Fatigue Considerations in the Development and Implementation of Mechanical Joining Processes for Commercial Airplane Structures

Robert Jochum[1](✉), Antonio Rufin[1], Tanni Sisco[2],
and Frederick Swanstrom[3]

[1] Structural Damage Technology, Boeing Commercial Airplanes,
Everett, WA, USA
Robert.L.Jochum@Boeing.com
[2] Product Development, Boeing Commercial Airplanes, Everett, WA, USA
Tanni.Sisco@Boeing.com
[3] Advanced Developmental Composites, Boeing Commercial Airplanes,
Seattle, WA, USA
Frederick.M.Swanstrom@Boeing.com

Abstract. The durability of commercial airplane structures is strongly influenced by build quality and the extent to which assembly processes can be controlled such that the fatigue quality is consistent with that assumed in the design throughout the production life of airplane programs. New developments in assembly technology and the continual quest for manufacturing cost reductions, as well as rising production rate pressures are translating into new, often non-traditional parts and build processes being applied to commercial airplane products. This technological evolution can only take place by exercising close coordination between the structural and manufacturing engineering functions in planning, evaluating, and bringing these parts and processes safely into production. Described in this paper are some of the new processes being used at Boeing Commercial Airplanes to produce metallic and hybrid (composite + metal) assemblies for large commercial transports, viewed from a broad structural engineering perspective. The discussion focuses on two specific mechanical joining technology thrusts: (1) One-up assembly (OUA) and process automation, and (2) assembly using pre-drilled holes at the part fabrication (detail) level. A number of case studies are outlined and considerations such as process selection, control, and qualification, and fatigue characterization are highlighted. This includes a discussion of the trade-offs in fatigue capability between traditional and new methods, including some quality issues that can arise with the new approaches.

Keywords: Fatigue · Mechanical joints · One-up assembly · Assembly using fastener holes · Boeing

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A. Rufin—Structural Damage Technology, Boeing Commercial Airplanes (Retired).

A. Niepokolczycki and J. Komorowski (Eds.): ICAF 2019, LNME, pp. 215–227, 2020.
https://doi.org/10.1007/978-3-030-21503-3_17

1 Structural Build Processes and Fatigue

Years of empirical evidence show that the fatigue performance of mechanically joined assemblies is highly sensitive to build parameters and quality. Key parameters include hole quality, hole fill, and joint clamp-up.

Figure 1 shows a sample cross section of a titanium hex-drive fastener installed into a match drilled, interference-fit hole in an aluminum joint. These types of permanent installations are very common in aerospace products. The aluminum parts in this example have finishes applied (in addition to shot peening, if needed) at the detail part level; that is, prior to final drill and ream. At that stage, the parts are clamped, the hole drilled and reamed (if reaming is called out), often with the aid of a drill jig or tool, then separated to be cleaned and deburred, and finally re-stacked for bolt installation and final torque application to the nut or collar. In this example, the co-linearity of the holes attained by drilling and reaming as a stack (except, on occasion, for the possibility of some movement as the parts are separated, cleaned, and deburred and then brought back together) allows for interference fit to be used, which increases relative fatigue performance (Crews 1975 and Boeing data, see Fig. 2). If hole coldworking is required, the corresponding additional process steps usually take place during assembly, and the same requirements concerning hole and joint cleanliness apply. Similar considerations apply to riveted assemblies as well, with the obvious exception that riveted joints are typically only drilled (not reamed).

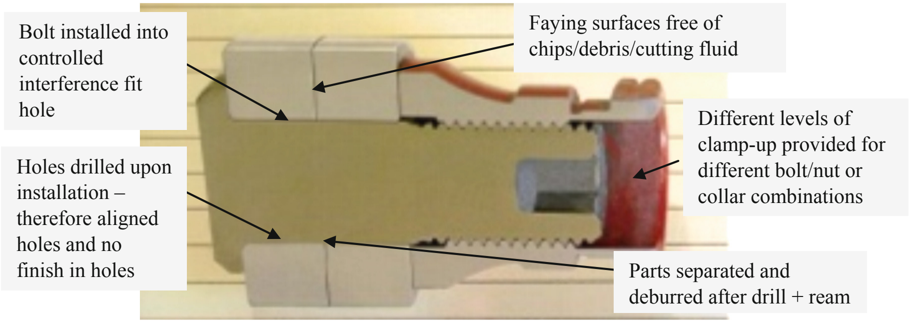

Fig. 1. Example bolt installation in aluminum joint

‘Deburring’ is the term used in industry to denote the physical removal of burrs, which for holes can be generally described as a rough edge created by the process of drilling or reaming, located where the hole meets the surface of the part, on both the drill (or reamer) entry and exit sides. Burrs also often project out of the hole, and can, in extreme cases, contribute to the formation of interfacial gaps or impede fastener seating, among other issues. They furthermore also often adversely impact fatigue life, by acting in effect as local stress concentrations. As a result, it has long been common practice in industry to remove burrs, typically by hand (Gillespie 1999).

In addition to hole quality, fastener installation parameters can significantly influence the fatigue performance of a joint. Figure 2 shows an example of the standard

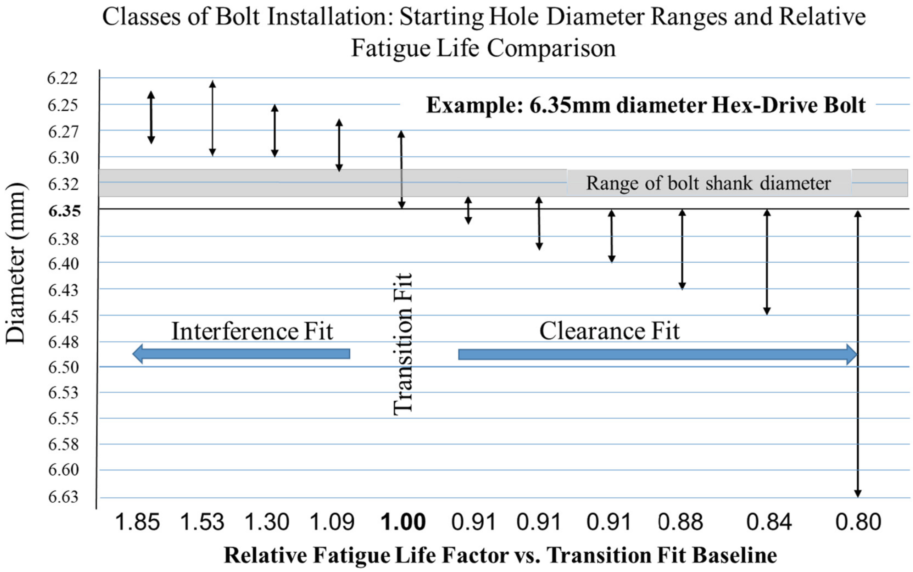

Fig. 2. Classes of bolt installation: bolts installed in aluminum with relative fatigue life factors vs. a transition fit baseline (Boeing data)

starting hole size ranges used for different classes of bolts in typical aluminum structural installations. Joint fatigue testing consistently show a trend of increasing fatigue performance (moving from right to left in the figure) for higher levels of hole filling (Crews 1975). An approximate life ratio is provided in Fig. 2 – using transition fit as a reference point, using Boeing data.

Clamp-up is another fastener installation-related item that can affect joint durability. Clamp-up controls the degree to which load is transferred by friction rather than fastener bearing, and usually has a beneficial effect on fatigue (Minguez and Vogwell 2006) and (Benhaddou et al. 2018), as it results in a gradual transmission of the load across the joint, rather than a more damaging direct bearing of the fastener against the hole, unless, of course, the joint constituent materials are sensitive to fretting, in which case, some or all of this benefit can be negated.

Why is this all important to the structural engineer? Because in addition to the obvious design and cost trade-offs, the process and parts used to produce the joint, and the degree to which that process can be controlled over time in production will directly impact the durability of the structure and its ability to meet the intended life goals at an acceptable level of reliability (see, for example, Moore 1978). This requires the stress analyst to work closely with the assembly specialist or manufacturing engineer at all stages of production to ensure that the right process is used for the application, that its limits or potential pitfalls are understood and properly characterized, and that the process is sufficiently controlled over the production life of the airplane.

2 Commercial Airplane-Specific Design Considerations

Economic design service objectives of Boeing commercial airplanes, representing a minimum of 20 years of predicted operation, range from 10000 flights for 747 aircraft flying in long-range service, to 75000 flights for a 737 model operating in a short mission regime. During that time, the structure is expected to maintain a high degree of reliability, meaning that the occurrence of fatigue cracks has to remain below a certain target level that, for primary structure, is typically less than one percent, with a high degree of confidence (Chisholm et al. 2015). Along with these relatively stringent goals, are operating loads that are relatively low with respect to yield and ultimate strength capability. For example, for the wing lower surface, a critical limit load case is a 2.5 g symmetric up-maneuver, which results in an ultimate load case of 1.5×2.5 g = 3.75 g when the required factor of safety is applied. On the other hand, typical operating maneuver loads are in the range of only 1 g $\pm$ 0.2 g to 0.4 g. These values demonstrate that operating loads are typically only 30–40 percent of ultimate loads. For metal structure designed to this load environment, it is uncommon for details like holes to experience local yielding during typical flight operation. This means that for commercial airplanes structures, not only are life goals high, but the potentially forgiving effects of high stresses and occasional overloads are absent, making the structure uniquely sensitive to build quality. By way of contrast, military fighter aircraft target lives are seldom greater than 10000 flight hours, at only a few hours per flight on average, though with flight loads that can approach structural limits.

3 The Quest for Quality and Production Efficiency

Figure 3 shows a few of the many possible types of hole quality issues that can arise in production with drilling and assembly processes. The picture on the left shows a joint with insufficient clamping during drilling, which allowed large metal chips and other debris to be trapped into the interface. Chips trapped in the interface of high load transfer parts can affect joint clamp-up and also can cause fretting fatigue. The image on the right shows a large burr formed during drilling, along with some “rifle marks” in the bore of the hole. This poor quality can be due to either improper drilling parameters (feed, speed, cutting tool) or by dull or damaged cutting tools. Burrs and rifle marks can create local high stress concentrations capable of triggering premature fatigue cracking. Other forms of drilling-induced damage caused by poor, insufficiently controlled, or inadequate practices can have even more dire structural fatigue consequences (see, for instance, FAA Lessons Learned 2019). With rivets, improper tool alignment or insufficient rigidity with machine riveting, or a torque tool inadvertently going out of calibration in a bolted joint installation can likewise have an unforeseen negative effect on joint durability, by compromising hole fill or joint clamp-up. The clear takeaway is that the finer details of the assembly process and the ability of the process to remain in control over time (and monitor itself, or be externally monitored) are critical in order to meet fatigue life goals and avoid costly, burdensome fleet service actions down the road.

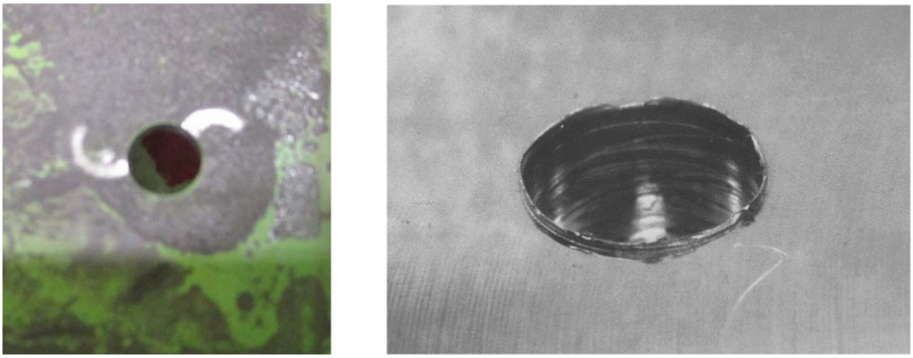

Fig. 3. Examples of poor hole quality

Against this backdrop, the drive to reduce airplane acquisition costs to customers means that structural components need to be produced less expensively, while maintaining an adequate level of quality and consistency in order to prevent fatigue-related service issues after the airplane enters service. Part of reducing cost is to hold assembly time and assembly labor as low as possible. The pressure is compounded by the increase in delivery rates now happening across most Boeing models. One of the most dramatic examples of this can be seen in Fig. 4. The graph shows the yearly delivery rate of Boeing 737 airplanes over time, showing a significant rate increase – especially in recent years. Superimposed on this graph are a few milestones in total final assembly factory days needed per airplane. It can be seen that over an approximate 20-year period where yearly deliveries have nearly doubled, the final assembly time has been reduced from 22 to only 9 days. The impact in the factory could not be clearer, as Fig. 5 illustrates.

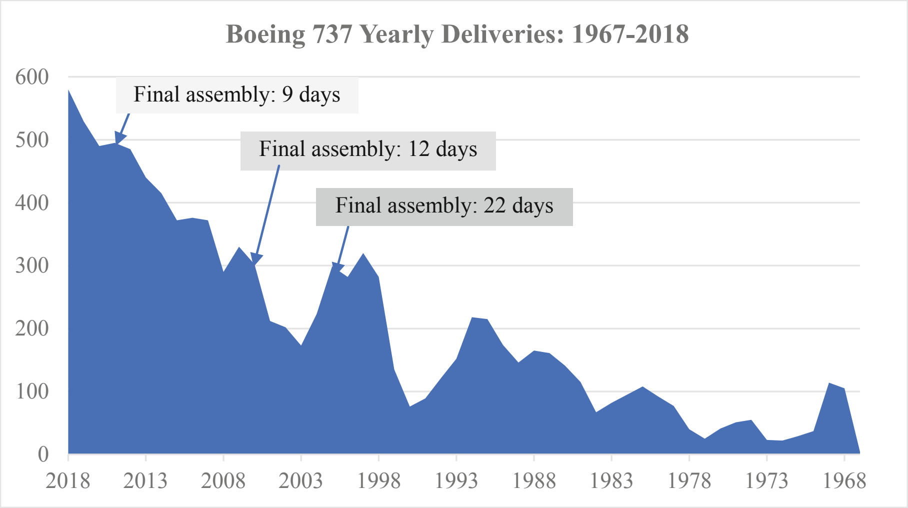

Fig. 4. Boeing 737 deliveries per year vs. final assembly days

Fig. 5. The Boeing 737 final assembly, circa 1970 (top left), 1985 (bottom left) and at just prior to completion of the first 737 MAX, in 2015 (right)

Automation and the elimination of large monument tooling and assembly jigs are some of the means used to deliver these kinds of gains. Moving away from traditional means of assembly (manual drilling, hard tools, and hand riveting and conventional bolt + collar or nut installations) to make these processes a reality unfortunately can also adversely impact engineering properties, chiefly fatigue. These effects, which are discussed later in this paper in the context of specific processes, require careful, deliberate a priori consideration, by properly accounting for the impact from the initial design stages, and by considering appropriate mitigation solutions where necessary.

4 One-Up Assembly

One-up assembly (OUA) is used at Boeing as a generic term to designate assembly processes (often machine-based) where fastener holes are drilled upon assembly without the joint being separated, cleaned, inspected, and holes deburred after drilling, as would be the norm under a more traditional build process. OUA processes can support high interference-fit bolt and rivet installations, as OUA is still a match-drill operation. However, the process does leave interface burrs, and the potential for debris in the stack if parts are not sufficiently clamped during drilling. The interface furthermore is no longer inspectable.

OUA has the obvious benefit of reducing process labor and increasing production throughput, but it may also come at the expense of reduced fatigue lives. Figure 6 shows typical fatigue life reductions in aluminum and titanium joint members in qualified (tightly controlled and verified) OUA process with no mitigation. 'Mitigation' in this context means a process or characteristic of the joint that, while not physically removing the burr, offsets the loss of fatigue performance caused by it. Mitigation strategies may be used when the negative effect of OUA on fatigue is deemed structurally unacceptable.

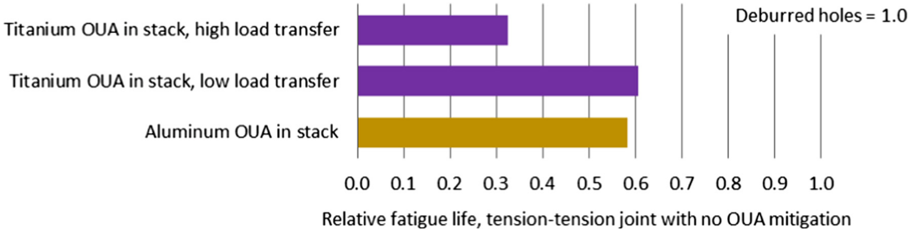

Fig. 6. Typical fatigue life reductions in non-mitigated OUA joints in tension-tension fatigue (Boeing data)

The left image in Fig. 7 shows an example of a mixed-material joint after drilling but before fastener installation. Note the presence of sharp edge/burrs at the interface surface. The picture on the right shows a non-deburred hole after fatigue testing, with the origin of the fatigue crack common to the interface burr. Clearly, hole preparation and burrs matter.

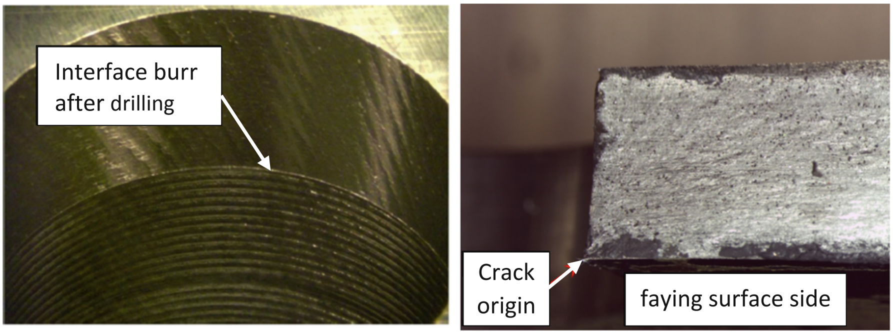

Fig. 7. Fracture origin at burr – titanium joint fatigue test specimen

OUA is not a new idea – it has been employed at Boeing in production for decades in all Boeing 7-series wing assembly lines, but with the increased drive toward machine automation and robotics – where OUA often becomes an intrinsic process feature, use of OUA is rapidly spreading. Among new examples of the process are the new Boeing 737 wing panel assembly line (PAL) and spar assembly line (SAL), which are helping make the current 40 + airplane-per-month 737 NG/MAX production rate possible and economical, and across many major structural components on the 787 and 777X models.

The 737-MAX production line uses the PAL (Panel Assembly Line) and SAL (Spar Assembly Line) automated drill-and-fill systems. PAL is an automated assembly system that has enabled major portions of the 737 wing to be built 33 percent faster than the legacy machine system. With PAL (Fig. 8) and SAL, over 84 wings a month are made at the Boeing Renton plant. The new system can drill 90 percent of all the holes and install bolts as well as other fasteners, considerably expanding the level of automation in the factory ("First 737 MAX Wing Assembly", Boeing 2018; Assadi et al. 2015; Tomchick et al. 2015). The SAL system additionally provides a drastic reduction in factory space and considerable efficiencies (Calawa and Smith 2017).

Fig. 8. 737-MAX panel assembly line (PAL)

The Boeing 787 Dreamliner features numerous OUA applications, including moveable trailing edges (De Vlieg and Feikert 2008) and large areas of the fuselage, drilling through composite and composite-metal stacks, including titanium. Some of these developments are being carried forward to the new Boeing 777X program, for example, on the control surfaces in the wing and empennage. Complex robotic multifunction end effectors that comprise a drill spindle, hole measurement probe, vision system camera, and one or more fastening modules (Fig. 9) allow true "drill-and-fill" operations with a high degree of accuracy and repeatability (Mir and DeVlieg 2017). Many of the new systems are capable of installing blind or one-sided installation structural fasteners, allowing the entire process to be accomplished from one side only (Sydenham and Brown 2015; Mir and DeVlieg 2017). While greatly facilitating the build process, these multi-piece fasteners are heavier and costlier than conventional fasteners and are structurally less capable than their conventional counterparts, including in terms of joint and fastener fatigue. Positive proof of a successful installation is also a more complex matter with current blind fasteners. As a result, they are at this time generally limited to secondary structure.

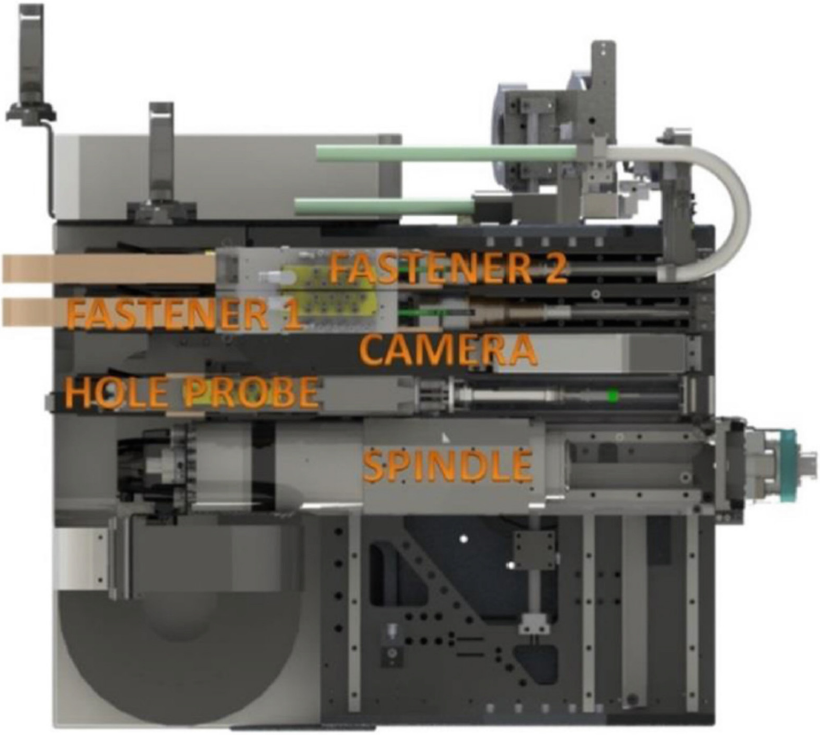

Fig. 9. OUA robotic end effector layout (Cutaway View, from Mir and DeVlieg 2017)

One common thread across all OUA applications in structurally significant components on Boeing airplanes since the introduction of the first wing riveting machines, has been the active participation of the structures engineering community. This participation involves determining the adequacy of the process for the intended application, understanding its impact to the durability of the structure, working in partnership with the manufacturing community to develop process requirements, and supporting qualification activities, which in many cases included fatigue testing. Figure 10 provides an illustration of one such evaluation, in this instance in support of the 737 PAL system. Dozens of test specimens were tested under that effort to evaluate key installation parameters and sample all production machines. This type of team effort has proven invaluable over the years in assuring the integrity of the process and compliance with regulatory and internal requirements and, in a few cases, has served to identify and correct problems with the process that had escaped detection up to that point, before the process entered production.

It is clear that implementation of OUA in production requires an early structural assessment that considers the effect the process could have on fatigue performance, establishing mitigation strategies where possible and pertinent, and process qualification (once the process is deemed stable), the latter often involving dedicated fatigue tests. Qualification is especially important because once in production, inspection of

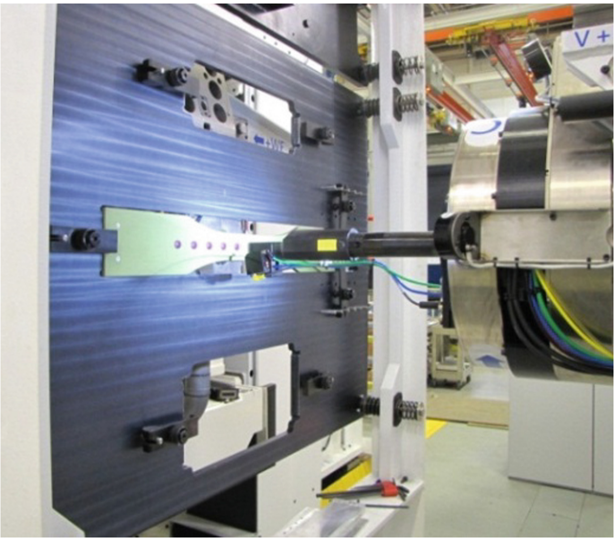

Fig. 10. Boeing 737 PAL system fatigue qualification (image shows a fatigue test specimen being drilled and riveted)

one-up assemblies is impossible; process control is paramount. As already noted, process qualification is a step that is co-owned by the manufacturing and structures engineering functions.

5 Assembly with Pre-drilled Holes

Assembly using undersize fastener holes is commonly used to help eliminate large tooling jigs and provide other assembly benefits, but this process involves final drilling/reaming upon assembly. Assembly using undersize fastener holes can be part of a traditional drill/separate/clean process or an OUA process. Using pre-drilled full diameter holes is an assembly strategy centered on the principle that with the right machine tools and process controls, it is possible to build structure at the detail part level to an extent where drilling on assembly can be sharply reduced or eliminated altogether. This process involves producing full sized holes (including deburring) at the detail level that can be used for part location, and then fasteners can be installed with no drilling upon assembly.

Due to the potential for minor amounts of mismatch at the final hole locations, this approach works best for clearance fit installations involving bolt/collar or bolt/nut installations. Also, this approach is recommended for machined parts and composite parts with controlled surface variation or machined surfaces. Applications using alternate forms of fabrication (such as sheet metal, castings, forgings, stretch/bump forming) would require additional development to ensure accurate hole locations. In addition, processing steps such as cold working and full part shot peening may introduce variations in hole locations requiring further development.

Like OUA, assembly using pre-drilled fastener holes is not a new concept. With the advent of precision machining, however, the range of applications is expanding into more fatigue critical primary structure and beyond the traditional domain of areas like airplane floor structure, where Boeing has been using this approach for more than 20 years. Recent, highly successful examples of assembling with pre-drilled holes include the 787 vertical fin (on all models, Fig. 11) and the horizontal stabilizer (starting with the -9 model), both of which are large all-composite and composite-titanium assemblies.

Fig. 11. Boeing 787 vertical fin

Focusing on the 787 vertical fin, this design extensively uses assembly with pre-drilled holes. There are hundreds of parts shown in Fig. 11 that utilize shared full-size clearance holes for indexing components. Note the lack of drilling equipment, FOD, etc. The biggest concern with this type of process is the possibility of hole misalignment. The error rate (measured by holes needing to be oversized due to misalignment) has been extremely low. For example, in one timeframe in 2013 only 10 holes out of 60000 required oversizing. Since 2013, there has been zero non-conformances due to hole misalignment.

Assembly using pre-drilled holes on structural components involves many of the same steps as with OUA, but with a well-planned, coordinated process and sufficient controls in place, the need for dedicated fatigue testing is not typically necessary for process qualification. The key to a successful implementation is understanding how the process works and how it is going to be controlled over years of production. From a structures engineering standpoint, a process such as this that is properly controlled and executed will not degrade the structural characteristics of the assembly; inconsistent hole fit/hole mismatch will not rise to become a fatigue concern. Fatigue testing of assemblies, which is at best a complex and expensive undertaking (it requires large-scale tests with the type, direction, and magnitude of an anticipated mismatch as test variables) can potentially be avoided.

One aspect that requires consideration with this approach is how the process can potentially affect many elements of the production stream, sometimes surprisingly. This also means that certain ancillary processes like shot peening, or coldworking, or in general anything that can cause critical features to move prior to assembly are no longer options or special provisions must be used to limit part distortion. An example of this is shown in Fig. 12 where a full-size hole is added at the detail part level on a part requiring subsequent shot peening, anodizing and priming. The presence of incomplete peening in the bore of the hole, along with presence of anodize and primer in the hole, are potential fatigue issues that must be addressed and either eliminated or tested and analyzed for this condition.

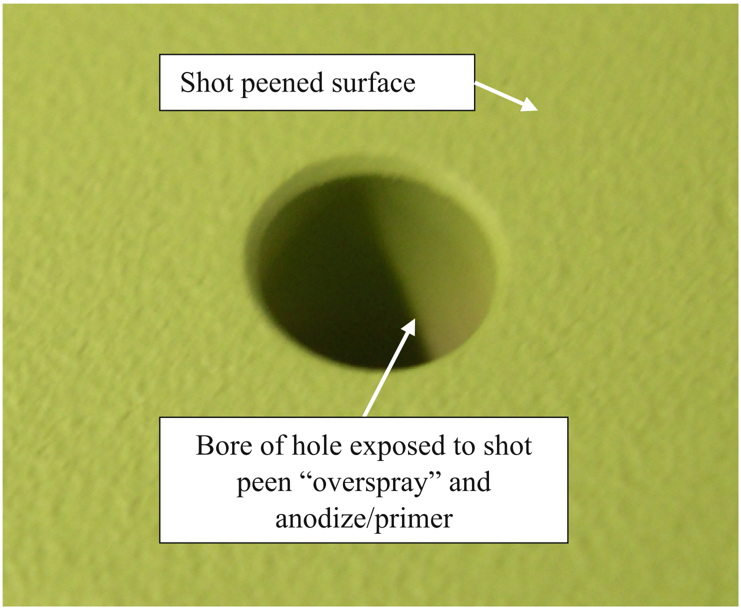

Fig. 12. Example of full-size hole with shot peen and finish in bore

6 Conclusion

One of the main drivers of final aircraft assembly cost and time is the drilling of holes and the installation of fasteners. Fastener locations also require a high level of precision and quality in order to achieve high levels of durability. A variety of methods which balance assembly efficiency and fatigue quality were discussed in this paper. The main approaches discussed (OUA and assembly using pre-drilled holes) use different methods to achieve this balance. OUA allows for machine drill-fill processes which can achieve high through-put but with the requirement of tight process controls. This process does allow for burrs to be left in the structure, which can affect fatigue performance. Assembly using pre-drilled holes can eliminate high cost assembly tooling and provide build efficiency due to the elimination of some drilling upon assembly. The challenges for this approach are a requirement for a high precision detail part build approach to ensure alignment of parts and holes. The main fatigue trade-off is the potential for finish in holes and the need to use clearance fit holes to allow for build tolerances. Boeing has successfully implemented both of these approaches in production and will continue to expand the usage to achieve cost reductions and to support increased delivery rates. A successful implementation of these technologies requires a non-traditional partnership between the manufacturing and structures communities due to the level in which the economics of airplane manufacturing and assembly and fatigue performance are intertwined.

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