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Cost efficiency, integration and assembly of a generic composite aeronautical wing box

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ABSTRACT

This paper presents a cost-efficiency study of part integration with respect to reduced assembly effort within aeronautical composite structures. The study is performed through the use, and continuous improvement upon, a previously developed cost model. Focus are on the assembly and basic inspection a wing box, part of a section of a full wing, where involved parts are all considered to be manufactured from carbon fibre reinforced plastic (CFRP). Treated cases range from traditional, mechanical joining, to high integration either through co-curing or co-bonding of composite structures. The outcome of presented cost study shows that increased integration decreases the overall production cost of said considered wing box. In general it is shown that co-curing or co-bonding reduces a number of cost-expensive assembly steps in comparison to mechanical joining.

1. Introduction

Composite materials are frequently used in the aeronautical industry in order to construct weight-efficient structures. To further increase weight-efficiency the current trend within aeronautics is to build larger, more integrated, composite structures that combines several separate parts into one. A similar trend is reflected by premium automotive producers where increased integration is shown through use of for example carbon composite monocoque structures [1]. However, with increasing market competitiveness within lightweight structure, weight-efficient structures also need to be cost-efficient. As such, the value of integration needs to be discussed. A previous cost study of the difference between an integrated structure and a mechanically bonded structure [2] shows that integration proves less costly. In contradiction, some propose that less integration decreases cost [3], likely a motivation behind the release of BMW i3, a carbon composite car design joined through automated bonding [4]. Indeed, the value of integration is not universal, but rather a function of application, production volume and choice of manufacture and assembly process. Here, application of interest is aeronautical structures produced at low to medium annual volumes. To further investigate the value of integration in such a scenario, this paper analyses the production and inspection cost of a composite aeronautical wing box with different levels of integration using, and further improving upon, a previously developed cost model framework [2,5]. The production cost for manufacture, assembly and standard non-destructive testing (NDT) for four different cases is studied in an attempt to find generic trends and discuss cost efficiency of each scenario. The four scenarios involve different levels of integration, using co-curing, co-bonding and mechanical fastening in different combinations throughout the wing box structure and study cases.

2. Strategic assumptions

The study focuses on high-performing structures made from carbon fibre reinforced epoxy prepreg. The application is low- to medium-volume production, ranging from 50 to 1000 units per year, where production techniques used are reflective of what exist within aeronautical production today with high amount of manual industry work as the norm. To that end, part manufacture is assumed to be done through manual layup and assembly techniques are dominated by manual operations. Co-curing, co-bonding and mechanical fastening are studied with the latter representing a more mature process while the former two are

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under development. It is important to note that less mature techniques such as co-curing and co-bonding imply larger costs through learning and increased amount of rework. In the current study however, learning is disregarded in order to treat the methods equally in a full production scenario. In addition costs due to rework are regarded future work and it is assumed that comparable level of assembly quality is achieved within each assembly strategy. Reoccurring non-value added operations are furthermore assumed to be of similar size and are disregarded. Co-curing and co-bonding is within the scope of this paper considered to be assembly methods, rather than part manufacturing methods. The cost of co-curing or co-bonding is therefore directly compared to the assembly cost of traditional mechanical assembly.

3. The cost model

Used cost model in this paper is based on previous work [2,5]. In short, developed cost model calculates the production cost of a structure by summarizing the costs of each process step involved in chosen manufacture and assembly method. Estimations of process step costs are found through extrapolating geometry complexity, leading to certain producibility limitations and production lead times. The hierarchy of developed cost model is given in Fig. 1, where scope and flow of new work presented herein, that of assembly, is illustrated within the context of previously developed framework. Cost contributes are investment, labour, facility space, electricity and tooling, which are moulds and jigs. Previous work included the typical aeronautical manufacturing methods manual layup (ML), automatic tape layup (ATL) and automatic fibre placement (AFP). Current paper implements structure assembly; co-curing, co-bonding and mechanical joining as well as required inspection, meaning non-destructive testing (NDT). Some manual part manufacture steps such as demoulding, mould cleaning and part bagging has been previously excluded, but are included in the current study and are therefore described within this paper.

3.1. Common production setup

As the effect of assembly is the focus of this study, manual layup of prepreg material is chosen as a common manufacturing approach. Studied full process of a manually placed part is exemplified in Fig. 2. The prepreg raw material is cut and draped in a clean tool. The part is then either bagged, cured and tested in the case of the production of a fully cured part or simply demoulded and stored for the production of a wet part to be placed in a larger integrated structure during assembly. Marked, dashed, process steps are removed in the case of the production of a wet piece. The prepreg cutting, layup with connection to part complexity, curing and final trimming is further described in previous work [5]. The part cure is carried out within an autoclave and is considered to have a full curing cycle of 8 h.

Different assembly strategies are studied within this paper, however, some general considerations apply. Defined assembly processes are governed by manual work, this makes the formulation of general estimation models challenging, both in the case of production times and general influence of structure complexity. As such, production times used within this study are in several cases conservatively assumed based on published data or communication with industry where possible. Also, the influence of complexity on the assembly of a structure is only applied within the step of NDT. Increased NDT complexity is herein simplified to be given by the fact that a part of higher complexity has a larger surface area and outer perimeter. Details regarding process costs involved in each joining method are described more in detail in the following sections.

3.2. Co-cured assembly

Considered co-curing process used within this paper is illustrated in Fig. 3. The co-curing process involves the use of wet parts. The largest wet part, such as a wing skin, is kept within its part drape tool and positioned on the floor. Wet parts to be integrated in the floor-based skin, such as stringers or spars, are loaded into a jig with internal support tools and compacted if necessary. The jigged parts are then positioned and compacted onto the stationary floor-based skin through the built-in mechanics of used jig. The jig finally releases the parts and the semi-compacted structure is rolled into an autoclave for curing. Full curing cycle is 8 h long, same as assumed for individual part curing. The cured structure is demoulded, trimmed and inspected before being placed in final storage.

3.2.1. Loading, positioning and dismounting

The loading and positioning of a part within a larger structure is within aeronautics often done manually and is thereby highly dependent on operator, plant setup and ease of assembly. With such high variability, the time to load and position is conservatively estimated to take at least 30 min per part to be placed. The same assumption is used for when a part is dismounted. If one part dimension is larger than 1 m, the number of operators used within the step is increased and calculated as

$$no_{operators} = 1 + \hat{d_{part}}$$

where $\hat{d_{part}}$ is the largest part dimension.

Manual positioning still makes use of assisting equipment which lifts, measures or guides the positioning. Assisting systems used include ceiling cranes [6] and manual measuring tools and jigs [7]. Positioning equipment considered herein is traditional and only includes assisting ceiling cranes, as well as positioning jigs. The cost of a ceiling crane starts at 1 M€ [6], and its use is limited to fully cured, larger parts, here at dimensions of 1 m^2 and larger. If a part is wet, the process is fully manual and only makes use of jigs.

3.2.2. Fixtures and jigs

Fixtures and jigs are one-time acquisitions that are tailored to a specific assembly. Their cost must therefore be covered purely by the assembly at hand. The cost of an assembly jig is challenging to estimate and is a function of carried structure weight, size and complexity. It is concluded that a reasonable jig cost can be determined from the jig weight together with its development effort according to

$$Cost_{jig} = b + Wke$$

where b is a constant representing the base cost that reflects that also a smaller, less complex jig, requires development time and effort and thus also cost. The jig weight, W, is here simplified to only include that of the actual assembly frame according to Fig. 4 and is dimensioned from weight and area of carried structure under the assumption that the frame bars are hollow and of a square cross-section. The frame cost factor k is set to 30 €/kg which is representative of a Swedish workshop item produced from a combination of standard parts [7]. To account for further features, such as that of adding turning and translation devices for positioning of wet parts when co-curing, the engineering factor, e, further influences the frame cost. With an engineering factor of 1, approximate cost curves for a jig holding a CFRP, aluminium or steel plate of 50 mm thickness are exemplified in Fig. 5. The jigs are dimensioned with respect to an allowed deflection of 0.1 mm.