2019-01-1882 Published 16 Sep 2019

Optimization of Automated Airframe Assembly Process on Example of A350 S19 Splice Joint

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Citation: Lupuleac, S., Shinder, J., Churilova, M., Zaitseva, N. et al., "Optimization of Automated Airframe Assembly Process on Example of A350 S19 Splice Joint," SAE Technical Paper 2019-01-1882, 2019, doi:10.4271/2019-01-1882.

Abstract

The paper presents the numerical approach to simulation and optimization of A350 S19 splice assembly process. The main goal is to reduce the number of installed temporary fasteners while preventing the gap between parts from opening during drilling stage. The numerical approach includes computation of residual gaps between parts, optimization of fastener pattern and validation of obtained solution on input data generated on the base of available measurements. The problem is solved with ASRP (Assembly Simulation of Riveting Process) software. The described methodology is applied to the optimization of the robotized assembly process for A350 S19 section.

Introduction

The assembly of an airframe is done by means of riveting, that implies multiple drilling and reaming operations. In the process of assembly, the temporary fasteners are installed into the holes for permanent rivets to join the parts and prevent the gap opening while drilling and reaming. As it is noted in [1], the presence of residual gaps between joined parts may cause hole eccentricity and swarf ingestion between the mating surfaces during drilling, which eventually effects the fatigue life of the final product. Therefore, it is critical to install a sufficient number of temporary fasteners in certain stages of the assembly process. On the other hand, the installation and further removal of fasteners is the time-consuming process. In addition, as it is mentioned in [2], in case of automated assembly, the presence of large number of installed temporary fasteners complicates the navigation and positioning of drilling robot. Therefore, the number of fasteners should be kept reasonably low yet sufficient to minimize gaps between parts on certain stages of assembly process (drilling, reaming).

The residual gap between parts after fastening is a function of both the initial gap and the positions (pattern) of fastening elements. The sequence of temporary fastener installation does not vary from one airframe to another in the assembly line. However, compliant parts exhibit different dimensional variations, and the initial gap between assembled parts changes from one aircraft to another in the series within the allowed assembly tolerances. Consequently, the initial gap field between joined parts is generally unknown during the numerical optimization of assembly process.

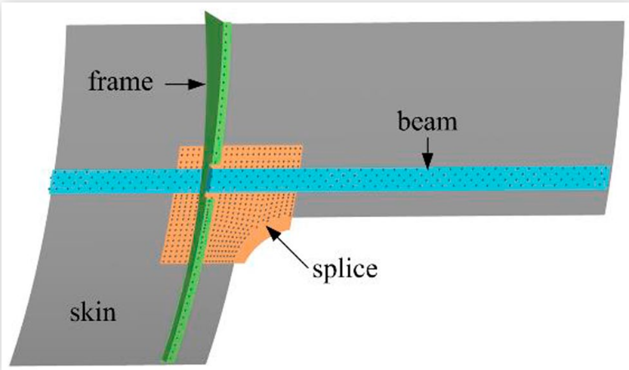
All these features make the problem of fastener pattern optimization very specific, and its consideration requires the use of special tools. The numerical analysis was carried out with adopted version of the ASRP (Assembly Simulation of Riveting Process) software complex [3]. The ASRP is designed for simulation and optimization of the assembly process for large scale compliant airframe parts (see [4, 5, 6, 7, 8, 9]). ASRP combines variation simulation analysis with contact problem solving [10, 11, 12, 13, 14].

Assembly Procedure

We consider one stage of the section S19 assembly. Section S19 (see Fig. 1) is the rear element of fuselage. The considered assembly stage involves the joining of the splice to the S19. The location of splice is framed in Figure 1.

FIGURE 1 The A350 S19 section (www.icas.org) and the considered junction area (in rectangle).

FIGURE 2 The assembly scheme (inside view of the fuselage).



The splice is positioned against the fuselage skin, beam and frame, as it is schematically shown in Figure 2[1].

The splice is joined with fuselage skin, beam and frame by installed temporary fasteners, shown as large black circles in Figure 3.

The drilling robot sequentially reams predefined holes for forthcoming installation of final rivets, as it is illustrated in Figure 3, where reamed holes are marked by green circles. In certain stage of reaming process, the drilling force contributes to the opening of the gap between parts close to the drilling point (see Figure 4). It can lead to eccentricity of holes and poor quality of final assembly.

The special technology requirements are imposed on the maximum allowable gap opening: the gap needs to be within 0.3 mm during the reaming operations. This requirement is met by positioning of temporary fasteners. However, presence of many fasteners (in particular, in vicinity of reamed holes) significantly complicates the navigation of drilling robot. Therefore, it is needed to minimize the number of installed temporary fasteners, taking into account the requirement on maximum allowable gap. The fasteners can be installed to any empty hole. Such holes are shown in Figure 3 by small black circles.

FIGURE 3 The positions of drilled holes (green) and temporary fasteners (black).

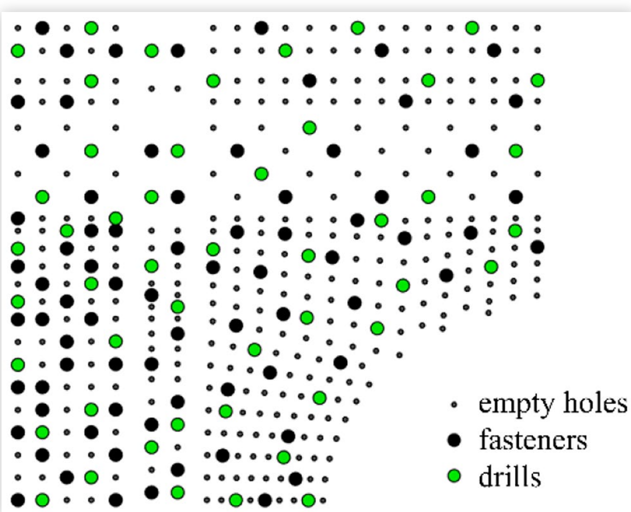
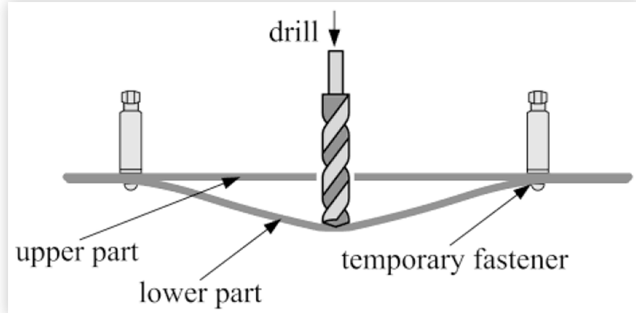


FIGURE 4 Gap between two parts opens during drilling.

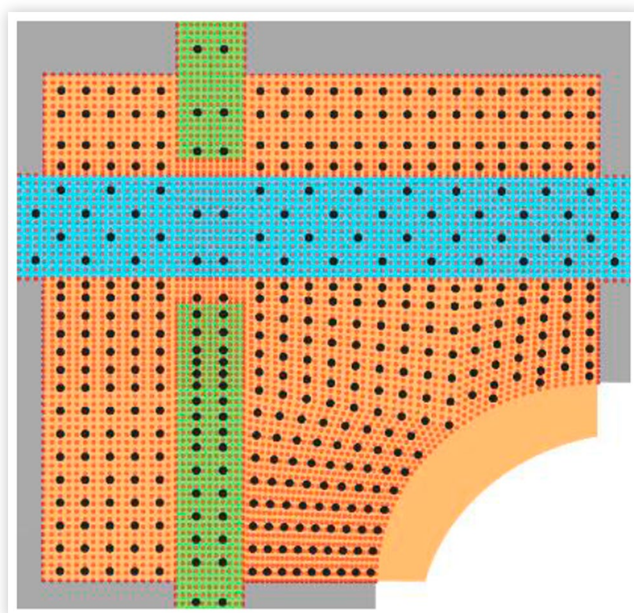


Assembly Process Simulation

For the assembly process simulation and optimization, the contact problem is solved to determine the residual gap in the assembly loaded by the forces from fastening elements and drills. Here we give only the main idea of the method implemented in ASRP software complex, the detailed description of numerical algorithms can be found in [5].

For the considered splice joint model there are four parts in the assembly (Fig. 2). The zone of possible contact between parts is denoted as the junction area. The finite element nodes in junction area (Fig. 5) are denoted as computational ones.

FIGURE 5 Computational nodes (red).



[1] Since it is impossible to disclose the real A350-900 models and details of the assembly process, we use the artificial models and fastener arrangements that resemble the actual ones for illustrative purpose. Similarly, all the numerical values, given in this paper, in particular related to assembly requirements and specifications, have been changed.

With the help of finite element modeling technique and substructuring we formulate the contact problem in the reduced discrete variation form [15]:

$$\min_{N \cdot x \leq G} \left(\frac{1}{2} x^T K x - f^T x \right). \quad (1)$$

Here x is the vector of normal displacements in computational nodes, K is the reduced stiffness matrix of finite element system, f is the vector of applied loads (e.g., from fastening elements or drills), N is the linear operator which defines the contact pairs and G is the initial gap vector that is the initial distance in normal direction between nodes that may come to contact. Matrices N and K_C describe such qualities as overall topology of junction, mechanical properties of parts and fixations of parts in the assembly jig.

The number of nodes in a finite element model is typically much bigger than number of nodes in the junction area. Thus, the dimension of the reduced problem (1) is much smaller comparing with original finite element model.

Optimization Problem and Optimization Algorithm

The optimization problem is to minimize the number and find more appropriate positions of temporary fasteners (find new fastener pattern) so that the gap between parts in drilling stage does not increase compared to the initial pattern. The initial gap between all joined parts is set to zero, thus only gap caused by drilling is considered. All fastened holes are of the same diameter and all fastening elements are installed with equal force.

There are 48 drills (i.e., sequential reaming operations), 76 installed temporary fasteners and 283 empty holes in the considered assembly model. We note that for each calculation of residual gap, the contact problem (1) is solved, that takes several minutes of computational time. Therefore solving 48 problems on a personal computer for each pattern change is not an option. The task-parallelization on supercomputer was used to reduce computational time.

At first, we calculate the residual gap in each drilling point one-by-one with given initial fastener pattern (Fig. 2). Due to the technology requirements, the gaps in each drilling point needs to be within 0.3 mm, but simulation shows that this condition is violated in several drills, especially in ones close to the splice edges (Fig. 6). In total we have 19 drills with gap bigger than 0.3 mm. We denote them as violated drills (see Fig. 6b).

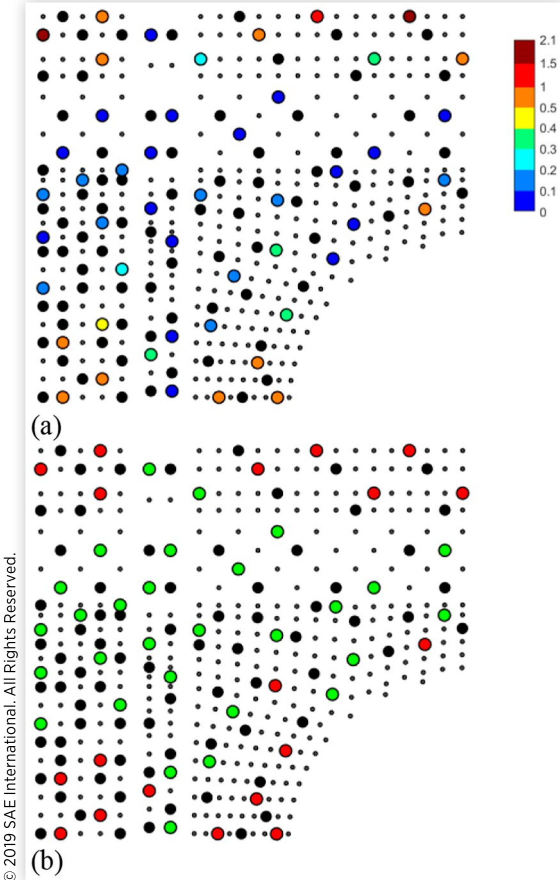
The temporary fastener pattern optimization consists of two stages:

1. Reduce the number of fasteners in junction area keeping the number of violated drills.
2. Rearrange the fasteners (change their positions within fixed set of admissible holes) to minimize the sum of gaps in all drilling points.

These steps are repeated until there is no more improvement in the pattern.

As the first step, we try to remove fasteners one-by one, calculating the residual gap in drilling points for each new pattern modification. As a result the 58 fasteners are left in

FIGURE 6 Residual gaps in drilling points (a) and violated drills marked by red (b).



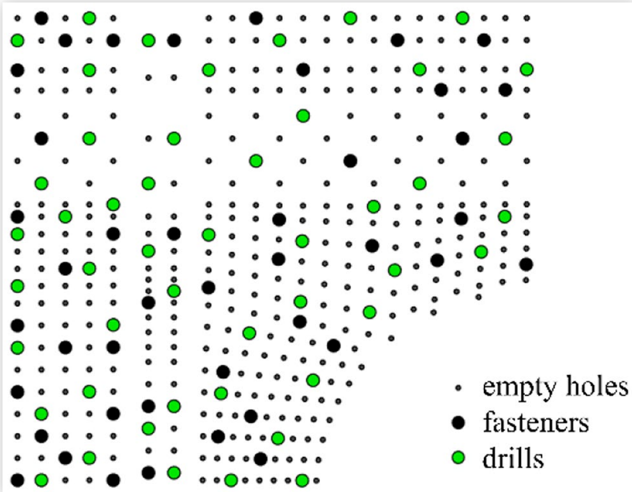
the pattern (18 fasteners are removed from junction area) with the same number of violated drills.

For the second optimization step, the Local Variations Algorithm (LVA) is used. LVA is an iterative exhaustive search of optimal position for each fastener one-by-one among predefined holes [13].

Let us denote the fastener pattern (vector of hole numbers where fasteners are installed) as P and the initial pattern as P_0. The LVA for minimizing function $F(P)$ is as follows:

Initialization: $P := P_0$, *Iteration* := 1.
Repeat
  Set *Progress* := false;
  For each hole i with installed fastener
    For each empty hole j
    Obtain pattern P^* by moving fastener from hole i to hole j;
      For each initial gap of the cloud
        Calculate the resulting gap with fastener pattern P^*;
      End for
      Evaluate $\Delta F = F(P^*) - F(P)$;
      If $\Delta F < 0$, keep the new pattern $P = P^*$, set
        Progress := true;
    End for
  End for
  Iteration := *Iteration* + 1;
Until *Progress* = false (no $F(P)$ improvement in one iteration).

FIGURE 7 Fastener pattern after 3 reduction-optimization steps.



Iterations continue until the algorithm has converged to some local optimum. In our case the function $F(P)$ is the sum of residual gaps in all 48 drills. For the optimized reduced pattern sum of gaps decreased from 18.63 mm to 15.25 mm. After rearrangement fasteners are more uniformly distributed over the junction area.

Reduction and optimization steps are repeated two more times until a suboptimal solution is obtained. We end up with 53 fasteners in the pattern (in junction area) and 19 violated drills, sum of gaps in all drilling points during drilling stage is 17.13 mm (for the initial pattern 16.77 mm). The optimized pattern is presented in Figure 7.

Fastener Pattern Verification

For the fastener pattern optimization we assume that the initial gap between joining parts is zero. It corresponds to situation when the joining parts fit perfectly and the assembly process is ideal. However, in practice the joining of compliant parts is coupled with different geometrical and dimensional variations. Thus, some non-zero initial gap appears between assembled parts. This gap has stochastic behavior and affects the subsequent displacements of parts during fastening and reaming.

To assure the robustness of the proposed fastener pattern, it should be tested for assembling of non-ideal parts. The common method for such analysis is variation simulation. In our case the variation can be modeled as random initial gaps, thus we use the Monte-Carlo simulations to predict the stochastic outcome of assembly. The detailed procedure of pattern verification is described in [11,14]. It implies that the big amount of different initial gaps is generated; then the fastener pattern is tested for each initial gap and the gathered results are analyzed with statistical methods.

The general model for initial gap generation is described in [11]. According to this methodology the stochastic initial gap can be modeled as Gaussian random filed. The choice of type and parameters of this field should be based on the available measurements.

FIGURE 9 Isotropic (left) and anisotropic (right) Gaussian random fields.

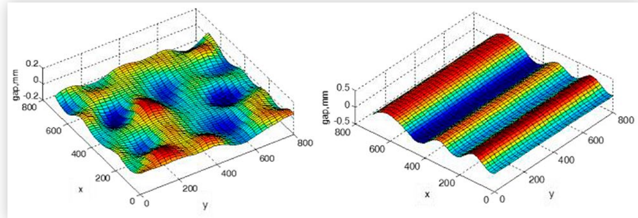
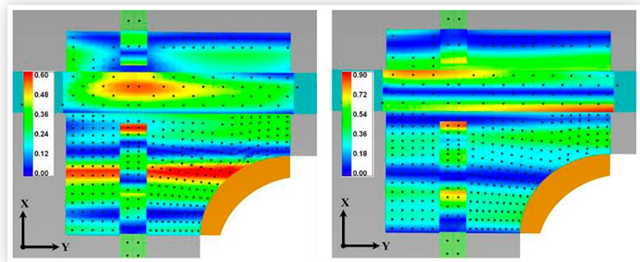


FIGURE 10 Generated initial gaps.



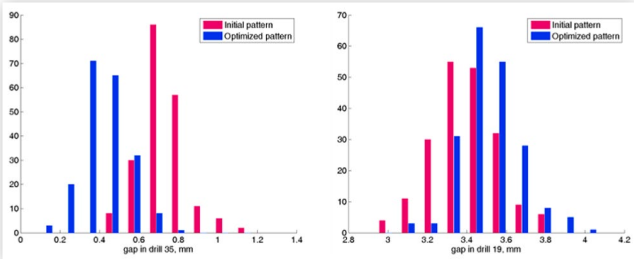
For considered A350 S19 splice assembly the initial gaps between parts is measured on the previous step of the assembly process before drilling. These gaps were measured on the borders between all the joining parts. For technical reasons the set of available data consists of only several measured gaps. The analysis of measurements shows that the initial gap has anisotropic behavior as in X-direction it varies more than in Y direction. In such case the initial gap can be modeled as the anisotropic Gaussian random field. In Figure 9 the examples of isotropic random field (most common type of random fields) and anisotropic field are shown. Using the model with anisotropic filed, the cloud (a set with big amount of samples) of initial gaps is generated. Some examples of generated initial gap for A350 S19 assembly is shown in Figure 10.

The solving of contact problem (1) for each initial gap from the cloud gives us the set of residual gaps that shows how the fastener pattern and the presence of initial gap influence the gap opening during drilling. Based on the set of residual gaps we can estimate the distribution of the gap values in each drilling point. In Figure 11 there are examples of obtained histograms for initial and optimized fastener patterns. Obtained results show that the change of pattern shifts the range of gap values, and for different drills the gap either decreases or increases. However, these shifts are not critical, and even for the most problematic drills the gap values do not differ significantly.

Summary/Conclusions

The optimization of airframe assembly process by minimization of number of installed temporary fasteners is considered in the paper. The study is carried out by means of numerical

FIGURE 11 Examples of gap distributions in drilling points for initial and optimized fastener patterns



simulation on the base of available results of measurements. An example of automated joining of the splice to the section S19 of A350 was considered. Implementation of the developed optimization approach allows to reduce the number of temporary fasteners by 30% without significant loss of quality.

The next logical step in implementation and development of describe above optimization technique is its combination with metrological equipment and navigation systems for automated tools (for drilling, fastening, machining). Resulting intellectual assembly system will be capable to optimize the assembly process exclusively for each item.

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Acknowledgments

The results of the work were obtained using computational resources of Peter the Great Saint-Petersburg Polytechnic University Supercomputing Center (www.spbstu.ru).

ISSN 0148-7191