methodologies developed to assess compliance with the requirements require several inputs, such as material properties, manufacturing methods, etc. A significant amount of work is in progress to produce input information specifically for AM, but limited investigations have been done on assessing the applicability of the methodologies themselves to AM-designed components. Approaches currently implemented in designing components produced by additive manufacturing (AM) create shapes that hardly fit in the existing, standardized methodologies used to assess structural integrity. The risk of assessing structural integrity in a conservative way is to hinder AM to realize its full potential and to make the implementation of AM non-competitive compared to traditional manufacturing.

Description of work

In this paper, several aspects related to structural integrity assessments in aerospace are presented and their applicability to AM processes and components discussed. The current regulations, and the approaches implemented to fulfil them, are based on conventional materials and traditional design philosophies. New thinking needs to be brought into established methods for structural integrity, in order to maximise the benefits AM technologies can bring to the aerospace industry. It would not be the first, or the last, time that structural integrity requirements, and consequently the methods used, are questioned, adjusted and improved to account for new technologies or findings .

Assumptions embedded in damage tolerance philosophies and existing damage tolerance requirements are evaluated, and alternatives (when identified) are offered.

Results and conclusions

The aim of this paper is to bring attention to the topic of structural integrity in AM components, hoping to create the conditions to discuss structural integrity requirements at an earlier stage of the industrialization of AM. Without incorporating the correct structural integrity philosophies in AM, the risk is to repeat mistakes made during the development and introduction of composite components, overdesigning AM components, and therefore making a new promising technology less appealing in terms of weight saving and manufacturing costs.

Applicability

The considerations discussed in this report can be generally applied to structural integrity analysis of metal additive manufacturing components.

GENERAL NOTE

This report is based on a presentation held at the ESIAM2019, Trondheim (Norway), 9th-11th September 2019.

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Summary

Approaches currently implemented in designing components produced by additive manufacturing (AM) create shapes that hardly fit in the existing, standardized methodologies used to assess structural integrity. The risk of assessing structural integrity in a conservative way is to hinder AM to realize its full potential and to make the implementation of AM non-competitive compared to traditional manufacturing. Within the aerospace environment, structural integrity is ensured by satisfying specific requirements. Methodologies developed to assess compliance with the requirements require several inputs, such as material properties, manufacturing methods, etc. A significant amount of work is in progress to produce input information specifically for AM, but limited investigations have been done on assessing the applicability of the methodologies themselves to AM-designed components. In this paper, several aspects related to structural integrity assessments in aerospace are presented and their applicability to AM processes and components discussed. Assumptions embedded in damage tolerance philosophies and existing damage tolerance requirements are evaluated, and alternatives (when identified) are offered.

Contents

Abbreviations

ACRONYM	DESCRIPTION
a	Crack length
AI	Artificial Intelligence
AM	Additive Manufacturing
DFAM	Design For Additive Manufacturing
DNW	German-Dutch Wind Tunnels
EIFS	Equivalent Initial Flaw size
N	Number of cycles
NDI	Non-Destructive Inspection
NLR	Royal Netherlands Aerospace Centre
R&D	Research and Development
S	Stress
SHM	Structural Health Monitoring

1 Introduction

Aerospace and aviation businesses have shown a prominent interest in industrializing the production of additive manufacturing (AM) components, thanks to the possibility of manufacturing highly specialized, lightweight parts. Those benefits clearly overrule the complexity connected to AM, in terms of new infrastructures, workflows, design, and processes; such complexity is amplified when moving away from an R&D environment and into industrial-scale production.

First, the high rate at which new AM processes and materials are developed and offered to the market is a challenge towards investment for industrial production. To give an indication, the number of patents related to AM issued in the United States only in 2017 increased by 76% compared to 2016, following an exponential trend that started in the 1990s [1]. The constant introduction of new technologies can be an obstacle to industrialization, as the enormous initial investment costs do not facilitate the easy replacement of technology in case it becomes obsolete or outdated within few years.

A second aspect to consider is that, despite the first applications of rapid prototyping (considered the first AM technology) date back to 1980s, AM is still a niche technology. Processes are not sufficiently stable to produce consistent quality, which, combined with the lack of knowledge about defects (and their effects) occurring in AM parts, result in a market request for defect-free components, generating a high volume of scrap parts. When this uncertainty on quality of the AM parts is combined with the post-processing costs and the high initial investments for facilities and training, it results in a vicious circle, where high costs make AM less appealing for industrial solutions, which in turn keep costs high.

Luckily, the foreseen advantages of AM are so overwhelmingly significant that the push to industrialize AM solutions is inevitable. A fundamental element for commercializing AM components is the fulfilment of quality standards and certification requirements. Quality standards for AM are still under development; most of the work already accomplished regards the qualification of base materials (e.g. powders, or specific alloys) and manufacturing processes, and it focuses on the production phase, determining the quality standard AM components should meet to be utilized [2]. Limited research has been carried out on ensuring quality and structural integrity during the life of the AM components [3, 4]. Part of this imbalance can be explained precisely with the desire of industrializing AM rapidly. Therefore, the primary concern has been so far towards bringing reliable, high quality products to the market, leaving in-service considerations for a later moment.

Questions on how to maintain and repair AM components are starting to arise now as consequence of AM’s own success and the currently available possibility to build larger (> 1 m^3) and more integrated components. Until recently, AM focused on the production of complex, high value, and highly specialized parts, of small or limited size (for example engine components). Replacing those parts, when damaged, has been considered acceptable, despite the high value of the part and the high cost of manufacturing, due to the higher value of the system in which the AM components had been installed. Now that the push of AM technologies is towards bigger and more integrated components (for example, entire assemblies in aircraft wings), the decision between repair and replacement is more convoluted. In addition to the intrinsic part value, in the aerospace industry, larger components almost exclusively belong to the category of structural relevant and critical components, which could also be more difficult to disassemble and replace. Furthermore, in current aircraft design, such critical components are certified based on “damage tolerance” philosophy, which is radically different from a single-use, “safe-life”, approach. In order to certify components as damage tolerant, structural integrity requirements need to be fulfilled [5]. Despite AM components already being used in aircrafts, those components were not classified as critical [6], therefore not requiring any structural integrity assessment; consequently limited or no work has been performed on the principles of structural integrity of AM components in aerospace applications.

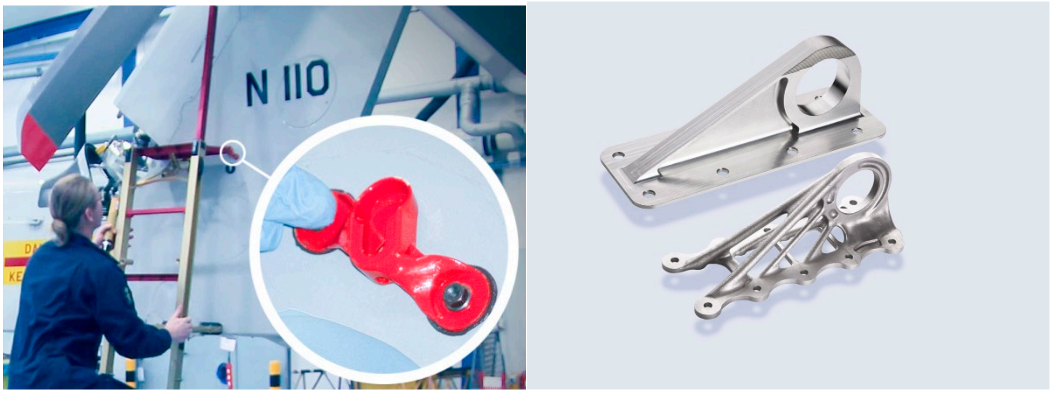

Figure 1: Examples of additively manufactured aeronautical components: ladder bracket for NH90 helicopter (left, Image credit: NLR [6]) and Airbus A350 XWB design (right: traditional design (top) versus optimized design (bottom), Image credit: Airbus Operations)

This paper wants to address the impact that applying current regulations regarding structural integrity, and the current methodologies to asses it, to AM components could have on the design and industrialization of AM in the aerospace business.

2 Design aspects for structural integrity in aerospace additively manufactured components

Ever since structural integrity requirements had been introduced within the aerospace certification requirements, structural integrity assessments were regularly performed in a later stage of the design process, when all major design decisions had already been defined, the static assessments completed and, in some cases, testing and production even started. This approach stemmed from the fact that design workflow mirrors the historical introduction of regulations: from initial design based on previous experience, through static assessment, to structural integrity and ending with maintenance and repair considerations. A drawback of this design workflow is that it limits the implementation of design changes necessary to mitigate possible structural integrity issues. One way to compensate for this had been to develop design and manufacturing guidelines, which could be used during the initial design to avoid the most common and predictable stress concentrations and defects. A first step to cover structural integrity for AM components could be to implement a similar set of design rules, in combination with design rules dictated by the AM process used. This is already ongoing, but there are two main drawbacks. The first one is that current structural integrity design rules are based on conventional metal design and manufacturing. This implies the size of the details is at times incompatible with the typical design features of AM components, for example, differences in hole edge distance or thicknesses (Figure 1). This drawback has already been influencing design of composite components, by applying design rules developed for different materials and manufacturing processes, which in the end generated suboptimal and highly conservative designs. A second drawback, partially linked to the first, is that some design rules have been developed based on knowledge the type and size of possible defects in conventionally manufactured metal parts. This kind of knowledge is still missing in AM. Though significant advancements have been made towards in-situ monitoring during production in order to determine what type of defects could be generated during the print (and of what size), results are far from conclusive, also due to the still existing uncertainties linked to AM processes.

As structural and topology optimization have become synonymous of design for AM in the engineering world, another option to account for structural integrity requirements is to include them when the design is generated, as constraints in the optimization process, as investigated in [7-9]. Currently the approaches are to include either design rules or a damage equivalent load as constraint in the optimization. The limitations of the first approach have been explained in previous paragraphs. The limitations of the second approach are intrinsic in the “equivalent fatigue damage” concept; fatigue is too complex a phenomenon to be comprehensively captured by “equivalent” quantities and attempts to describe fatigue in terms of “equivalent” quantities (i.e. damage, spectrum, etc.) have consistently produced unreliable results [10].

Another possibility related to design is to consider bionic design solutions. Bionic design is sometimes mistakenly considered equivalent to topology optimization. The similarities are limited to the resulting appearance of the parts (for example, compare Figure 1 and Figure 2), but the design principles generating the shapes are nowhere comparable. The essence of bionic design is to look into nature to identify solutions to problems and then apply the derived design principles to solve an engineering problem. Generative engineering has been developed to implement bionic design principles in actual structural components, as implemented by ELISE [11] in software automatically generating lightweight designs, based on design principles extracted from nature, with real time adaption to changing boundary conditions. Structural integrity constraints could be embedded in the process, in order to generate designs that automatically fulfil the requirements.

Figure 2: 3D printed Airbus A320 Auxiliary Stabilizing Point, based on Bionic Generative Design by Elise [11] (Image credit: PremiumAEROTEC)

3 Methods for structural integrity assessment for aerospace additively manufactured components

As creating design directly fulfilling structural integrity certification requirements is still a topic for research, the alternative solution is to apply existing certification strategies to AM components. Currently aerospace components can be certified based on safe-life or damage tolerance philosophies [5, 10]. In order to fulfil the certification requirements detailed in [5], inspection thresholds, locations and modes of damage, and fatigue lives need to be determined. Current (commercial) analysis methods are almost exclusively based on traditional concepts such as S-N curves, da/dN curves, stress intensity factors, and others [10]. Applying those existing methods to AM components may seem to require only minor adjustments to the workflow and the used tools, for example, by changing specific parameters and by incorporating new material data. In reality, those adjustments already represent major challenges.

Despite AM material data being continuously generated by different sources in multiple research programs, those data are rarely publicly available and still not of the same reliability as conventional alloys data. This has several explanations. First, similarly as with composite materials, in AM the final material properties depend as much on the base material as on the process that the base material undergoes. Therefore, a plain list of material properties may be of limited use, if not correlated to the base material and process parameters used, and if the process itself cannot produce the same properties consistently. This explains the considerable efforts in the areas of process certification, mentioned earlier in this paper. Second, several aspects are mixed up in the determination of the AM material data. Those data have not been acquired by testing standard coupons used for conventional material qualification. Multiple different geometries of AM samples have been considered, coupled with a variety of test-set ups [12-14]. The main reasons to deviate from the conventional testing standards are the limitation in manufacturable size due to the build volume of available printing machines, the costs involved (proportional to the size of the part), and the desire to reduce the time required to generate the material data. Despite the validity of the given motivations, the influence of the test geometries and set-ups on the material properties has been known for a long time. This applies also for AM material properties [9], limiting the validity of the produced data and making the necessity of standardized test instructions for AM more stringent.

Even when AM material data were available, the methods mentioned above still rely on specific assumptions and limitations. Some of methods are already known to over- or under-estimate lives and intervals even when applied to conventional alloys, principally because those models do not account for the entirety of the damage phenomena considered. For example, S-N curves and da/dN curves, used for fatigue and crack growth analyses, are the results of data fitting of test results performed at constant frequency, load direction, surface and environmental conditions, etc. Traditionally, to account for different conditions than tested, factors have simply been applied to the curves, shifting them to model beneficial or detrimental effects. A well-known limitation of factorizing curves is that the effect of a certain parameter may not be the same on the entire curve. In fact, the said curves are the attempts to represent in one graph completely different physical phenomena, from micro-displacements at grain level to macro-cracks, of lengths of the same order of magnitude as the component under investigation. This helps understand also the flaw in the “equivalent fatigue damage” concept, discussed in the previous section.

Another assumption widely used in crack growth analyses is to model the crack growth as starting from a defect of a specific equivalent initial flaw size (EIFS) [15]. Despite being a very sensible, thus popular, assumption, the foundation for the most used value for the EIFS is derived from one teardown programme. Several subsequent studies have proven how different materials and manufacturing processes may indicate a different EIFS value. On top of this, the average EIFS values used are comparable with the size of the details achievable in AM, thus invalidating any analysis based on that assumption.

It is also important to remark that the methods mentioned are valid when the structure can be assumed (mainly) in the elastic regime. This is already a significant limitation for conventional structures, even more when considering the small details of AM components, in which plasticity cannot be assumed negligible. Approaches accounting for plasticity have been already proposed, as those based on the concept of strain energy release rate (e.g. J-integral). The energy variable captures the phenomenological nature of damage, making such approaches more comprehensive, but less intuitive (thus still less implemented), than approaches based on stresses or crack lengths (which are easier to measure).

An alternative approach to support the certification of AM components has been proposed in [3], based on the combination of zoning considerations and probabilistic fracture mechanics. Zoning considerations have been applied to castings for several decades; as the analogy between castings and metal AM processes is well established in the AM community, applying certification philosophy for castings to AM parts follows logically. Another advantage of the framework described in [3] is that it deviates from the standard deterministic methods described above (and their limitations) and it integrates a probabilistic approach to perform the fatigue and damage tolerance assessments. In fact, despite the nature of fatigue and crack growth phenomena has been correctly identified as probabilistic, the initiation and the evolution of damage are treated as deterministic (e.g. the application of factors to model the effect of parameters). This mixed approach is questionable, especially when the support data are limited and have significant scatter, as in the case of AM material data. In such cases, agreement between a deterministic analysis and test data can be fortuitous.

Considering the overall probabilistic intrinsic nature of both structural integrity and AM, a stochastic analysis should be seriously considered for AM components, as the approach proposed in [17]. Tools for stochastic analysis are already available, but not widely used, due to unfamiliarity to probabilistic tools and lack of input data for generating the needed distribution functions.

Another non-deterministic approach to structural integrity could be the holistic HOLSIP [18]. This approach attempts to model the physics of failure in its entirety, recognizing that failure and damage mechanisms are interconnected and influenced by all time-dependent and time-related mechanisms of degradation. By supporting the development of a reliability and integrity centered design system, HOLSIP can be seen as a parallel to Design for Additive Manufacturing (DFAM) philosophy. Both strongly advocate how all (known and unknown) parameters affecting a process, whether it is damage or design, should be taken into account at all times, in order to gain the correct understanding of the behaviour of a structure (and its structural integrity, in this case) [19].

Another possible approach can be based on the model investigated for damage initiation and evolution in metallic foam detailed in [16]. When metal AM lattice structures and metallic foam are compared (Figure 3), the similarities between the two are evident, suggesting that a model which can describe damage initiation and growth in metal foam could be applied to metal lattice, or, more in general, to topology optimized structures.

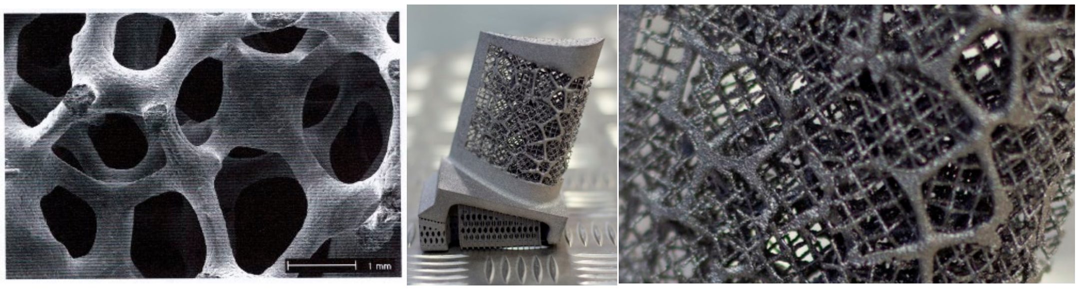

Figure 3: Similarities between metallic foam (left, SEM photo [16]) and 3D printed metal lattice (centre and detail, left, Image source: 3dprintingmedia.network)

Some final remarks should be given to the application of neural networks (whose first application to fatigue assessment dates back to the 1990s [20]) and artificial intelligence (AI) methodologies to structural integrity assessments. Currently AM in-situ monitoring is being researched as technique to identify when and where defects are formed during manufacturing process. Those data can be used as input to build a digital copy ("digital twin") of the part. By combining this digital twin with damage models, knowledge of the microstructure and the manufacturing process parameters, neural networks or AI algorithms can be trained to predicting when defects may be created and how they would evolve, thus generating a virtual real-time assessment of the structural integrity of the AM component even prior to its actual manufacturing. Until this scenario becomes reality, the initial damage map from in-situ monitoring only provides indications of (possible) locations of damage and of the process parameters which created them.

4 Non-destructive inspection methods for aerospace additively manufactured components

Fundamental to the damage tolerance certification is to develop a solid inspection program, based on the identified/predicted damage locations, on the calculated fatigue lives and inspection intervals, and on methods to find the damage and monitor its evolution. Therefore, suitable non-destructive inspection (NDI) techniques for complex AM shapes need to be identified.

Depending on the location, the type and the size of damage and of structure, inspection methods currently used on conventionally manufactured components are:

- General and/or detailed visual;
- Liquid penetrant and magnetic particles;
- Eddy current;
- Ultrasonic and/or acoustic emissions;
- CT scan and X-ray.

The same NDI techniques are, potentially, available for AM components. Unfortunately, some of NDI methods present technological limitations (e.g. accessibility or reduction of sensitivity) which might make them not suitable for AM parts [2]. Some NDI cannot be performed in-situ, but require disassembling of components, a complication with large AM components. Another complication is, as mentioned previously, that limited research has been performed on the type of damages associated with AM processes, their minimum and/or average dimensions, and the evolution of damage in an AM component. As NDI is useful only when capable of detecting damage, not having enough information about what needs to be detected makes the selection of an appropriate NDI method difficult.

Within the aerospace regulations [5], without the possibility to perform inspections, the only possible certification philosophy would be safe-life. Limited research is currently ongoing to address those challenges, as NDI in AM is mainly focusing on production quality checks, during manufacturing, as detailed in the previous section. A possibility to allow certification based on damage tolerance philosophy, while exploiting the advantages of AM, is to integrate structural health monitoring (SHM) system in the AM components, allowing real-time monitoring of the performance of the part and identifying the need of repairs, when performance indicators fall below a specified threshold. Unfortunately, SHM comes as a weight penalty against the lightweight character of AM components and requires handling large amount of data, thus requiring a specific cost/benefit assessment per individual AM component.

5 Structural integrity assessment of an additively manufactured aerospace component: a mental exercise

In order to summarize all the considerations of this paper and to give a better idea of the actual workload and challenges which certifying AM components could entail, a mental exercise is presented in this section: how to prepare an inspection program for structures as shown in Figure 4?

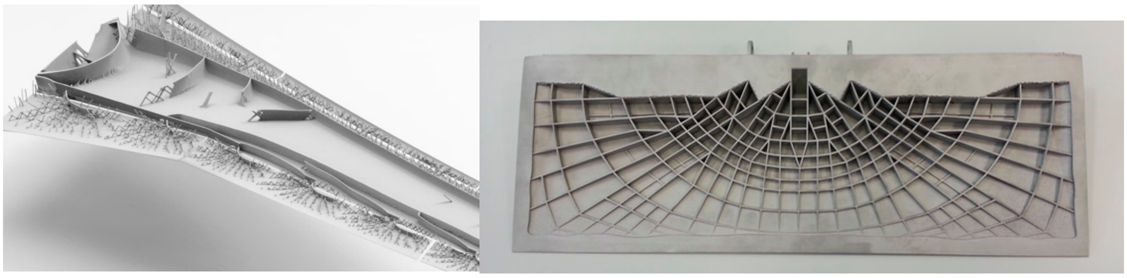

Figure 4: Examples of conceptual designs of integrated aerospace structural components to be manuafctured by AM technologies: complete wing (left, [21]) and spoiler (right, Image credit: Airbus Group)

The structures shown in Figure 4 are only two of a myriad of available examples of AM conceptual designs and prototypes. Whether they represent a realistic expectation of what AM will realize is debatable; more realistically, they do present design details that could be implemented in smaller structures or components.

When setting up the structural integrity assessment of such structures, a first, blatant, observation is about inspectability: how can those structures be inspected? While disassembling the spoiler is doable, inspecting a complete wing needs a radical new approach in order to perform NDI, as current in-situ NDI methods are limited and accessibility to such complex structure is challenging. The locations of defects can be known from in-situ monitoring during manufacturing. Manufacturing defects, though, do not cover all potential damage initiation locations; additional stress concentrations can be identified, for example via finite element models of the part, but also based on engineering judgment.

Assuming a valid NDI technique can be found, fatigue lives, inspection thresholds and intervals need to be determined. Considering the size of a complete wing, certification based on safe-life approach is not realistic, mainly due to manufacturing costs (setting aside any other consideration). Based on its size, the spoiler could be certified as safe-life component; nonetheless costs, but also sustainability, considerations shall be weighted in the decision over the certification philosophy. Sustainability has not been mentioned earlier in this paper, but reduction of waste and energy consumption related to manufacturing and in-service operations is predicted to become a strong constraint also for aerospace industry. All those considerations are pointing towards certification based on damage tolerance philosophy.

Independently on the certification philosophy, AM material data is needed. Considering the size of the discussed structures, it could be speculated that those are multi-material structures, or that the material properties have been optimized throughout the structure (taking advantage of known anisotropy of AM material properties), as done in composite structures. Those optimizations make difficult to use material data based on AM coupons. Virtual material qualification may be inevitable.

After having identified critical locations and ensured the availability of material data, theoretically a traditional damage tolerance assessment can be performed, by performing a crack growth analysis and assuming an EIFS crack at the critical location. Considering the size of the AM details (which could be as low as 0.2 mm with selective laser melting process, for example), assuming the conventional EIFS (corresponding to 1.27 mm) in one of the integrated stiffeners of the spoiler could mean that the crack would have no possibility to grow, causing early failure of the stiffener. Following the load redistribution to other part of spoiler, more failures could occur, either due to the presence of more defects (widespread fatigue damage) or for having reached ultimate load. In conventional structures, load redistribution paths are designed accurately, to ensure that the main failure could be identified prior to secondary failures, avoid catastrophic consequences. In AM components, load redistribution has not yet been considered during the design phase. Considering the size of the AM details, the risk is that the first (local) failure could initiate a chain of local failures, exponentially spreading to the entire component, as described in the damage model for metallic foam [16]. With knowledge of actual AM defects, a better estimate of EIFS for AM components can be available, improving the results of the structural integrity assessment, but without incorporating load redistribution strategies to ensure that the component would not experience a catastrophic failure, certification of such component as damage tolerant will not be possible.

Having ruled out a traditional certification approach covering safe-life and damage-tolerance philosophies, the necessity of new structural integrity methods and approaches is evident if AM structures, as those shown in Figure 4, are to transition from conceptual renderings to real structure in flying aircrafts.

6 Conclusions

This paper highlights how to bring successfully components manufactured by AM technologies to the aerospace market the current structural integrity requirements need to be taken into consideration. Those requirements may turn out to be the limiting factors to achieve a successful industrialization of AM. The current regulations, and the approaches implemented to fulfil them, are based on conventional materials and traditional design philosophies. New thinking needs to be brought into established methods for structural integrity, in order to maximise the benefits AM technologies can bring to the aerospace industry. It would not be the first, or the last, time that structural integrity requirements, and consequently the methods used, are questioned, adjusted and improved to account for new technologies or findings [22]. Unfortunately, the changes in requirements occur at a slower pace than the development of the technology. The aim of this paper is to bring attention to the topic of structural integrity in AM components, hoping to create the conditions to discuss structural integrity requirements at an earlier stage of the industrialization of AM. Without incorporating the correct structural integrity philosophies in AM, the risk is to repeat mistakes made during the development and introduction of composite components, overdesigning AM components, and therefore making a new promising technology less appealing in terms of weight saving and manufacturing costs.

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