18 Structural Repair

The process of building the airframe of an aircraft is a complex undertaking with literally thousands of parts coming together to result in the finished product. It is inevitable that during the machining, assembly and build process, defects will occur and some parts will not be manufactured per blueprint. This section describes the process of salvaging these parts and designing and analyzing appropriate repairs. This section focuses on metallic structure. Section 19 of PM4056 focuses on repairs for composite structure.

Also discussed are some of the unique issues associated with the design and analysis of repairs for fielded aircraft where the damage is due to corrosion, cracking, mishandling, or other induced damage rather than the anomalies associated with the manufacture of the airframe.

All salvage and repair must be performed to result in a repair which lasts for a specified life in the environment in which it operates. The repair should not change the load path which can result in making other parts of the airframe more critical than per design or negatively affect the life.

The repairs and structure should have compatible strains which are achieved by using repair materials which are attached with a sufficient number of fasteners to ensure they work as one with the parent material. Repairs should start at existing holes sufficiently remote from the area being repaired to allow for any reinforcement material to become a part of the load path.

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18.2 Introduction

This section is concerned with how to perform and analyze typical aircraft structural repairs. The repairs may be the result of a mistake during the manufacturing process, handling of parts, modifications to structure as a result of test findings or aircraft modification contracts, corrosion, fatigue cracking, post-delivery repairs or aircraft accidents/ mishaps. Each of these may have slightly different criteria for what the repair must accomplish in terms of restoration of strength and life and will most certainly have different accessibility for actual performance of the repair which can limit the repair options. These criteria will be discussed in Sections 18.2.1-18.2.2 for each of the repair environments.

Crucial to being able to design and analyze a repair is the availability of the inspection data. All information about the damage or defect that can be measured and quantified should be provided. The analyst needs this information to properly set up the analysis problem and boundary constraints. When applicable, non-destructive inspection (NDI) should be used to provide further information.

18.2.1 Production Aircraft Material Review

Material Review activities during the production of a new aircraft are an important part of producing quality products. Parts can have defects due to material processing, machining, transport in the shop, drilling, installation and anywhere in-between. It is the analyst's responsibility to evaluate any structural defects and determine if they are minor enough to be used with no repair, can be repaired, or must be scrapped and replaced with a non-defective part. All parts which get installed on the aircraft must have

- Ultimate strength capability
- Equivalent Structural Stiffness
- Full service life
- Meet control surface unbalance limits
- And, if applicable, meet required fail-safe damage tolerance concepts.

In rare cases, particularly in a pre-production or engineering manufacturing development program phase, limited life parts may be accepted via a waiver by the customer. The internal process for Material Review and disposition is documented by AC-4276.

For most aircraft programs, there is a Standard Disposition Manual which has standard repairs with specific limitations and applicability that may be implemented by Quality. It is, generally very restrictive in the types of repairs that are allowed without engineering approval. The Standard Repair Manual or SRM is an extension of the Standard Disposition Manual. This document, for internal use only, describes a standard catalogue of recommended repairs which Liaison Engineering can implement. Analysis may still be required, depending on the repair and application; however, these repairs are designed using best practices from previous programs. These repairs have specific limitations in applicability and extent of damage and have no negative impact on the structural integrity of the airframe when used correctly. Additionally, each program will have a Standard Repair Manual, supplied to the customer, which has recommendations for repairs along with applicability and limitations. These manuals are used at the various customer maintenance facilities.

Figure 18.2.1-1 illustrates a typical production aircraft material review organization. Coordinating and leading the activity is the liaison engineering group. Each program tailors this general plan to fit their needs and sometimes there are no MRB stress, design or damage tolerance engineers and all work is done by program engineers.

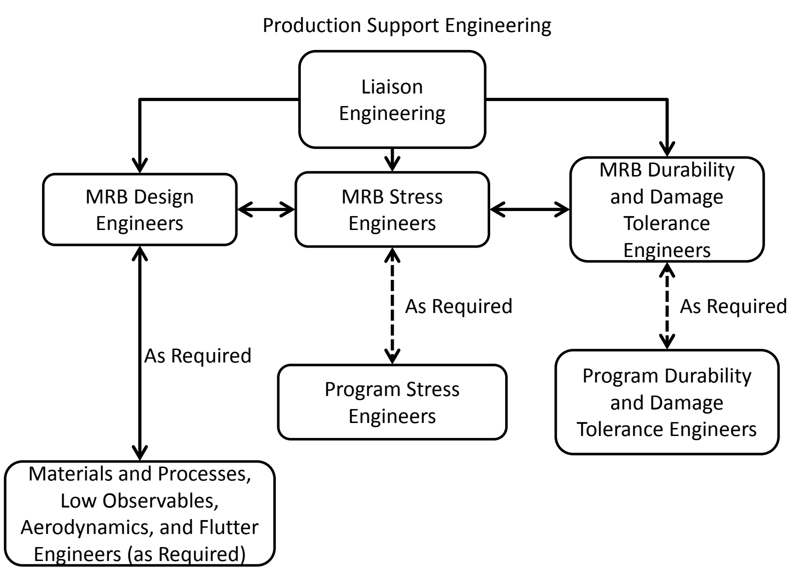


Figure 18.2.1-1 Production Support Engineering Organization

Liaison engineers are experienced in the area of repair, rework and disposition of defective or damage parts and have overall signature authority meaning they can sign the discrepancy report and repair instructions and release it without other signatures. Some programs override this requiring, as a minimum, signature by DADT for all

Durability or Fracture Critical parts and still other programs require all pertinent, affected engineering functions to sign the discrepancy report and repair instructions before release.

18.2.1.1 Production Aircraft General Salvage Guidelines

The recommendations listed in this section have been used successfully on aircraft programs at Lockheed Martin and should be used in the absence of specific program guidance. In the event of a conflict, written program guidance and criteria govern.

The goal for salvage of structural parts should be to provide a part with equivalent strength and service life as that of the original non-defective part fabricated to at least the minimum tolerance dimensions shown on the engineering drawing. This provides for retroactive changes such as future gross weight increases without having to perform a structural audit on all repairs of all aircraft to determine which aircraft do not meet the new requirements.

When a large static margin of safety exists, a reduction in strength is permissible if

- The minimum margin of safety for the reworked part is + 0.10 which means the strength of the salvaged area of the part must be at least 90% of a non-defective part requiring a minimum margin of safety for the original non-defective part to be greater than or equal to 0.22.
- The remaining service life of the whole structure is unaffected

It is recommended that a record be kept of all post salvage/repair margins of safety which are reduced from the original margin to less than 0.25. Information which should be kept as part of that record would include: part number, description of discrepancy, post-salvage margin and failure mode, aircraft number, Quality Action Report[1] or QAR reference number and any other pertinent facts. These should be kept in an electronic database for easy search and retrieval.

Structural Engineering shall not sanction blanket deviations from the engineering drawings in a “salvage-in-advance” situation. This lowers the standards and can lead to the anticipation of further latitudes to deviate from the engineering drawings in the future. Any multiple-ship repairs shall have a reasonably limited effectivity until corrective action can be put in place to eliminate the problem so that the aircraft can be manufactured per drawing. Some of the reasons behind this include

- Engineering is responsible for the airworthiness of the design, as reflected in the pertinent engineering drawings and specifications, and is the sole judge of airworthy parts.
- Salvage, repair, alterations, substitutions, alternates, etc., are emergency expedients which can only be evaluated by engineering and should not be construed as the lowering of engineering standards and shall not be regarded as precedents for acceptance of or resolutions to manufacturing deviations.
- The circumstances which permit a part to be accepted, in spite of deviating from the drawing, can change in time. On a single part or a small number of parts, the risk may be low enough to permit acceptance, while on a large number of parts, the risk may be prohibitive.
- The acceptability of a repair can vary from one area of the aircraft to another due to loading, thermal environment, adjacent structure, etc.
- The engineering drawings must reflect the delivered physical airplane in all respects. Overriding or blanket deviations must be confined to specific cases and these must be documented by aircraft number and QAR number.

[1] The quality action report or QAR is a document, issued by the quality organization, which details the part number, part classification, production number, with a detailed description of the discrepancy. This document is also used by engineering to detail the disposition and any repair. A SQAR or supplier quality action report, is a similar report for a part manufactured by a supplier.

18.2.1.2 Component, Static and Fatigue Test Article Salvage Guidelines

Salvage of parts for use on the various engineering test articles should be handled in a similar manner as a flight-worthy aircraft. The test article is not supposed to be in any way a special model but rather should be representative of production aircraft. Further, in some cases an 'over-strength' repair might be acceptable on a flying aircraft, such repairs should be avoided on test articles since questions can arise as to the validity of the test in the over-strength regions. Additionally parts which have a large number of "minor" defects can change the strain results making correlation of test results to nominal finite element models challenging if not impossible.

The use of over-strength repairs might be acceptable under the following circumstances:

- If additional strain gages can be installed in the region of the repair so that the actual load distribution in the area can be verified
- If the defect is in a part which has symmetry and there is no defect in the same area of the opposite side. Care must be taken to ensure that both the original non-defective part and the loading are symmetric.
- If the discrepancy and repair are located in a non-critical area of the part, *i.e.*, another location on the part is more critical, then an over-strength repair might be acceptable if any instrumentation present in the area also exists on the opposite side of the aircraft. It also must be verified that the over-strength repair does not cause load redistribution within the part such that is affects the critical location.
- Structure is non-structural such that it would have no impact or effect on the outcome of the test.

18.2.2 Post-Production Repair

Post-production repairs may be one of several categories. These might be repairs initiated by Lockheed Martin due to a test finding or due to a service life assessment or extension program, repairs requested by the customer due to discovery of corrosion, aircraft damage or cracking, or repairs required due to a specific incident for a single aircraft. The first two groups are repairs that will likely have to be performed on a number of affected aircraft, while the latter, is related to a specific incident and aircraft and will likely result in a unique repair.

> Caution: Although aircraft are built to drawings, specifications, and tooling, each have unique features. There may be changes in a particular area due to material review activity, prior repairs done by the customer, grind out due to corrosion or changes resulting from an aircraft modification. Lockheed Martin engineering may or may not have been involved in defining these changes. So when designing and analyzing a post-production repair assume the engineering drawings are only a starting point. It is important to obtain on-aircraft information as soon in the process as possible.

Many repairs performed on post-production aircraft by the customer do not involve Lockheed Martin engineering because there is a Standard Repair manual which is developed and provided by Lockheed Martin[2] with the aircraft. It defines the repairs, zoned drawings, damage limitations, and repair instructions. The SRM is used for a majority of the repairs performed at customer facilities. There is another category of repair known as an "engineered repair" which is typically more extensive and invasive than a standard repair and for these, the customer may engineer the repair, they may contract it to another company or they may approach Lockheed Martin for repair design and analysis. The discussions in Section 18 and PM4056 Section 19 would apply both in the development of the Standard Repair Manual as well as for the engineered repairs when the effort is performed by Lockheed Martin..

In general, post-production repairs must meet full static capability and full life requirements, although repairs resulting from Service Life Assessment (SLA) or Extension (SLE) programs may have a specific life designated for that program which differs from the original aircraft life requirements.

The analysis requirements for post-production repairs are the same as for the basic airframe and may be a contractual deliverable. As a minimum a static analysis is required, along with a durability and damage tolerance assessment, if not a full analysis. The requirements related to durability and damage tolerance analysis of post-

[2] Some customers prefer to design and develop their own repairs and may develop their own SRM.

production repairs are typically a function of aircraft, customer and contract. Additionally a fail-safe analysis may also be required, particularly if the repair is a result of aircraft cracking.

For post-production repairs, many operators are more inclined to accept an expedient salvage solution resulting in a positive margin and acceptable life than a more complicated solution which preserves the original margin of safety. Typically, the minimum margin requirements recommended for salvage of production aircraft, described in Section 18.2.1.1 do not apply to in-service aircraft; however, a minimum static margin of 0.0 and the specification life requirements do still apply.

18.2.2.1 Field Repair

Field repairs are repairs that may be performed at forward bases with, sometimes, limited facilities and training and as a result tend to be limited in scope. Sometimes these repairs are done by teams sent by the contractor and sometimes by customer maintenance personnel. Often these repairs come from a handbook of repairs prepared by the Original Equipment Manufacturer (OEM) called the Standard Repair Manual or SRM. These repairs provided rigid “extent of damage limits” and repairs that have been reviewed for acceptability by the structural integrity organization. If the customer exceeds the limits, it is their responsibility to perform structural analysis substantiation or to contract with the OEM or another organization to perform one.

In rare cases, the field repair that can be accomplished is insufficient to restore the life and static capability of the airframe. This is usually done in response to a specific incident, generally occurring in a war zone, which may include damage due to an improper landing, a ground collision with another aircraft, small arms fire, and so forth. Because the aircraft may be located at a remote airfield, which has limited or no capability to perform repairs, temporary repairs may need to be designed and installed for the purpose of repairing the plane to a state where it can be flown to a depot for further, final repair. Typically, in these types of scenario, the margins of safety for a full flight envelope may be negative, but the flight speed and maneuver envelope is restricted such that, for that limited envelope, the margin of safety is 0.0 or positive. This one-time limited flight envelope flight is typically called a ferry flight.

18.2.2.2 Depot Level Repair

Depot level repairs are repairs performed at customer aircraft depots which have trained maintenance personnel and repair facilities that have near factory level capabilities. More complex repairs and scheduled structural maintenance and inspections are performed at the depots where there are also customer engineers to aid in the design of repairs which fall outside of the limitations of the OEM supplied Structural Repair Manual. Additionally OEM engineered repairs will likely be performed at the depot level.

18.2.2.3 Aircraft Battle Damage Repair (ABDR)

Battle damage repairs are generally handled by the customer using the Aircraft Battle Damage Repair (ABDR) handbook which is developed by the specific aircraft program. This document outlines repair limits, types of repairs and the extent of the repairs that can be performed in the field or at the depot under combat conditions. The repairs in the ABDR handbook typically restore full static capability but may not restore full life. The repairs have been reviewed and analyzed, as required, by the cognizant program structural analysis group. For more extensive repairs that fall out of the limits provided by the ABDR handbook, special repairs, to be performed by the contractor or by the depot, may need to be developed. These are usually unique to the specific aircraft and damage and while the basic tenets and guidelines of this section may apply as do the standard analysis methods of this process manual, these types of repairs are not covered in this section.

18.3 Damage Assessment, Inspection, and Classification

Once the defect or damage has been identified the next task is to determine the magnitude of the defect or damage and what parts or assemblies are affected. For production aircraft, as noted above, this responsibility belongs to the

Quality Control organization and there is a process in place for obtaining the information. This is discussed in Section 18.3.1. For post-production aircraft the process is not as straightforward. It is discussed in Section 18.3.2.

18.3.1 Production Aircraft

The statement of condition of the part is documented on a Quality Action Report (QAR) or the Supplier Quality Action Report (SQAR). This document is prepared by the quality organization and must contain all of the quantified information and NDI results since it is the official documentation for the defect. If it is lacking in detail, return it to the quality organization for the missing information. This QAR will also document the disposition including repair details, required post-repair finish restoration, required inspections and all of the authorizing signatures. Samples of the types of information which can reasonably be expected to be quantified on the QAR or SQAR, depending on the defect, are listed in Table 18.3.1-1. No list could cover every possibility but if information is required for the analysis, it should be requested and documented in a revised Statement of Condition (SOC).

Table 18.3.1-1 Types of Defects with Sampling of Quantified Data Required on QAR/SQAR

Defect Category	Documented Numerical Information	Discussion
Location	Part number, fuselage station, butt line and waterline	Knowing exactly where the defect is allows the analyst to use the appropriate loads, thermal profiles, pressures, etc.
Hole defect: Diameter	• If out-of-round what are the dimensions • If oversized, what is diameter • If double drilled what are major and minor dimensions • If two holes are drilled close together, what is fastener spacing	All hole defects affecting the size of the hole should also include edge distance to nearest edge and fastener spacing to nearest adjacent fastener. If the holes are match drilled into substructure, is the defect only on one part or through multiple parts? If multiple parts, edge distance on all parts is required.
Hole defect: Perpendicularity	What is the angle of tilt, diameter of hole – full size or pilot? Gap at Head?	
Hole defect: Short edge distance	What is the edge distance/ tear out?	
Incorrect radius on a machined part	What is the radius?	
Wrong material or heat treat or grain orientation	What is the specific material used, heat treat and/or grain orientation?	
Rough Surface	What is the finish? RA 125; RA 250…	
Part is dented/scratched/gouged	How deep is the dent, scratch or gouge? What is the radius of the scratch or gouge at the bottom?	For composite materials, impacts can result in hidden defects. All impact events of a composite part must undergo NDI to determine the full extent of the damage. See PM4056 Section 19 for further discussion
Part is too thick or too thin	What is the thickness dimension? Is there a taper present? Is there a step or mismatch present? What is the extent of the discrepancy (length/width) and where?	
Gap is present between joint layers	How big is the gap? Is it tapered? What is the extent of discrepancy?	

Part is deformed, warped, bowed, oil-canned	How extensive, *e.g.*, is it the whole part or is it local to a flange or pocket? What is the magnitude of the warpage/bowing/deformation?	In the case of overall warping of a machined part, a map of the deformation may be required and design engineering should determine the overall form, fit, and function impact.

If further damage is suspected, additional inspections may be required such as dye penetrant inspection if a part has been yielded and cracking is suspected.[3] These should be requested prior to the determination of the repair. Section 2.9 discusses some of the more common methods of NDI.

There are 3 nonconformance levels for the overall disposition process described in AC-4276. AC-4276 levels are defined based on the impact to the overall system and is not focused on only structural integrity:

- Minor nonconformance: A nonconformance that is not likely to reduce, to a significant degree, the usability of the supplies or services for their intended purpose, or is a departure from established standards having little bearing on the effective use or operation of the supplies or services. Multiple Minor nonconformances, when considered collectively, may raise the category to a Major/Critical nonconformance.
- Major nonconformance: A nonconformance, other than Critical, that is likely to result in failure, or to materially, *i.e.*, to a significant degree reduce the usability of the supplies or services for their intended purpose. A nonconformance adversely impacting any of the following guidelines is considered Major.
    - Performance
    - Reliability
    - Effective Use or Operation
    - Maintainability
    - Interchangeability
    - Safety or Health
    - Weight or Appearance (when a factor)
- Critical nonconformance: A nonconformance that judgment and experience indicate is likely to result in hazardous or unsafe conditions for individuals using, maintaining, or depending upon the supplies or services, or is likely to prevent performance of a vital mission.

Note that assuming the selected repair restores full structural strength and life with no additional required field inspections, any defect affecting structural integrity could be categorized as a Minor Nonconformance, although the extent of the damage or repair may raise the nonconformance category to a Major Nonconformance. If the extent of the repair is such that structural testing of the repair is warranted or if post-repair scheduled inspections are required, then that might again raise the classification to a Critical Nonconformance.

There are 3 possible dispositions to any damage or defects. These are shown in Table 18.3.1-2. Note that if DADT analysis was required for blueprint part, DADT analysis or evaluation is required for defective part. Also, depending on the part criticality, the extent and type of the repair and availability of supporting data, validation of the analysis by test may be required. See Section 18.7 for discussion of possible testing requirements.

[3] Note that production inspectors are instructed to document visible discrepancies and NDI inspectors are told to document non-visible damage, hence the terminology “No damage beyond visible” may be used meaning the only damage present is visible.

Table 18.3.1-2 Dispositions for Damaged or Defective Parts

No.	Disposition	Requirement	Discussion
1	Use-As-Is	Perform an effect of defect (EoD) analysis to determine impact of defect on structural integrity of the part. The analysis must demonstrate: a. Static Strength[4] M.S. ≥ 0.0 b. All RTR ≥ 1.0 (including stability and deflection criteria)[5] c. DADT Life has not been compromised.	This category includes: “Use-As-Is” with no repair and non-structural repairs that restore form, fit and/or function but have no impact on structural integrity. If the defect/and or repair has no impact on the part structural integrity, then a statement of “no impact to structural integrity” and a restatement of the blueprint margin of safety and life may be documented on the QAR for completeness.
2	Repair	Perform an effect of defect (EoD) analysis to determine impact of defect on structural integrity of the part. Notify the liaison group of any necessary repairs and work with them to determine repair options. Repair analysis must demonstrate: a. Static Strength[4] M.S. ≥ 0.0 b. All RTR ≥ 1.0 (including stability and deflection criteria)[5] c. DADT Life has not been compromised.	For multiple defects on the same QAR, there may be multiple repairs or multiple dispositions.
3	Scrap	Perform an effect of defect (EoD) analysis to determine impact of defect on structural integrity of the part. If a repair option is not available which results in positive static strength margin of safety, meeting all stability and deflection requirements and full DADT life requirements, the part is scrapped.	Scrapped parts are deemed unfit for use on a flying aircraft. They may be sent to engineering for further evaluation and testing. If not, per customer requirements they are indelibly marked and cut-up.

One other term, which is often used in reference to dispositions, is cosmetic repair. It has a number of meanings from the obvious one of serving no purpose other than making the part appear undamaged. An example of this might be a rework of a damaged finished. It can also mean a repair that provides no structural benefit, but may be advisable and necessary to preclude further damage or to obtain proper fit. An example of this is found in the repair of loose fibers on the surface of a composite through the use of resin or an adhesive. This prevents the fibers from fraying further and provides a smooth interface surface but adds no discernable structural improvement to the damaged area. Analysis is generally required for the damaged area when a cosmetic repair is used but no benefit of the repair is taken, so from a structural integrity standpoint it is essentially a “use-as-is disposition”

18.3.2 Post-Production Aircraft

Repair of a post-production aircraft is always based on a request from a customer and is never undertaken in isolation. Depending on the circumstances triggering the request for assistance, the amount of available information available to assess repairs for post-production aircraft may be harder to obtain. For some programs, the inspection information will be provided by the aircraft owner/operator and may be extremely limited in detail since there is no standard process which is followed while for other programs the process may be very similar to the QAR/SQAR process in-place for production. With the initial report, it is incumbent on the analyst and the designer to try to

[4] See Section 18.2.1.1 for recommendations if margin has been reduced from Design Margins.
[5] RTR: Ratio-to-requirement. See Section 2.5.5

envision the information that is being communicated and request additional information to try to narrow the focus and support the best repair and analysis options.

Below is a list of typical types of inspections performed on post-production aircraft and what anomalies or symptoms might be present indicating an issue.

- Damage found by the aircraft maintainers while doing routine maintenance and walk-around inspections will typically be paint bubbling which could be indicative of corrosion or heat damage, symptoms of fasteners working, paint flaking which might indicate impacts or cracks, and obvious dents.
- Damage found during inspections following an incident such as a ground collision with another object or the drop of a heavy object on an upward facing surface will typically fall into the category of paint damage, impact damage, holes in the structure, and permanently deformed/displaced structure.
- Damage found during inspection following an in-flight incident could include permanently buckled skins, yielded structure, control surfaces that have deformed sufficiently to have interference, and structural failures.
- Damage found by planned inspections or by inspections as result of an aircraft modification, installation of a Service Life Extension kit, or an unrelated repair could be corrosion, fatigue cracking, broken fasteners or symptoms of fasteners working.

For each of the scenarios listed above a good starting place for understanding the defect and possible repair options would be the design drawings. However, actual aircraft structure may vary from the design drawings, either due to variability in manufacturing or because that particular area may have already had repairs or modification performed by the customer which Lockheed Martin is unaware of. Requesting photographs of the area on the airplane or airplanes in question provides an invaluable look at the area. When requesting photographs, ask that at least one of the photographs be from a sufficient distance that both the defect and identifiable features of the aircraft can be seen to allow for locating the defect. Additionally, at least one photograph close enough to show the entire discrepant area and finally close-up photographs of various aspects of the discrepancy.

In the case of aircraft incidents on the ground, such as a moving aircraft impact with another aircraft, ground vehicle or stationary object or a stationary aircraft being impacted by a forklift, ground cart or other ground support equipment, it is important to understand the cause of the damage to be able to properly ensure a wide enough area has been inspected and all possible damage discovered. Collisions with other objects can dynamically load the aircraft and may cause issues outside of the area of obvious concern. Having a forklift run into the aircraft, on the other hand, would likely cause damage in a limited, obvious area. Both visual and NDI inspections of the area of impact to determine the full extent of the damage may be necessary. The size and shape of any obvious holes or tearing of structure, along with loose or broken fasteners and damage to fastener holes should be fully documented. Any area with paint damage is a candidate for the appropriate NDI inspection looking for subsurface damage particularly in composite laminated or honeycomb structure. Also in the local area, examination of substructure for possible yielding and cracking should be performed.

In the case of aircraft incidents in the air it is crucial to understand what occurred. It will be the responsibility of the analysts and the designers to determine what areas of the airplane need to be inspected, what is likely to have been damaged or overloaded and what symptoms might indicate an issue. If there is an in-flight failure that is a starting point, but there may be collateral damage as a result of the failure or there may be undiscovered damage that precipitated the failure. If there is no overt failure as in the case where the aircraft exceeded its flight limits, *i.e.*, an over-g case or over-speed case, structure may still have been yielded, permanently buckled or otherwise damaged and sensor data from the aircraft can be used to determine possible damage scenarios.

Finally in the case of anomalies found during planned inspections, the damage may be very localized as in a single crack in a specific area or it could be more general as in multi-site cracking in an area or corrosion covering a wide area or multiple areas. For appropriate repair, it is important to obtain crack lengths, shape, if it has turned into an upstanding leg, where specifically the cracks are, how much of the cross-section is engaged, how many hours has the aircraft flown, and has it had any hard landings or tail impact incidents. For corrosion, key questions include how widespread and what type of corrosion is present. If it is pitting corrosion, questions which need to be addressed include how deep and how sharp the pits are and has this compromised the surface finish? PM4057 Section 3.4 discusses the different types of corrosion.

18.4 Typical Repair, Design Guidelines and Best Practices

This section provides a description and discussion of typical repairs which are used for Material Review and Post-Production repair of aircraft. The discussion is to provide guidance and background information for various defects/repairs. Section 18.6 provides a concise table for specific defects, recommended repairs and analysis requirements.

Note that any repairs done to:

- Control surfaces or control surface back-up structure or landing gear or landing gear back-up structure should be done in consultation with the Flutter and Dynamics engineering as the response of these flight critical structures could be affected.
- The Outer Mold line surfaces should be made in compliance with program requirements or in consultation with Flight Sciences engineering

The repairs described in this section have been successfully used on Lockheed Martin programs; however, every program may not approve every repair technique due to differences in customer, platform, governing specifications and program culture. Each analyst is responsible for checking with program guidance to ensure a particular repair technique and its limitations is acceptable to their program prior to implementing the repair.

18.4.1 Repair of Defective Holes

Repairs of defective holes, which might include oversized, elongated, figure-8, non-perpendicular, burned, or rough internal surface finish are typically accomplished by first cleaning up the hole to true (perpendicular to the surface) and round to some diameter larger than blueprint and then evaluating the repair options depending on the size of the hole. These might include using oversize or next-sized fasteners, bushing or plugging the hole to achieve blueprint fastener size. Each of these options is described in detail in Sections 18.4.2-18.4.4.

Defective oversized or irregular holes are detrimental because they

- Overload of adjacent fasteners as the joint must deflect sufficiently before the fastener in the elongated or oversized hole picks up load
- Increase in stress concentration due to elongated hole shape
- Result in bending in the fastener
- Allow movement of the connected parts which result in wear on the faying surface known as fretting, Fretting roughens the surface, leads to a break down in corrosion prevention materials and also creates a washboard type surface which opens the door to crack initiation.
- Wear under the head or nut of the fastener

It is for these reasons, that defective holes must be repaired.

18.4.2 Oversized Fasteners

Oversize fasteners are special fasteners which are used in salvage operations that have shank diameters that are 1/64th, called a first oversize, or 1/32nd inch, called a second oversize, larger than the baseline fastener. The heads and threads remain the original diameter so that they use the same nuts, collars or nut plates. They are used in defective holes that have been cleaned up to round and true but slightly larger than the hole required by the engineering drawing. The same hole fit as the blueprint drawing should be maintained. Note that oversized fasteners are typically not approved for use in removable panels since the threads are the same as for standard size fasteners and an oversized fastener could inadvertently be replaced with a standard size fastener during panel removal. In removable panels, either the hole must be bushed or the fastener should be replaced with the next full size fastener. Note that a full fastener size diameter increase is typically 1/16th inch.

The fastener shear allowables for protruding head fasteners may be assumed, conservatively, to remain the same as the basic fasteners, although a new allowable may be calculated using the increased shank area and the specification shear strength of the fastener, e.g., 95 ksi, 108 ksi, etc. The fastener shear allowable for oversized countersunk fasteners is typically the same as the standard size fastener because the countersunk heads are unchanged.

Fastener tension allowables remain the same as the basic fastener because the threads or the head are typically the critical area.

For many commonly used aircraft fasteners first oversize fasteners are available. Some fastener types also have second oversize fasteners available. There may also be limitations on what diameters and grip lengths are available in oversize. Typically the smaller diameters such as 5/32nd and 3/16th inch may not have oversize fasteners available and a repair will require going to the next size fastener. Sometimes an oversize fastener is not available for a particular part number; however a very similar fastener of perhaps a different (stronger) material is available. It may be used as long as the hole fit is the same and the fastener type is similar. For instance a blind fastener is not a “similar fastener” to a solid Hi-Lok or HiTigue.

Another alternative, used by some programs, is to use a sleeve over the blueprint fastener if first and second oversize fasteners are not available. The steel sleeve comes in 1/64th and 1/32nd oversize and has circumferential grooves to allow the mechanic to shorten it to the correct grip length. Sleeve grip lengths are limited to 1 inch, therefore, for grips longer than 1 inch, multiple sleeve segments are required. Additionally, if the grip is greater than 1 inch, it is recommended that the sleeve breaks be aligned with the faying surface. Some programs do not allow the use of sleeves because of reported problems with the sleeve shearing in service and the sharp edges causing joint damage and downstream fatigue failure. If sleeves are used it is recommended that the number of affected fasteners be limited to no more than 2 adjacent and no more than 10% of the total number of fasteners in the joint. Sleeves should not be used on blind fasteners due to limited available test data.

The fit of oversized or sleeved fasteners must be the same as the fit for the standard size fasteners in the same joint and the fit should be noted as part of the repair. If a defective hole can be repaired by an oversize fastener that is generally the best alternative. If not, then a bushing repair is recommended. Many of the Lockheed Martin program specifications allow up to 10% of a fastener pattern to have oversized fasteners installed without material review action.

18.4.3 Bushing Repairs for Discrepant Holes

Bushings are used in the repair of damaged, elongated or oversized holes. Bushings can have a number of applications in aircraft structure and can be made from a number of materials. This section looks at different aspects of bushing repairs.

In a typical joint, the use of a bushing to rework a part where holes do not conform to the drawing requirements is a good alternative if a 1/64th or 1/32nd inch oversize fastener is insufficient to match the hole fit after the defective hole has been cleaned up round and true. The use of a bushing eliminates the redistribution of load in the joint due to one or more large fasteners being added to the joint. Because it is installed with an interference fit, it has the additional advantage of adding compressive stresses to the edge of the hole and improving the fatigue life, although many programs do not account for any life benefit in the analysis. The exception to this might be in post-production or field repairs which typically do account for the life benefit.

In addition to repairing the hole to nominal size, bushings also protect the part they are installed in. The hardness of the bushing should be between the hardness of the part and the hardness of the fastener. For this type of repair application, typically, bushings are made of the same or stronger material than the part. They are never softer or weaker than the material they are installed in. For instance in an aluminum part, an aluminum, stainless steel or titanium bushing could be used. But in a titanium part, an aluminum bushing would never be used. Good bushing materials include: Ti 6AL-4V Titanium, 15-5PH, PH13-8Mo, and Inconel 718 steels. If an aluminum bushing is desired, try to match the alloy of the part.

The outside diameter of the bushing should be a minimum of 0.03 inch smaller than the head of the fastener or the washer to keep the bushing trapped within the structure. If this is not possible, use an oversized steel washer or a shoulder bushing. A number of different style bushings are shown in Figure 18.4.3-1. Note that the shoulder on shoulder bushings should have a minimum flange thickness of 0.060 inch for wall thickness up to 0.070 inch with larger thickness is required for larger bushings, particularly if they are made from aluminum. For high strength tension applications, steel flanged bushings are strongly recommended. The shoulder flange shall provide adequate bearing strength above (fastener to shoulder) and below (shoulder to joint surface) and the shoulder flange also needs to provide adequate strength to resist bending and shear where the flange extends beyond the head.

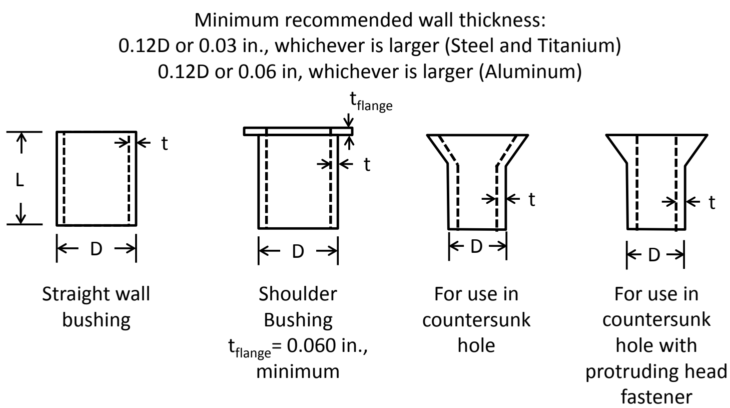


Figure 18.4.3-1 Typical Bushing Types used in Joint Repairs

Bushings should not be installed in removable panels unless they have some type of retention, otherwise, there is a risk that during the life of the aircraft the bushing could work loose and fall out.

Bushings may be inserted with only a pilot hole predrilled; however it is more common for the bushing to have a full-sized hole with only a final ream occurring after installation. The hole should be concentric with the wall of the bushing. To maximize the strength of the bushing it is recommended that a wall thickness of 12% of the outer bushing diameter be used, with a minimum allowed value of 0.030 inch for steel and titanium bushings and 12% of the outer bushing diameter be used, with a minimum allowed value of 0.060 inch for aluminum bushings. Note that per Section 5.2.5.2 the allowable bearing strength of the bushing is affected by bushing wall thickness. Section 5.2.5 discusses the analysis of bushings and is applicable for repair bushings.

It is also recommended that the edge distance of the bushing be 1.5 times the outer diameter of the bushing or greater. At edge distances of 1.2 times the outer diameter of the bushing a tension field may be set up at the edge of the part due to the decay of the compression stresses from installation making that a critical area for DADT. This is illustrated in Figure 18.4.3-2. An absolute minimum edge distance of 1.2 times the diameter of the bushing is recommended for wrought alloys with elongations greater than 5%. In some low elongation materials such as aluminum lithium or 7000 series aluminums in the short transverse direction, depending on the size of the bushing, could crack during bushing installation. Castings, which exhibit low elongation, should use edge distances of 1.5 times the bushing outer diameter as a minimum. In any event shot peening of the edge of the part in the region of the short edge distance is recommended for improved life. See Section 18.4.19 for discussion.

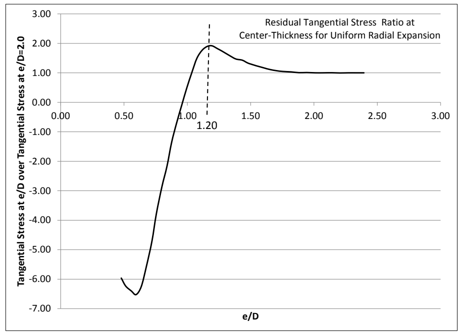


Figure 18.4.3-2 Increase in Tangential Stress Ratio for FTI Forcemate™ Bushing versus e/D Ratio[6]

Bushings are installed in an interference fit hole, typically on the order of 0.0005 to 0.0015 inch diametrically larger than the hole and are chilled and inserted. The degree of interference affects the amount of life benefit. Each program has a process specification and the degree of interference fit varies by program. Fatigue Technologies Forcemate™ or Bushloc™ bushings may also be used. These are expanded into the hole, performing limited coldwork of the material at the same time the bushing is installed. The Forcemate™ is intended as an original bushing installation and may be useful in material review or production. The Bushloc™ is a replacement in a hole that has already been cold worked or previously bushed and may be more commonly used in post-production applications. Most programs have a specification for the installation of these bushing. The minimum sheet thickness that a repair bushing can be installed in is on the order of 0.050 inch. A drawback of the Forcemate™ bushing is that they may require a larger hole outer diameter than is acceptable for a particular installation. Whether a custom, Forcemate™ or Bushloc™ bushing, the fastener fit in the bushing should be the same as the blueprint fastener.

Multiple layer stack-ups which require bushings should be bushed separately because a single bushing will act like an interference-fit hollow pin until the applied load breaks it. Since it is a tighter fit than adjacent fasteners, in most joints, the bushing will load first, break and then the joint fasteners will load up. At the break, there may be sharp burrs which could damage the material in the joint or the fastener and shorten the overall life of the joint. If it becomes necessary to bush multiple layers with a single bushing, validation testing of the specific installation is required.

The key to getting a good bushing installation is proper hole clean-up. Only after the hole is prepared, should the bushing be manufactured to match the final dimensions of the hole since the hole may not clean up round and true to the diameter specified on the disposition. Manufacture of multiple bushings is recommended which allows for a back-up in the event that a problem is encountered during installation.

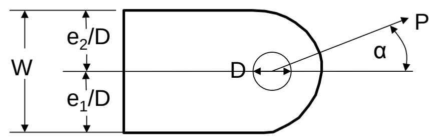
18.4.3.1 Special Case: Bushings for the Repair of Aircraft Lug and Clevis Fittings

Bushings used for lug and clevis fittings are more critical because the magnitude of the loads transferred and the single load path nature of these types of fittings. Bushings installed in lug and clevis fittings are typically of a different higher strength material such as corrosion resistant steel or aluminum-bronze. The analysis of Section 5.4 applies to the lug or clevis portion while Section 5.2.5 also applies to bushings used in lug and clevis fittings. Sometimes post production aircraft exhibit corrosion in the hole of a lug or clevis fitting which must be removed by grinding or drilling followed by the installation of a bushing.

Bushings used in lug or clevis fittings are recommended to be shoulder bushings with a minimum shoulder thickness of 0.060 inch, if geometry permits, with the shoulder oriented in a way that traps the bushing. Also a minimum wall thickness of 0.060 inch is recommended because it more efficiently redistributes the high bearing load into the lug fitting.

[6] Generated by nondimensionalizing data in Reference 18-9.

Edge distance in a lug or clevis should be 1.5 to 2.0 times the outer diameter of the bushing with 2.0D preferred. In-service history has shown that as the edge distance decreases, the lug or clevis gets increasingly flexible and deforms under load such that moisture can get trapped between the bushing and lug or clevis and cause corrosion. An absolute minimum of 1.0 times the outer bushing is recommended and anything below 1.5 should be analyzed closely for static margin and DADT life. Also note that the most robust lug or clevis fitting is symmetrical about the hole. So if a discrepant condition results in the edge distance on one side of the hole being less than on the other, the minimum edge distance times two should be used in the analysis for the width of the lug, shown in Figure 18.4.3-3.



If $e_1/D \neq e_2/D$, $W=\min(2e_1/D, 2e_2/D)$

Figure 18.4.3-3 Short Edge Distance Lug

18.4.4 Plug Repairs for Discrepant Holes

Cylindrical plugs are sometimes used to fill extra holes, pilot holes or tooling holes, and on rare occasions, in the place of bushings with the fastener hole drilled after installation. It can be much harder to install plugs using shrink fit techniques, as compared to using expanding rivets per Section 18.4.6, as there is a larger mass of material to cool down; however, if the hole is larger than 0.25” in diameter a solid plug is required. The selection of material for the plug repair should, as a minimum, be the same alloy as the parent joint material. Since it has the same bearing strength and stiffness, it will transfer the load across the hole effectively. See Section 18.4.6 for more discussion on using plugs to fill holes.

Using a plug repair in lieu of a bushing has some inherent risk and is therefore recommended as a last resort repair. When the plug is drilled, it can spin because the interference stresses are insufficient to resist the rotation of the drill and, as a result, work better in thicker materials. Also, because of the residual installation stresses, the plug can deform inward after drilling and shrink the fastener hole, requiring a second drill or ream. This can potentially lead to a wall thickness below minimum requirements. Minimum wall thickness requirements of Section 18.4.3 apply to plugs after drill.

There has been some limited success on some programs with using a plug for the repair of holes where the final hole center is not in the correct location in the structure as bushings can be drilled slightly off-center; typically no more than about 5% of diameter off-center, which is about .012 inch on a ¼ in diameter hole and minimum wall thickness shall be maintained. <u>It is strongly recommended that this first be attempted off-aircraft to develop a procedure</u>. Reiterating, this is considered a difficult to accomplish repair and should not be used on a routine basis.

All of the guidelines discussed in Section 18.4.3 for bushings apply as do the cautions about cracking aluminum lithium or short transverse 7000 series aluminum parts.

18.4.5 Dissimilar Fasteners in Repairs

When considering fasteners for a repair, the mixing of different types and fits of fasteners such as rivets, bolts or screws should be avoided. In general, the execution of a repair should be consistent with and maintain design analysis assumptions. This means use of the same type, material and fit of fastener is a priority in repair design. Combinations of different type fasteners due to different fits, stiffness and hole fill may introduce any or all of the following:

- Premature failure of fasteners.
- Detrimental redistribution of loads to adjacent structure

- Load increases due to dynamic effects
- Stress concentrations because of unequal load distributions.

The difference in the fastener hole clearances used for different fasteners is a primary source of trouble. For instance, if bolts are used in combination with driven rivets, the rivets will carry the load until sufficient deformation occurs to place the bolts in bearing in their respective holes. Depending on hole clearance, the rivets may fail. This condition is even more detrimental where a joint carries reversal of loads as the total deformation increases and the rivet life is reduced.

Where it becomes necessary to mix fasteners, special attention should be given to the fit of the fasteners in the hole. The fit in any one pattern should be consistent in itself and with adjacent patterns where there is a multiple joint arrangement such as a wing surface. Where bolts or screws are added in a driven rivet pattern, it may be necessary to fit each bolt or screw separately and obtain a light drive fit in order to obtain a satisfactory joint. Hollow rivets or blind fasteners should not be mixed in with driven rivets or interference fit fasteners.

Attention should also be given to the fastener strength and stiffness. Larger or stiffer fasteners can cause load redistribution in the joint resulting in static or fatigue failure. This is one reason why, if more than a single or double oversize fastener is needed, a better solution might be to bush the hole and use a blueprint fastener per guidance in Section 18.4.2.

18.4.6 Extraneous Hole Fill Using Expanding Rivets or Plugs

In metallic structure it is recommended that all holes be filled unless they are used as drain holes. Tests have demonstrated that an open hole, even as small as 0.125 in. will create an adverse stress concentration, but if the hole is plugged it will reduce the stress concentration to a minimum and improve the life over an open hole. Note that this type of repair does not improve the net section tension stresses which are present and could cause failure. Net section analysis of the structure with the material removed for the hole needs to be performed and a positive margin of safety obtained.

The recommended repair is an AD rivet for extraneous pilot holes, holes up to approximately 0.25” in diameter or tooling holes[7]. Note that use of a blind fastener for this application does not provide the same structural benefit as it does not fill the hole and provide the beneficial stress field around the hole.

If the hole is larger than 0.25” in diameter, consider using an interference fit solid plug, typically on the order of 0.0005 to 0.0015 inch larger than the hole and chilled prior to insertion. The selection of material for the plug repair should, as a minimum, be the same alloy as the parent joint material. Since it has the same bearing strength and stiffness, it will transfer the load across the hole effectively. A stronger/stiffer plug is acceptable.

The rivet or plug expands in the hole resulting in a compression stress field at the edge of the hole. If necessary the rivet can be made double flush by installing a flush rivet, touch countersinking the backside before bucking and then grinding flush. This type of repair can also be used for drill starts in metal structure by drilling through, cleaning up the hole and then installing the rivet.

Plugs should be positively restrained against falling out or being pressed out due to internal pressure. This is achieved for the rivet through the countersunk head/touch countersink method described above.

Separate plugs should be used when plugging two or more layers of material. If a single plug is used it will act as a fastener and transfer load which could result in a failure of the plug.

Close on-center holes in which one will be used for load transfer may be plugged with a single plug if the holes are in line of the load path and the plugged hole does not transfer any load. In this direction, one hole “shadows” the

[7] Note, tooling holes in fatigue critical structure should be plugged per blueprint.

hole behind it and the stress concentration is not magnified. If the holes are across the direction of the load, a doubler may be required for improved fatigue life. In this configuration, there is an increased stress concentration because of the interaction of the increased stresses between the two holes. Figure 18.4.6-1 illustrates these scenarios.

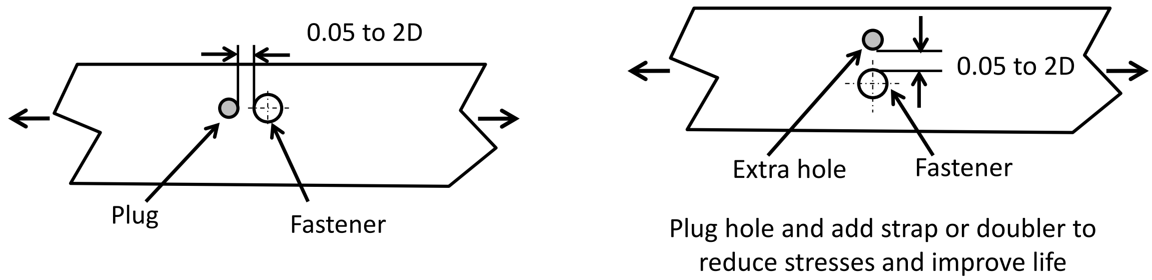


Figure 18.4.6-1 Plug Repair of Extraneous Adjacent Holes

The use of interference fit plug repairs for extraneous holes in composite parts in not recommended. See PM4056 Section 19 for possible repairs.

18.4.7 Repair Fastener Selection

Different aircraft programs typically have specific fasteners that are approved for use on that program. In addition to the fasteners which are used for design, there may also be fasteners that are approved for repair applications. Using a fastener that does not have prior program approval can take a significant amount of time even if it has been used on another program and is available, since the approval process will include the customer and/or the certifying authority.

The first choice in the selection of a repair fastener would be to use the same fasteners that are already in use in the structure in the area of the repair if they meet the strength, fit and geometry required in the repair. If an oversized fastener is required, many of the fastener systems have first and second oversize fasteners available. See discussion in Section 18.4.2.

PM 4057 Figure 5.2.3-20 illustrates the relative strengths of different types of fastening systems and may be useful in aiding in the selection of a repair fastener. Some considerations which must be addressed when selecting a fastener for a repair are given in Table 18.4.7-1.

Table 18.4.7-1 Considerations in Selection of Repair Fastener

Feature	Repair Considerations
Fastener strength	Both the fastener shear strength and tensile strength must be adequate for the expected loads. Be aware that repairs can cause additional eccentricities which result in moments and tension loads in fasteners which were not present in blueprint structure.
Fastener fit	Repair fasteners, added to an existing joint, should have the same fit as the blueprint fasteners. If not, load redistribution in the joint can lead to overloading either the repair fasteners or the adjacent blueprint fasteners resulting in fastener failure or increased potential for fatigue failure of the joint material.
Fastener Stiffness (modulus or diameter)	Caution should be used in selecting repair fasteners that are of different, stronger materials or larger diameters than adjacent existing fastener as this can cause load redistribution in the joint resulting in fastener failure or increased potential for fatigue failure of the joint material.
Fastener Material/Coatings	Material and/or coating selection on repair fasteners are a concern from a corrosion standpoint. If the joint material and fastener with finishes are incompatible, the joint may be weakened due to galvanic corrosion.

Feature	Repair Considerations
	• Do not use cadmium plated fastener in Titanium or graphite/epoxy or graphite/BMI joints. • Do not use aluminum fasteners in graphite/epoxy or graphite/BMI joints.
Fastener Head style – Countersink head	If selecting a countersink fastener for an existing hole, be sure the countersink head is of the same geometry to fill the hole. Tension head countersink fasteners are recommended. Use of shallow head or 130 degree head countersinks is discouraged as these types of fasteners often undergo head failure possibly on installation.
Fastener Head style – Protruding Head	Typically a tension head fastener would be selected for a repair fastener because of the potential for additional eccentricities which result in moments and tension loads in the fasteners. If a shear head fastener must be used because of space constraints, ensure that the fastener loads are fully understood.
Composite/Metallic Joints	Because of the potential for crushing fibers in composite joint layers, selection of repair fasteners for joints which include composite layers should not include interference fit fasteners or expanding fasteners such as rivets or expanding blind rivets.
Blind installation fasteners (bolts or rivets)	In some cases a fastener which allows for installation from one side is required due to lack of access. Be aware that the strength of this type of fastener is less than a solid fastener and may be further reduced with an improperly formed tail. Inspection of the formed tail, required by most LM specifications, is strongly recommended when this type of fastener is selected, *i.e.*, don't waive this requirement. See Figure 18.4.7-1 for some examples of poorly formed blind-installation rivet tails. NOTE: The fasteners perform poorly in thin sheet metal installations in high vibration zones. Prior to selecting the fasteners for use, consult with the program dynamics/vibrations engineers.

Figure 18.4.7-1 Malformed Tails on Blind Installation Fasteners

18.4.8 Fastener Substitution

Selection of fasteners for substitution is governed by the same considerations as are discussed in Section 18.4.7 Repair Fastener Selection and 18.4.2 Oversize Fasteners. Some programs, as a part of their fastener installation specification, have a list of suitable fastener substitutes by part number. Other programs do not have such a list and the Program Fastener Standards Engineers should be consulted.

18.4.9 Short Edge Distance Considerations and Best Practices

Holes with short edge distance should be analyzed with full consideration of loading direction, magnitude and local joint geometry such as edge distance, hole size, part thickness, etc.

When the load is parallel to the edge of the part, as shown in Figure 18.4.9-1, edge distances greater than 1.5D are typically acceptable if the part has been designed to standard 2D edge distances and is not fatigue critical. If as-designed fatigue margins are low, a fatigue analysis should be performed, and consideration should be given to cold work of the hole (Section 18.4.11) if allowed by program and shot peen of the edge of the part (Section 18.4.19) to inhibit a crack starting at the edge of the part. Short edge distance conditions under this loading/geometry are typically not critical for static strength with the possible exception of net section tension. For net section calculations in a fastener row located at one edge of a large skin or panel, it is slightly conservative to use an effective width, w_{eff}, of 2 times the edge distance for the net section calculation, even in a large skin. This is also shown in Figure 18.4.9-1.

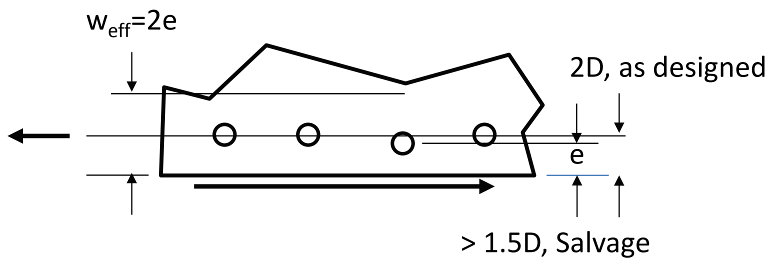
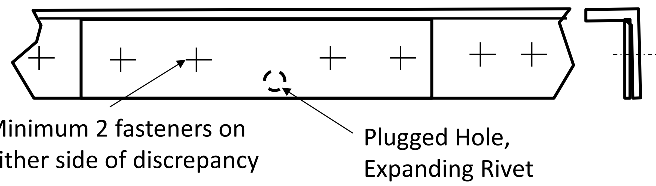


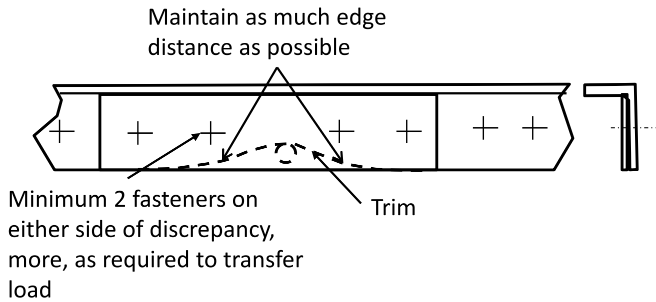
Figure 18.4.9-1 Short Edge Distance with Load Parallel to Edge of Part

Shorter edge distance holes, $1.2 \leq e/D \leq 1.5$, may be acceptable if fatigue analysis of the discrepant condition results in a positive margin. Mitigation of the stresses may be accomplished through increasing fastener sizes of adjacent fasteners to cause local load redistribution and reducing load transfer through the discrepant hole. If an entire row of fasteners is discrepant and durability and damage tolerance life predictions have reduced below the critical design life prediction or the life prediction is less than 115% of the design requirement, part replacement or a doubler to reinforce the area and reduce stresses should be considered. Net section tension may be critical at these edge distances. For net section calculations, use an effective width, w_{eff}, of 2 times the edge distance as shown in Figure 18.4.9-1.

Short edge distance holes below 1.2D are strongly discouraged. The hole should be abandoned and, preferably trimmed away with as large a radius as possible, maintaining edge distance on adjacent fasteners. Refer to Section 18.4.18, Blend and Smooth on guidelines for removal of material. If it cannot be trimmed, consider plugging the hole. Adjacent fasteners could be oversized to handle the additional load or if space permits, fasteners could be added. If the strength capability of the joint is reduced significantly, part replacement or a doubler to reinforce the area, assist in load transfer and reduce the stresses should be considered. This is depicted in Figure 18.4.9-2. Note that plugging the hole does not improve the net section tension margin and it should be checked using the effective width of 2e as discussed above. If a fastener is abandoned and no additional fasteners are added, inter-rivet buckling per Section 8.6 and maximum fastener spacing per Section 5.2.3.1.8 should be checked. Any addition of straps or other reinforcements need to consider material tapering per Section 18.4.21 and the doubler discussion of Section 18.4.27.



(a) Fill Hole and Add Strap



(b) Trim Away Hole and Add Strap

Figure 18.4.9-2 Repair of Short Edge Distance Hole By (a) Filling or (b) Trimming and Addition of Strap

When the <u>load is perpendicular to the edge of the part</u>, edge distances greater than 1.5D are typically acceptable if the part has been designed to standard 2D edge distances and a check of the bearing margins of safety indicate positive margins. If as-designed fatigue margins are low a fatigue analysis should be performed, and consideration should be given to cold work of the hole, if allowed by program, and shot peen of the edge of the part. These are discussed in Section 18.4.11 and 18.4.19, respectively. This geometry is shown in Figure 18.4.9-3.

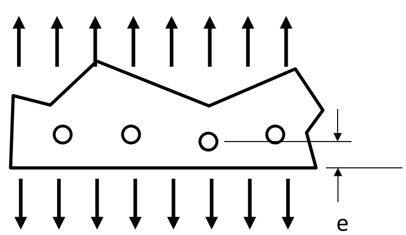


Figure 18.4.9-3 Short Edge Distance with Load Perpendicular to Edge of Part

Shorter edge distance holes, $1.2 \leq e/D \leq 1.5$, may be acceptable if the bearing and shear tear-out checks per Section 5.2.3 with reduced bearing material properties result in a positive margin and if fatigue analysis of the discrepant condition results in a positive margin. For e/D less than 2.0 but greater than 1.5, interpolation of handbook properties can be used. See Section 18.4.10 for a discussion of bearing allowable for e/D less than1.5. Mitigation of the stresses may be accomplished through increasing fastener sizes of adjacent fasteners to cause local load redistribution and reducing load transfer through the discrepant hole; however this may result in a short edge distant condition in the adjacent holes, albeit presumably not as severe as the discrepant hole. If an entire row of fasteners is discrepant and static or fatigue margins are low, part replacement or a doubler to reinforce the area and reduce stresses should be considered.

Short edge distance holes below 1.2D should not be used. The hole should be plugged and abandoned with additional fasteners added or adjacent fasteners increased in diameter. If a fastener is abandoned and no additional fasteners are added, inter-rivet buckling per Section 8.6 and maximum fastener spacing per Section 5.2.3.1.8 should be checked.

Programs may have specific guidelines on minimum salvage e/D which would take precedent.

18.4.10 Bearing Strength with e/D<1.5

Material bearing strength is given for e/D=2.0 and e/D=1.5 in Reference 18-4 and IDAT/metdb. For values between these two points, the value is typically interpolated. However, below e/D=1.5, it is assumed that the bearing strength is zero at an e/D of 0.5 where the edge of the hole would be right at the edge of the part. This is depicted in Figure 18.4.10-1. The bearing strengths can be interpolated between the value at e/D=1.5 and F_{bru}=0 at e/D=0.5. Holes with e/D below 1.2 should not be considered.

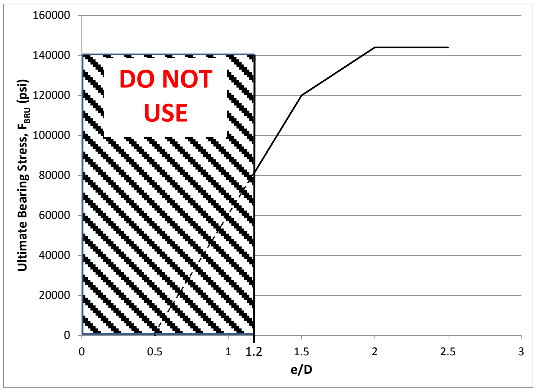


Figure 18.4.10-1 Sample Bearing Ultimate Curve

18.4.11 Cold Work of Holes for Improved Life

Cold working of holes sets up a beneficial region of compression stress at the edge of a fastener hole which improves durability and damage tolerance life. On some aircraft built today, the customer does not allow cold working to be used in routine design; however, cold work of holes during salvage of production aircraft or in post-production aircraft is usually acceptable. Check with program leadership and the Structural Design Criteria Document before assuming cold work is acceptable.

Specifications set up by the programs provide the method and degree of cold-work. There are traditional means of cold-work where a tapered mandrel is forced through the material enlarging the hole and additionally, most programs have specifications for use with Fatigue Technologies′ (FTI) Split Sleeve mandrel. This approach uses a collar which is split on a mandrel which is run through a material and gives a precise degree of cold-work. This leaves a small ridge at the split, which serves as a visual verification that the cold working has been performed. Some programs leave this ridge in place as verification of the coldwork process, other programs perform a final ream of the hole to remove the ridge and clean up the hole. Program specifications govern the approach used on individual programs.

The ridge should be located 90 degrees away from the edge of the part. There have been cases where parts have cracked during cold working with the use of split-sleeve cold working in 7000 series and aluminum lithium alloys when the ridge is oriented toward the edge and the fastener is 0.25 in in diameter or larger.

Another area of concern is cold working through multiple layers of dissimilar materials. Because each material may require a different diameter coldwork tool, it is impossible to achieve the correct degree of coldwork for each layer. Dissimilar materials should be separated and coldworked independently.

Typically cold working can improve the life if a hole has short edge distance (1.4D or larger) or has short spacing to the next fastener. Limited finite element modeling has shown that if the edge distance is below 1.4D, cold working can result in large tangential tension stresses at the edge of the part increasing the likelihood of fatigue cracking at the edge. This is illustrated in Figure 18.4.3-2.

The actual analytical benefit allowed by the customer due to cold working may vary by program. Different spectra and material result in different life benefits and most customers require some type of coupon testing to verify the life improvement. Testing is done once for the program and is not repeated with each application of cold working.

In post-production aircraft, holes may be cold worked for life enhancement in areas near where cracking has occurred, where short edge distance occurs as a result of rework or where stresses in-service are higher than predicted.

18.4.12 Improper Destack / Deburr Considerations

When a drilling operation occurs, on the exit side of the material being drilled, the hole is not smooth and clean. This incomplete cutting process leads to the formation of burrs on the exit side of the hole as depicted in Figure 18.4.12-1. The size, shape and sharpness of the burr are directly related to the type and shape of the drill bit. If the drilling of the hole involves multiple layers of material the burrs can form on the exit side of each layer.

If not removed, the burr has a potentially negative effect on the fatigue life of aircraft parts. Figure 18.4.12-2 shows possible shapes and sharpness of burrs. From this it can be seen that the burr can behave as a crack in the parent material, or can create a sharp edge which leads to crack formation in the parent material or can scratch or gouge the adjacent material and lead to crack formation.

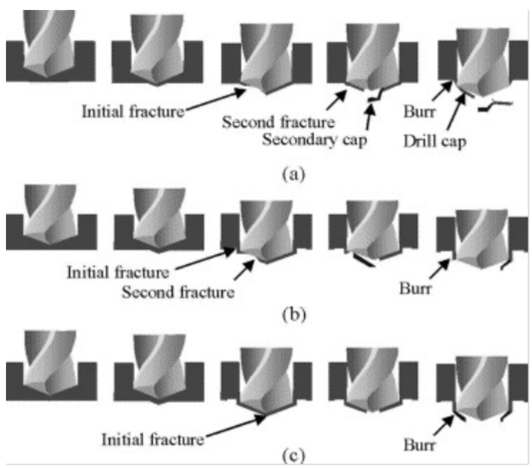


Figure 18.4.12-1 Formation of Burrs During Drilling Operation[8]

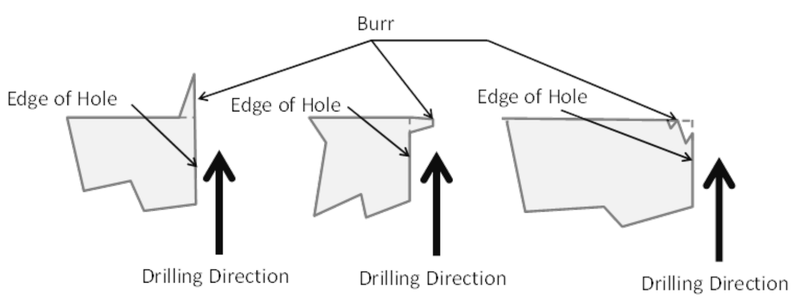


Figure 18.4.12-2 Possible Burr Shapes Resulting from Drilling Operation

In addition to the burrs remaining attached to the edge of the material or hole after drilling, chips and debris can result from the drilling operation which in a multiple layer stack-up can be lodged between the layers. This material,

[8] Reference 18-12

called swarf, can also lead to reduced life in aircraft parts and further prevent the appropriate clamp-up of material and preload in fasteners. The amount of swarf found between the layers is a function of the clamp-up during drilling and the presence or absence of fay surface sealant and the type of drill bit. Some experiments have indicated that the presence of fay surface sealant reduces the trapped swarf.

Figure 18.4.12-3 illustrates a scenario where two relatively thin parts were clamped, drilled and fastened with no destack and deburr.

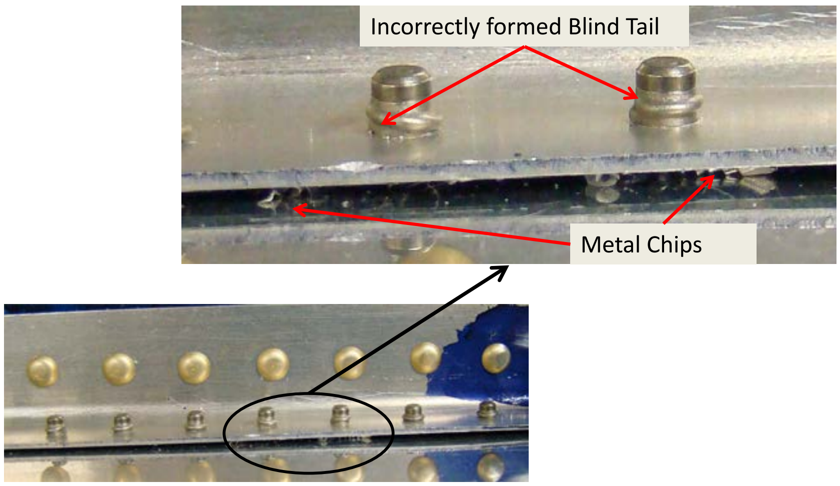


Figure 18.4.12-3 Improper Fastener Clamp-up Due to the Presence of Swarf

It is standard practice, per the various Lockheed program specifications, to destack all layers after drilling to clean out the swarf and to deburr the hole. Deburring is accomplished through the use of a touch countersink, a deburr tool or other suitable means. Destack and Deburr of assemblies drilled by automated drilling machines such as the Drivematic® or Spacematic® may not be required, at the discretion of the specific aircraft program; however, testing done at Lockheed has shown that the tooling clamp-up is sufficient to preclude the formation of burrs in typical transport structure. It should be verified through testing that any new automated drilling processes/machines exhibit sufficient clamp-up to prevent burr formation.

In general, destack and deburr are required of metal-metal joints whenever feasible. If the joint stack-up is a single layer composite to a single layer metal joint and the drill enters from the composite side, no destack and deburr of the faying surface is required but the exit side of the metal layer should still be deburred. If the drill enters from the metal side, then destack and deburr of the faying surface is still required.

During the program development phase, the manufacturing and producibility teams may ask for relief from the destack/deburr requirements in specific areas because of assembly sequencing. At that time the area is analyzed, and if acceptable, the design assembly drawing specifically identifies the holes which are not subject to destack and deburr. For production aircraft, occasionally, the destack/deburr step in a particular assembly is inadvertently skipped and requires salvage by analysis or repair.

The best salvage/repair of a “no destack/deburr” defect is to have the parts destacked and deburred. Sometimes this is not entirely possible since a significant number or fasteners may already be installed or there is the risk of some other collateral damage to the assembly by taking it apart for the rework. Areas that can be deburred or faying surfaces that can be cleaned out should be, but for the remaining areas, an analysis must be done to see if the predicted life is still within program requirements. The magnitude of the impact of no destack/deburr on the life of the parts is a function of the drill tip configuration, wear on the tip, the degree and proximity of clamp-up, and the thickness/stiffness of the parts being drilled. It is also a function of the severity of the aircraft loads spectrum. It is recommended that a stress concentration factor of no less than 1.40 be used in addition to any other stress concentration factors to increase the stress for the durability analysis of a hole in a metal-to-metal joint which has not been subjected to destack and deburr.

This factor may be reduced on specific programs with appropriate demonstration of drill techniques and clamp-up in the specific stack-up and thicknesses followed by cyclic fatigue testing of coupons manufactured using production tooling, drill bits, mechanics and production-representative hardware. For example, for the types of joints, tooling, materials, thicknesses and drill bits used on a legacy fighter program, additional coupon level testing was done and the factor was reduced to 1.2. In no case, shall the reduced stress concentration factor be less than 1.0.

Some programs also use cold working to offset the deleterious effect of no destack and deburr in a salvage or post-production situation. See Section 18.4.11 for discussion.

When fasteners are installed in joints which have not been destacked, consideration should also be given to the tension load in the fastener. If the joint surfaces are held apart, as shown in Figure 18.4.12-3, then the preload adds directly to the applied external load reducing the amount of load that can be applied. This is illustrated in Figure 18.4.12-4. This forced separation would also decrease the life of the fastener because the preload must be treated as a residual load with the externally applied load cycling about the preload. If it can be assured that the clamp-up of the joint during drilling or the presence of fay surface sealing in conjunction with clamp-up during drilling precludes the swarf from migrating into the faying surface, then no additional analysis consideration is required.

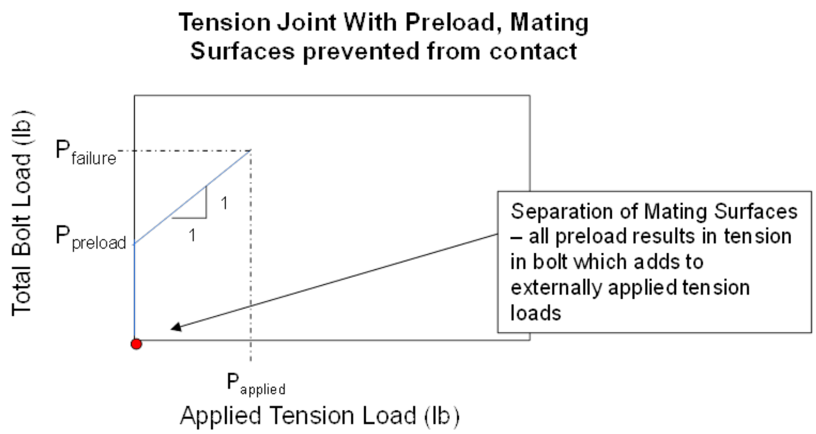


Figure 18.4.12-4 Tension Loading of Bolts with Faying Surfaces Prevented from Contact

18.4.13 Gap Pull-up and Non-Structural Shims

When mismatches between structural layers or between two structural parts occur they should be shimmed either using non-structural or structural shims. Rarely will it be acceptable to pull up the gap unless it is 0.005 inch or less since pulling the two surfaces together may cause permanent deformation and will result in residual stresses in the parts and potentially, significant tension loads in the fasteners. The residual stress can cause fatigue issues because it becomes the mean stress which applied stresses will cycle about. For some alloys, the residual stress can also lead to stress corrosion cracking. Gap pull-up stresses are typically derived through the use of simple beam or plate theory with assumptions on edge constraints or supports. See the discussion in Section 3.4.7 on stress corrosion cracking and the recommended maximum sustained tensile surface stresses. Maximum sustained surface stress is the summation of stresses due to part manufacture, cold forming, and part assembly, including gap pull-up stresses and stress concentration factors. Additionally, DADT engineers should always be consulted when gap pull-up of Durability or Fracture Critical structure is being considered.

Because determination of the stresses due to the other sources is difficult, good design practice has been to keep the sustained stresses due to pull-up low by not allowing pull-up of any gap larger than 0.005 inch or any gap pull-up requiring more force than “light hand pressure”.

Gaps can be filled through the use of non-structural shims which are shims which are inserted into a joint to fill a gap and have no additional fasteners beyond the joint fasteners and are not bonded to either side of the joint. In this case, the shim acts as a spacer. Per Section 5.2.3.4, this is typically acceptable for a shim thickness of approximately 15% -25% of fastener diameter, depending on the loading, fastener and geometry. This would result in a non-structural shim of 0.03 in a highly loaded joint with 3/16” diameter fasteners or 0.04 in a similar joint with ¼” diameter fasteners. Beyond this, structural shims are strongly recommended. Structural shims are discussed in Section 18.4.14. More guidelines can also be found in Section 5.2.3 in the bolt bending discussion.

The reason for the restriction on the use of thick non-structural shims or fillers is that they are detrimental to structural integrity for the following reasons:

- Increases eccentricity of loads causing high local moments and peaking of the bearing stress at the fastener hole
- The increased eccentricities induce tension-prying loads on attachments which add to stress and reduce margin of safety
- Reduces the strength of the joint due to bending on the fastener because of the increased moment arm between load carrying layers
- Introduces flexibility relative to surrounding structure because of increased fastener length and fastener deformation
- Introduces secondary bending into structure due to filler thickness and flexibility.
- Increases potential for slippage at joints and can causes continuous joint material to overload.
- Slippage in fuel tank regions can cause leakage.

While solid shims are strongly recommended, particularly in highly loaded joints, if shim adjustability is required, use a combination solid-laminated shim rather than all-laminated shims, which are sometimes called peelable shims. Solid-laminated shims consist of a solid metal layer and a portion which is made up of very thin metal layers bonded together, while peelable shims are all laminated layers. Some legacy programs have restricted the maximum thickness of peelable shims to 0.060 inch. There has been field data indicating that over time the bonds between layers of laminated shims become disbonded and what remains are multiple layers of very thin material which leads to joint slippage, fretting and early fatigue failure.

If the joint is double shear or a lug and clevis arrangement, it is desirable to shim both sides of a member symmetrically to give equal load distribution and prevent bending of the clevis due to clamp-up forces. A shim used only on one side of this type of joint will cause eccentric loading of member and overload the un-shimmed side; however, it is not always possible in a material review situation to accomplish symmetric shimming. In that event the additional moment must be included in the lug or joint loading. Figure 18.4.13-1 illustrates this condition for a lug/ clevis arrangement.

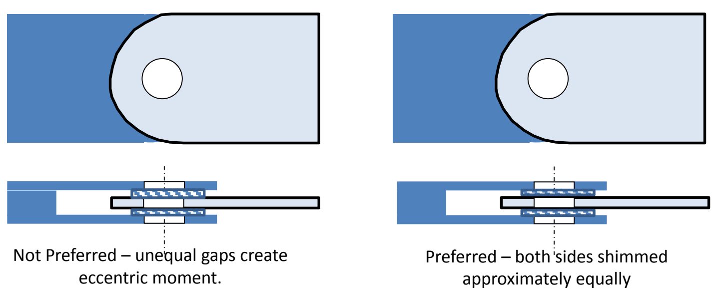


Figure 18.4.13-1 Symmetric versus Unsymmetrical Shimming in a Lug/Clevis

18.4.14 Structural Shims

In the event that the joint is highly loaded or the gap exceeds the recommended maximum thickness for a non-structural shim, a structural shim may be used.

To make the shim structural, extend shim beyond the joint members, having the gap condition, in direction of load. Attach shim to the continuous material beyond the joint with the same size and rivet or fastener pattern as exists in joint members. This is depicted in Figure 18.4.14-1. If the total shim thickness exceeds 0.064 inch, use guidelines of Section 18.4.21 to taper the material thickness.

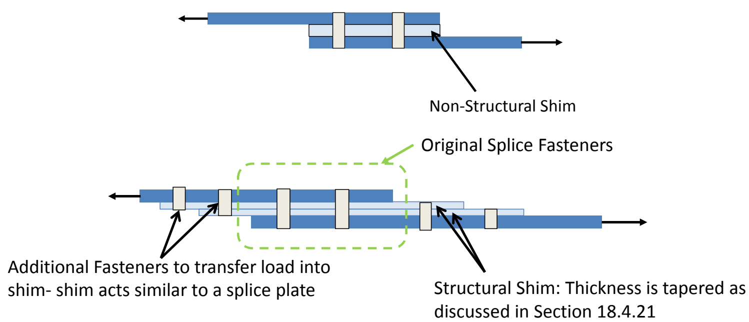


Figure 18.4.14-1 Example of Non-Structural and Structural Shims

The type and size of a fastener should also be considered when shimming is required. If, with the addition of the shim, the total stack-up of the joint increases to $t_{total}/D>3$, consideration should be given to increasing the strength of the fastener or increasing the diameter of the fastener or both depending on the geometry of the particular joint. Longer fasteners are more flexible, don't retain as much preload and are more prone to bending. If the geometry is such that there is bending or prying on the fastener head or tail present use a tension head fastener. Blind fasteners, shear head countersunk fasteners or 130 degree countersunk fasteners or aluminum collars should not be used as these have a strong potential for in-service failure under these circumstances.

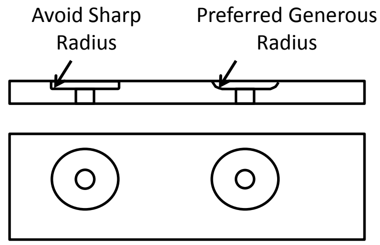
18.4.15 Spotfaces and Counterbores

Counterbores and spotfaces are typically not desirable due to the sharp radius at the base of the counterbore / spotface. This is considered a "last-resort" repair if all other means have been exhausted and never without the explicit approval of the cognizant DaDT engineer. Counterbores or spotfaces shall not be used in Class IA single load path structure as defined in PM4057 Section 2.2.

A spotface is a local lowering of the surface to allow for fastener installation and is generally a shallow counterbore or a counterbore which is not completely formed around the periphery. It is used to seat the head, nut or collar when the fastener is too close to a radius or a step if a radius block is impractical.

A counterbore is a cylindrical flat-bottomed hole that enlarges another coaxial hole used to seat a fastener head, nut or collar either partially or fully below the surface to clear an adjacent feature.

While the use of a spotface or counterbore is not recommended, if it must be used, the radius at the edge should be as large as possible, with 0.06 inch minimum and at least 0.13 inch recommended. The total depth of the counterbore/spotface should be kept to the minimum necessary to resolve the issue. Figure 18.4.15-1 illustrates the radius of a counterbore.



Spotface and Counterbores are not Recommended
Remove Minimum Material Necessary
Figure 18.4.15-1 Spotface / Counterbore Radius

18.4.16 Radius Blocks

Radius blocks are used to assist in the transfer of a tension load into a flange or clip. They are often used at the end of stiffener run-out areas, in tension clips, or in tension end-pads either by design or because the part is thin due to a manufacturing anomaly. Another place in which they are used is in the corner radii of composite stiffeners (integral or bonded) to reduce the interlaminar stresses.

Radius blocks must be machined to nest into the radius of the flange to web intersection or the analysis assumptions are not valid. The radius block should be machined/ground to the best fit possible and then installed with moldable plastic shim. Refer to Figure 18.4.16-1 for geometry and loading. Radius blocks shall be as stiff as or stiffer than the part they are mating with. Steel typically provides the best results because the high stiffness maximizes the effectiveness of the radius block, which will have the added benefit of reducing the repeated stresses in the fastener as discussed in Section 5.5.2. Because of corrosion concerns, titanium radius blocks are often used with graphite composites.

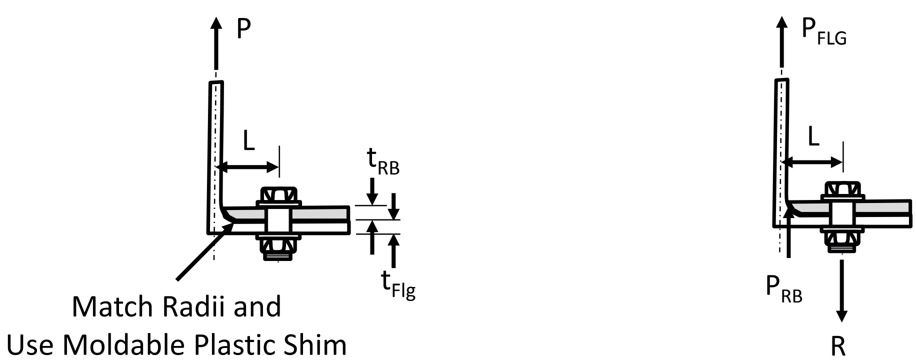


Figure 18.4.16-1 Radius Block Geometry and Loading

Analysis of the effectiveness of the radius block can be done be equating the deflection of the radius block, treated as a cantilever beam and the deflection of the flange, treated as a guided cantilever beam and apportioning the load accordingly. Referring to Figure 18.4.16-1, the deflection of the tip of the radius block is given as

$$\delta_{RB} = \frac{P_{RB}L^3}{3E_{RB}\left(\frac{bt_{RB}^3}{12}\right)} = \frac{4P_{RB}L^3}{E_{RB}bt_{RB}^3}$$ **Equation 18.4.16-1**

Where
L is the length between the centerline of the vertical leg and the fastener (in)
P_{RB} is the portion of the load reacted by the radius block (lbs)
t_{RB} is the thickness of the radius block (in)
E_{RB} is the Young's Modulus of the radius block (psi)

The deflection of the flange is given as

$$\delta_{FLG} = \frac{P_{FLG}L^3}{12E_{FLG}\left(\frac{bt_{FLG}^3}{12}\right)} = \frac{P_{FLG}L^3}{E_{FLG}bt_{FLG}^3}$$ **Equation 18.4.16-2**

Where
P_{FLG} is the portion of the load reacted by the flange (lbs)
t_{FLG} is the thickness of the flange (in)
E_{FLG} is the Young's Modulus of the flange (psi)

The total applied load P is equal to the sum of P_{RB} and P_{FLG}, thus Equation 18.4.16-2 can be rewritten as

$$\delta_{FLG} = \frac{(P - P_{RB})L^3}{E_{FLG}bt_{FLG}^3}$$ **Equation 18.4.16-3**

Equating the deflection of the radius block, Equation 18.4.16-1, to the deflection of the flange, Equation 18.4.16-3, and solving for P_{RB} and P_{FLG}

$$P_{RB} = P\left[\frac{1}{1 + \frac{4E_{FLG}t_{FLG}^3}{E_{RB}t_{RB}^3}}\right]$$ **Equation 18.4.16-4**

$$P_{FLG} = P - P_{RB}$$ **Equation 18.4.16-5**

While mathematically, it would be possible to make the radius block so thick that it analytically reacts most if not all of the load; practically speaking radius block becomes less effective the thicker the radius block gets relative to the flange thickness and the assumptions used are no longer valid. Typically the maximum thickness, t_{RB} is limited to $1.5t_{FLG}$ or when P_{RB} equals P_{FLG}, whichever is less.

The flange can be analyzed for the reduced load P_{FLG} of Equation 18.4.16-5 per method described in Section 5.3.5 and the radius block can be analyzed for bending using applied load P_{RB} of Equation 18.4.16-4 and assuming a cantilever beam of length, L_{RB}, and the gross area at Point A of Figure 18.4.16-2.

$$L_{RB} = L - {}^{2}\!/_{3}\,D - \frac{t_{FLG}}{2}$$ **Equation 18.4.16-6**

$$m_{RB} = P_{RB}L_{RB}$$ **Equation 18.4.16-7**

Where
L is as depicted in Figure 18.4.16-1 (in)
D is the fastener diameter (in)

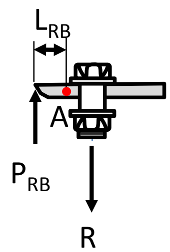


Figure 18.4.16-2 Radius Block Idealization

Typically the maximum stress in the radius block is limited to F_{tu}, so the allowable moment can be written as

$$M_{allow} = \frac{bt_{rb}^2 F_{tu}}{6} \qquad \textbf{Equation 18.4.16-8}$$

where b is the width of the radius block

The margin of safety of the radius block can be written as

$$M.S._{bending-RB} = \frac{M_{allow}}{m_{rb}} - 1 \qquad \textbf{Equation 18.4.16-9}$$

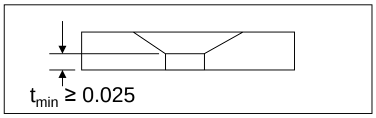
In some cases, radius blocks are used if fasteners are located too close to the radius as a means of providing a flat surface for the fastener. If this is the case and there is low tension load transfer, the radius block can be made from a material with equal stiffness as the mating part. Additionally thickness and fit requirements discussed above do not apply and no margin of safety need be calculated.

18.4.17 Sharp Corners and Knife Edges

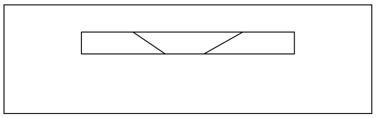
There should be no sharp corners or knife edges permitted anywhere in an airplane. In addition to this being a safety consideration, sharp corners are usually at points of maximum stress and can be rough with minute hairline cracks as a result of machining. They are easily nicked and bumped in handling and become an excellent source of fatigue cracks. The note "break all sharp edges" is supposed to remove the microscopic cracks and nicks, but this note will not prevent damage to completed parts. All sharp edges, either on the aircraft or on repair parts should be blended smooth or prevented by calling out a minimum thickness. Figure 18.4.7-1 illustrates this.

Figure 18.4.17-1Recommended Practice for Preventing Sharp Edges

A knife edge occurs on long edge of a chamfer or in a countersunk hole if the countersink extends through the thickness of the material or where a part is tapered. The knife edge is worse than just a sharp corner. Even though the sharp edge is "broken," the knife edge is a natural stress intensifier and has the potential to cause fatigue issues. If the potential for a knife edge exists, the drawings should specify a minimum height remaining, to preclude it from developing. An example is shown in Figure 18.4.17-2.



Preferred



Knife-edged

Figure 18.4.17-2 Illustration of a Knife-Edge Countersink Hole

If thin material is being used in a repair, alternatives to knife edging the material for a countersink fastener would be to use a dimple for the fastener to seat in, to go to a smaller fastener, go to a shallow head countersink fastener or to see if the fastener could be a protruding head. The latter option would require the approval of the aerodynamics group and possibly the low observables group. But if the repair is in an area where the flow field is already disrupted it may be acceptable. Another alternative is to use a reduced head countersunk fastener if significant tension loads are not present in the fastener.

Some older Lockheed Martin aircraft have knife edge countersink holes in selected areas by design. The preferred solution would be to avoid knife edging any repair fasteners, although this may not be possible in these areas. In any event, adding new areas where knife edge holes exist should be avoided.

18.4.18 Blend and Smooth

Blend and smooth is a disposition which is used for a number of reasons. It is primarily to restore the surface to an acceptable surface finish while removing cusps on mismatched radii, removing scratches or gouges, drill starts, or any other irregularity on the surface or the edge of the part. It can also be used at the edge of a part, either separately or in combination with a trim operation, to remove defects such as delaminations or gouges. On the QAR, often the disposition includes a caution to minimize the amount of material that is removed so that the part thickness or width is not reduced below the blueprint minimum.

If the defect to be removed is relatively sharp, a blend ratio, *e.g.* 20:1 minimum, is recommended with a minimum blend ratio of 10:1 if the local stresses permit. The QAR should also ask that the final remaining part thickness be reported at final inspection. The generous blend ratio is done to improve fatigue life by minimizing sharp changes in thickness or potential stress concentrations. A blend repair of this type is shown in Figure 18.4.18-1.

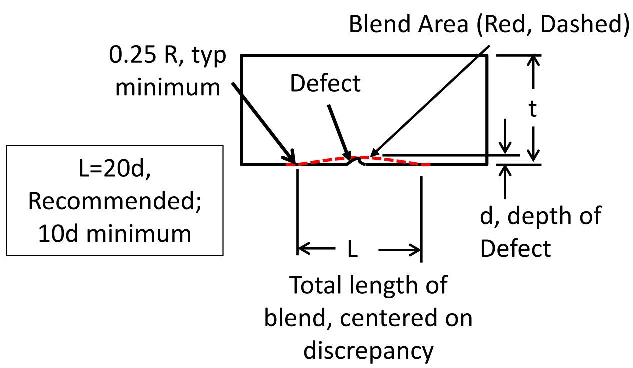


Figure 18.4.18-1 Blend of Shallow Scratch, Gouge or Notch in the Surface of a Part

For scratches, gouges and drill starts or any other defect which may have a sharp radius at the bottom of the defect, the sharp radius must be removed. If not, it will serve as a potential crack initiation site. This may require sufficient material removal to warrant the addition of a doubler. The blend is often dispositioned in conjunction with a penetrant inspection to ensure any sharp notches are removed.

Where defects occur at the edge of parts, such as a hole break-out or a dent or gouge, or in a composite section, the defective material should be trimmed away and blended with a gradual return to full material width. For further discussion on composite parts, refer to Reference 18-5, Section 18.

Radii should be generous to preclude any sharp edges or stress concentration effects. This is illustrated in Figure 18.4.18-2. Care should be taken to not remove any more material than is required to remove the defect.

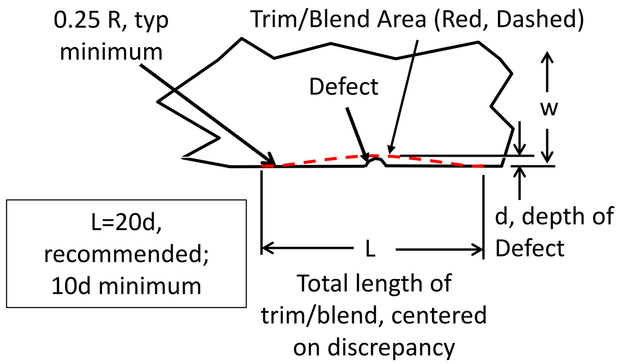


Figure 18.4.18-2 Trim and Blend of Edge Defect

If fasteners are located in this region, there may be some reduction of edge distance in the region of the trim; however, the reduction in e/D below blueprint design should be minimized. Trimming is acceptable if e/D restrictions discussed in Sections 18.4.9 and 18.4.10 are met and positive static and life margins can be shown for the reduced edge distance.

18.4.19 Surface Peening

Shot peening is a surface cold work process which creates compression residual stresses on the surface of the part improving fatigue life and reducing susceptibility to some types of stress corrosion. It is accomplished by impacting the surface of the part with round beads made of glass, organic material, or metal with sufficient force to plastically deform the surface. Controlling the intensity and coverage of the peening operation are keys to successfully obtaining the desired surface compression stress. Over-peening can cause fatigue cracks. Each program has program specifications which define and control the approved process.

Another peening process is laser peening or laser shock peening which uses high energy laser beams on part surfaces to create the residual compressive stress field.

Since many fatigue cracks start on the surface of the part creating a compression stress field in lieu of the surface tension stresses that result from many operations such as grinding, rolling, forging, etc. is very beneficial. Often the design drawings require overall shot peening of surfaces in durability and fracture critical machined parts. It can also be a useful tool in the repair and salvage of defective parts.

In repairs such as grinding, peening can remove the residual tensile stress on the ground surface. If an interference-fit bushing or a fastener is installed with edge distance under 1.5D, local peening on the edge of the part is recommended.

No benefit is typically taken in the analysis; however this remedial action can improve the life of the part.

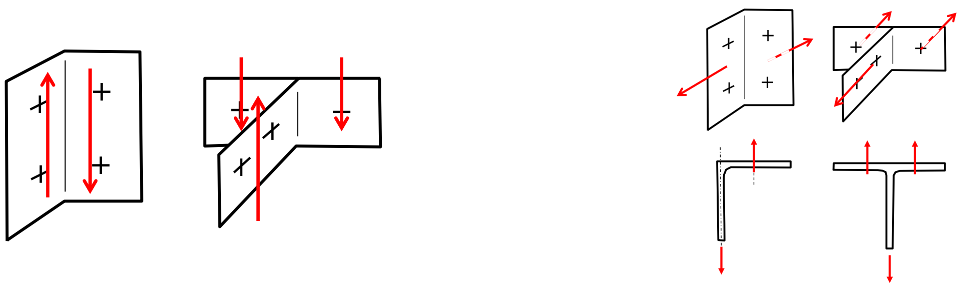
18.4.20 Shear or Tension Clip Repair

Repairs can involve the replacement of integral flanges with angle clips or fittings. A full understanding of the loads, both directly applied and induced is necessary to prevent early failure. Always draw a balanced free-body diagram and include all load components. When a tension load is applied normal to the outstanding leg of an angle, tension, bending, and shear stresses occur. If the outstanding leg is not rigidly supported, the allowable load is usually limited by considerations of permissible deflection and permanent set. If the attachment points through which the load is transmitted to the angle are spaced too widely, the full strength of the angle is not developed since local deformation at the attachment points becomes the limiting factor. Fastener spacing should be between 4D and 7D. Section 5.3.2, 5.3.5.and 5.3.6 should be reviewed depending on the types of loads present.

For the design of repairs involving repair angles or tees, the following guidelines should be followed:

- Generous corner fillets on extruded angles and minimum[9] bend radii on formed sheet metal angles shall be used in all cases where applied loads tend to "open" or "close" the angle.
- For maximum strength, the bolt or rivet head should be adjacent to the point of tangency of the fillet or bend radius
- Three (3) methods of attachment in their order of preference are: Bolt head inside the flange, manufactured rivet head inside the flange, formed rivet head (rivet tail side) inside the flange
- The repair angle should be no thinner than mating materials, and may need to be thicker depending on loading, geometry and fastener attachment scheme.

Many repair angles function as both shear clips and tension clips and the analysis and design should reflect both design cases. Figure 18.4.20-1 illustrates the terminology. For shear clips, a minimum of two fasteners is required in each flange for angles and for tees a minimum of two fasteners are required in the leg and one in each flange. See Section 5.3.2 for a full discussion of shear clips.



Shear Clips (Fasteners and flanges are loaded in shear) Tension Clip (At least one flange and its fasteners are loaded in tension)

Figure 18.4.20-1 Illustration of Shear and Tension Clips

Examples of acceptable shear clip configurations are shown in Figure 18.4.20-2. These configurations allow for the eccentric moments resulting from the shear transfer to be reacted by a force couple in the fasteners.

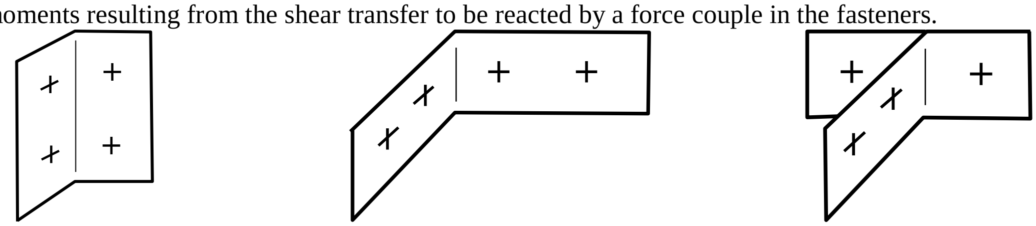


Figure 18.4.20-2 Acceptable Shear Clip Configurations

Unacceptable shear clip configurations are shown in Figure 18.4.20-3. Because of the single fastener in the flange, the eccentric moments resulting from the shear transfer must be reacted in the clip in bending rather than being reacted by a force couple in the fasteners. See Section 5.3.2 for further discussion.

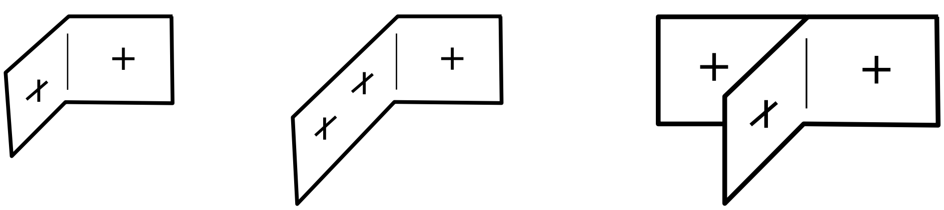


Figure 18.4.20-3 Unacceptable Shear Clip Configurations: Do Not Use

[9] Use the minimum manufacturing-recommended bend radius based on material and thickness. Do not use special limits on bend radius.

If the clip also functions as a tension fitting then

- Heel-toe effects per Section 5.3.5 should be considered for fastener loads. These need to be combined with any shear loads present.
- Flange tension strength calculations should be performed per Section 5.3.5 and combined with shear loads resulting from the shear clip analysis.

18.4.21 Material Tapering

Tapering of repair material whether it is thickness of a doubler or reinforcement or the run-out of a stiffener or the flanges of an I-Beam when the cap and web are not tied into adjacent structure, is an important part of designing a repair. Tapering the material reduces the stress concentration at the end of the repair section and allows the load to transition into adjacent structure in a more controlled fashion, minimizes the effects of load peaking on fasteners or bond line to improve both the static strength and life.

Figure 18.4.21-1 illustrates the tapering of stiffener run-out and flanges. Note the flanges are typically tapered symmetrically. This approach is necessary to reduce the stiffness of the stiffener and also to force a shift of the neutral axis of the cross-section toward the panel on which the stiffener is mounted because at the end of the stiffener, the neutral axis is at the mid-plane of the panel. Any difference between the neutral axis of the stiffener-panel combination and the panel-only when the stiffener ends results in a bending moment which must be coupled between the panel at the end of the stiffener and the last set of fasteners or bond line, if bonded. This additional moment, which can be significant, can cause unexpected static or fatigue failures. Additionally, if the stiffener is fastened tapering the stiffener results in a more uniform load transfer through the joint and ensures all of the joint fasteners are working. If the desired degree of taper cannot be achieved, as a minimum, the taper should begin at the first row of joint fasteners in the stiffener. Also, the addition of radius blocks can help to mitigate the effects of the bending moment. See Section 18.4.16 for a discussion of radius blocks.

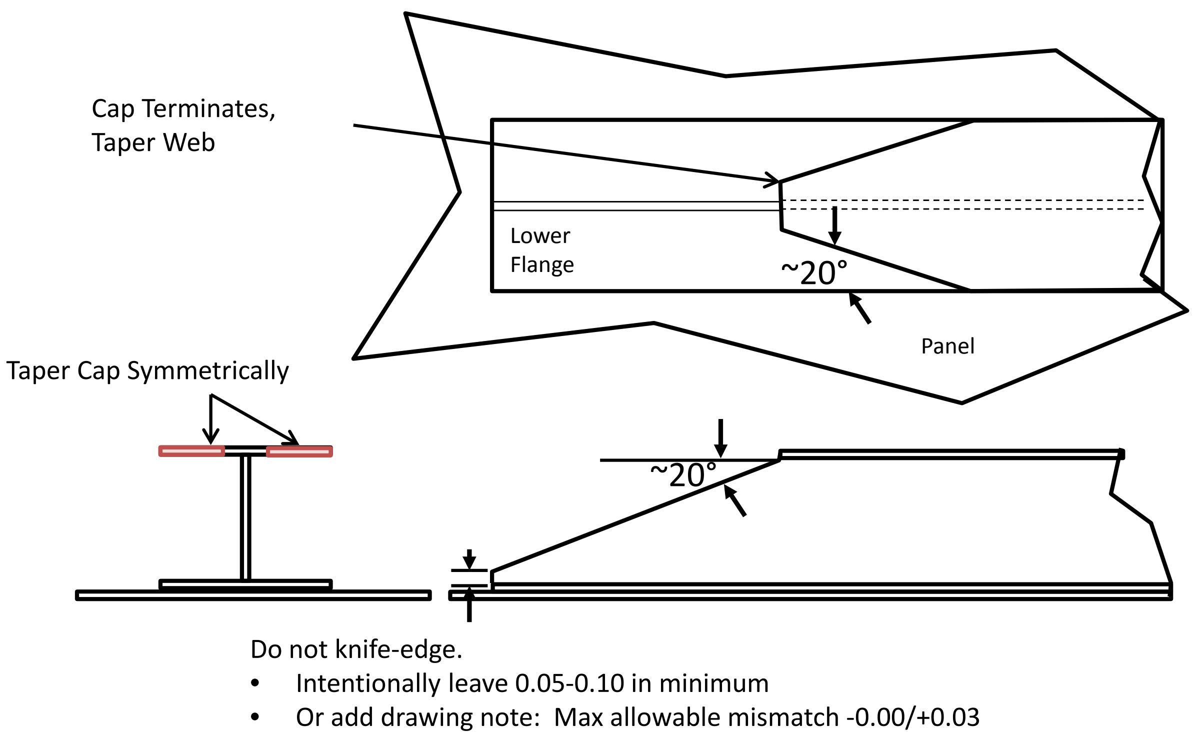
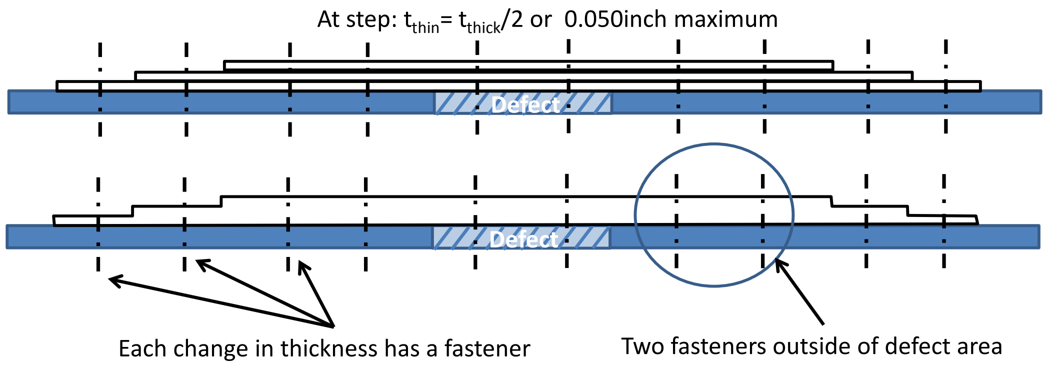


Figure 18.4.21-1 Recommended Tapering for Stiffeners

Doublers and reinforcements also require a tapering of material to minimize the “hard point effect” or the effect of having a sudden change in stiffness because of the addition of a thick layer of material. In addition, tapering of material can reduce the likelihood of the first or last doubler fastener causing a life reduction in the existing joint due to peaking of the load. Tapering results in a more overall uniform load distribution in the repair. At each material step, at least one fastener should go through each step to minimize working of the step due to eccentric bending. The recommended step size is, typically $t_{thick}/2$ with a maximum of 0.050 inch. Figure 18.4.21-2 shows the preferred geometry, while Figure 18.4.21-3 shows some approaches that should be avoided.



All corner and fillet radii should be 0.13 inch or greater (not shown)

Figure 18.4.21-2 Preferred Approach for Tapering of Material in Doublers and Reinforcements

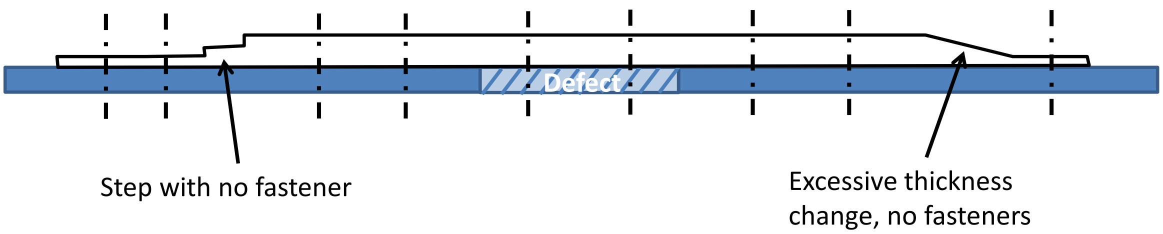


Figure 18.4.21-3 Geometry to Avoid in Tapering Doublers and Reinforcement Material

Note that for the machined detail, all corner radii should be at least 0.13 inch to minimize the effect of the stress concentration.

In analyzing a doubler reinforcement of critical locations it is crucial to determine the fastener load distribution. This may be done using spring model analysis tools found in IDAT or through the use of a local finite element model. Key areas to examine for durability or damage tolerance are the first and last fastener at the ends of the repair as well as fasteners adjacent to any discontinuities.

18.4.22 Cutout and Material Removal

For some repair scenarios, the removal of defect or damage is required. The shape of the removed material can have a major impact on the life of the part. Figure 18.4.22-1 shows the stress concentration resulting from various cutout shapes for axially loaded structure. The ellipse shape on the left is the preferred configuration while the diamond pattern on the far right, even with generous corner radii, shall not be used as it will have approximately 25% of the life expectancy of the preferred solution.

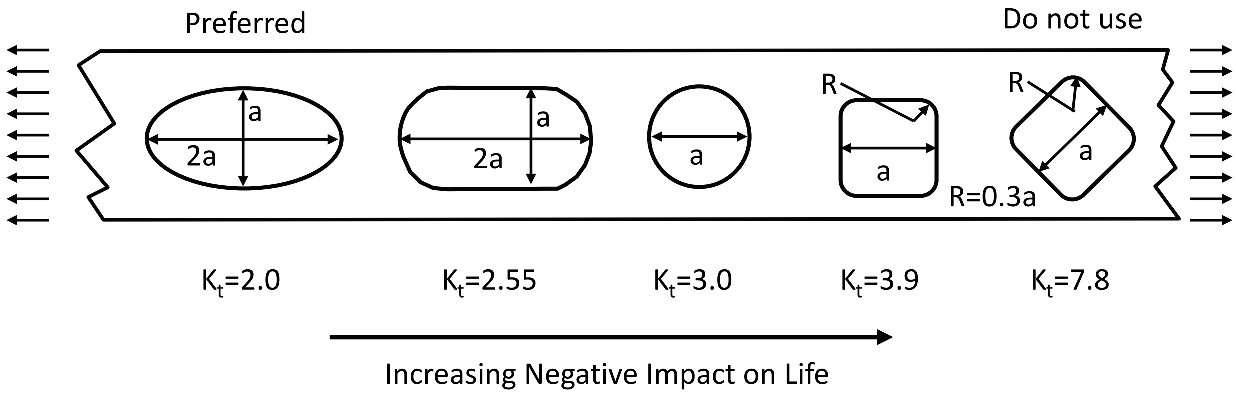


Figure 18.4.22-1 Preferred Cutout Shape

This same order of preference applies to the addition of a cutout for an access panel or antenna in post-production aircraft modifications. Rounded rectangular and diamond shaped holes should be avoided.

18.4.23 Stop Drilling of Cracks (Post Production Aircraft ONLY)

For repair of post-production aircraft, when repairing structure that has cracked, if the material containing the cracks cannot be removed, then prior to any additional repair, the crack should be stop drilled. This process adds a hole at the end of the crack to decrease the stress concentration of the sharp radius found at the end of the crack. Stop drilling can be an effective means of retarding the growth of the crack, particularly if the stress in the area is further reduced with the addition of a structural reinforcement. Not all customers approve of or will allow stop drilling.

Prior to pursuing this type of remediation, ensure that your customer is in agreement with the approach.

It is important that both surfaces where the crack is present be inspected using some type of non-destructive inspection such as eddy current or die penetrant because the very end of the crack must be located. The stop drill hole is centered at the crack tip and must eliminate the crack tip in order to be effective. Always check both surfaces of the material as there can be cracks which have crack tips in different locations. Some program repair manuals center the stop drill hole such that its outer diameter is at the end of the crack or slightly beyond. This is done to ensure the tip of the crack is captured within the drilled hole.

The recommended hole diameter is minimum of three times the thickness of the material in which the crack is located and may be as high as five times the thickness, with a minimum hole diameter of 0.098 inch and a maximum hole diameter of 0.25 inch.

Use an expanding rivet such as an AD rivet to fill the hole and cold work the periphery. If a reinforcement member is used to reduce stresses, the doubler should be attached using this rivet. It is preferred that the rivet not be hidden below the doubler as this makes further inspections and potential removal significantly more difficult. With this type of repair, a regular inspection plan for the area to monitor any new crack growth is recommended.

Never use stop drilling to repair a part or assembly on the production line. Cracked parts must have the crack removed or the part must be replaced.

18.4.24 Material Selection and Dissimilar Material Load Distribution

Reinforcement material, doublers and structural shims are typically made of the same material as the as-designed structure. If a particular material is unavailable, a stronger alloy of the same parent material is often used. For example a 7XXX aluminum alloy might be used in the repair of a 2XXX aluminum alloy.

If contour is involved the alloy might be chosen for its formability. Some recommendations for aluminum which can be formed are 6061-T4 or 6013-T4. Both should be heat treated to the –T6 condition after forming.

Table 18.4.24-1 provides a list of commonly used alloys and formability guidelines for comparison purposes. Always consult with Materials and Process Engineering and Producibility Engineering before the final material decision is made.

Table 18.4.24-1 Common Aluminum Alloy Sheet Materials with Formability Guidelines

Aluminum Alloy and Temper	Discussion	Formability Guidelines
2024-T3 Clad	• High tear strength, moderate formability • Do not use 2024-T3 Clad greater than 0.112 due to stress corrosion cracking concerns	3t bend radius for t<0.057″ 4t bend radius for 0.058″<t<0.110″ 5t bend radius for 0.110″<t<0.112″ t>0.120″, age material to 2024-T81
2024-T42	• Do not use – this is a "heat treat by user" temper and material properties in MMPDS are process capability only	
7075-T62	• Do not use – this is a "heat treat by user" temper and material properties in MMPDS are process capability only	
7075-T6 Clad	• High Strength • Flat and Single Degree of Curvature doublers. • Do not use bare sheet • Do not use 7075-T6 Clad greater than 0.112 due to stress corrosion cracking concerns	5t bend radius for t<0.057″ 6t bend radius for 0.058″<t<0.095″ 7t bend radius for 0.0.095″<t<0.110″
7075-T76 Clad	• High Strength, High Tear Strength • Flat and single degree of curvature doublers	0.110″<t<0.250″
7475-T76 Clad	• High Strength, High Tear Strength	

Aluminum materials with a "D" stress corrosion cracking (SCC) rating in any grain orientation should not be used in repairs. A full listing of materials that have been characterized for SCC is in Reference 18-4 Section 3.1.2.3. Materials with "A" or "B" ratings are preferred but a "C" rating is acceptable. Newer aluminum alloys no longer carry the "A"-"D" rating but instead have values of maximum sustained stress at which tension specimens will not fail when immersed in a 3.5% salt solution. These values are also published in Reference 18.4, Section 3.1.2.3. The published stresses are not for design, but should be used on a comparative basis, *e.g.*, a material with a higher value has better stress corrosion cracking resistance. Many programs set a minimum desired value of 25 ksi.

Often reinforcement materials are chosen for stiffness, superior strength or other reasons. If dissimilar materials come together to form an axial load carrying member, the load on the member must be distributed assuming all parts are straining together. It is insufficient to use only the area of the part, the Young's Modulus should also be considered.

Thus the distribution in a part would be given by

$$P_i = P \cdot \frac{E_i A_i}{\sum_{j=1}^{n} E_j A_j}$$

where
P is the total load (lbs)
P_i us the load in member i (lbs)
E_i is the Young's Modulus of member i (psi)
A_i is the cross-sectional area of member i (psi)
E_j is the Young's Modulus of member j (psi)
A_j is the cross-sectional area of member j (psi)

When using dissimilar materials, be aware of the potential for thermal stresses to exist based on the differences in the coefficient of thermal expansion between the different materials. These may add to the load in the joint in a deleterious way. Also of concern is the potential for galvanic corrosion and appropriate corrosion protection should be included as part of any repair.

18.4.25 Hybrid Composite/Metal Assembly Repairs

In many of today's newer aircraft, there are a large number of assemblies which comprise both composite and metal parts. Typically, the rules given in this section for the metals and those given in PM4056 Section 19 for the composites both would apply, respectively, to the hybrid structure. Additionally in some cases composite structure may be repaired with metal doublers and similarly metal structure may be repaired with composite straps. In addition to the discussion in Section 18.4.24, there are some other areas of concern.

Dissimilar materials in intimate contact can lead to galvanic corrosion and appropriate sealant, barriers, and wet installed fasteners should be used. Section 3.4 discusses different types of corrosion and the analyst should encourage participation of the Materials and Processing engineers at the earliest point in the process as possible. Another concern is differences in the coefficient of thermal expansion between the two materials and the potential for significant increases in the stress state due to thermal stresses developing. Any analysis of the parts should address this issue.

When installing repairs of dissimilar materials destack and deburr is required. This is typically easily accomplished; however, if one of the materials is a composite and the other is a metal and if the entry side for the drill operation is in the composite, destack and deburr may not be required but deburr of the exit side of the metal surface is still required. See Section 18.4.12 for further discussion.

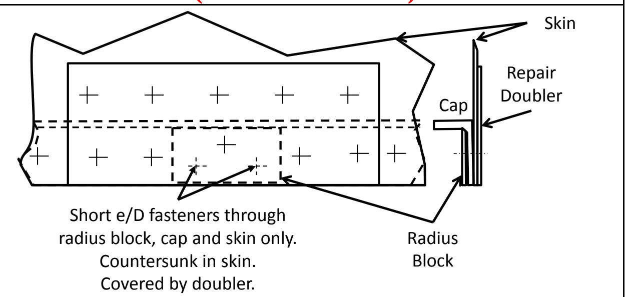
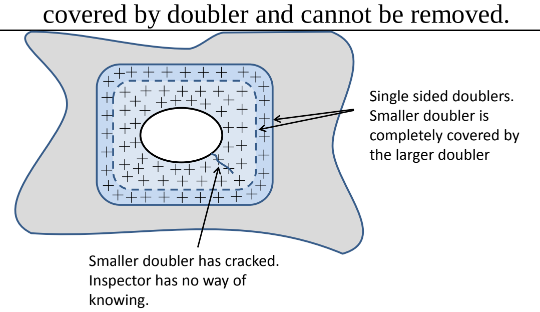
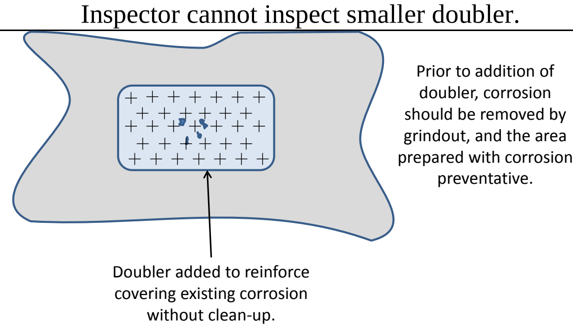
A final area of concern involves on-aircraft elevated temperature bonding of patches or repairs. Any metallic substructure can serve as a large heat sink for repairs performed using thermal blankets or heat lamps causing uneven heating of the repair. There is also the potential for damage to the metallic substructure (in addition to the composite skins) if the process is not followed or the thermal controller malfunctions. Repairs involving heat lamps or heat blankets should be monitored and not left unattended. If overheating of the metal structure is suspected contact Materials and Processing Engineering for help in determining maximum temperature and likely material property reductions.

18.4.26 Design for Inspection

Repairs installed on aircraft should allow for externally inspectable repairs, not only after the repair is completed to ensure it was done properly, but in the field, by the customer. In the field, the inspections are typically looking to confirm that the repair has not deteriorated, *i.e.*, no loose fasteners, no corrosion, etc., as well as making sure no fatigue cracking or catastrophic failure has occurred. As result, good, externally inspectable repairs typically do not hide features or details which may cause downstream fatigue issues.

Table 18.4.25-1 provides some examples of repairs that do not meet inspectability goals and should be avoided.

Table 18.4.26-1 Examples of Details to Avoid for Maximum Inspectability

Detail to Avoid	Examples of Uninspectable Detail (Do NOT use these)
Hidden Fasteners Do not cover up fasteners with doublers. If there are one or more fasteners under a doubler, the inspectors may not know they exist. • Remove any existing fasteners and reinstall through the doubler. • While there may still be cracking in a lower layer, the inspector and field engineer knows there are holes present, can remove the fastener and do an eddy-current inspection.	 Short e/D fasteners cannot be inspected because they are covered by doubler and cannot be removed.
Buried Doublers Do not install one doubler over another, completely covering the inner doubler. • Inspector may not know there is an inner doubler. • Inner doubler can crack with no outward indication so there is no reason to pull the fasteners and inspect further. • Inner doubler may have hidden corrosion.	 Inspector cannot inspect smaller doubler.
Hidden Corrosion Do not cover areas of corrosion with a doubler. Remove all corrosion by grinding out, NDI and apply appropriate corrosion protections (paint, sealant, etc.) prior to installation of any doublers.	

Following these guidelines can become more of an issue in post-production repairs than in production repairs since the post-production repair may be repairing an already repaired part of the aircraft.

18.4.27 Panel Reinforcement/Repair

As was discussed in Section 18.4.22, it is necessary at times to trim away defective material and as shown in Figure 18.4.22-1 there are preferred shapes for the cutout to improve life. There should be no attempt made to merely reinforce an irregularly shaped hole. In the case of a hole, a filler should be placed in the hole area and additional fasteners at 4-6D spacing added through the entire stack-up.

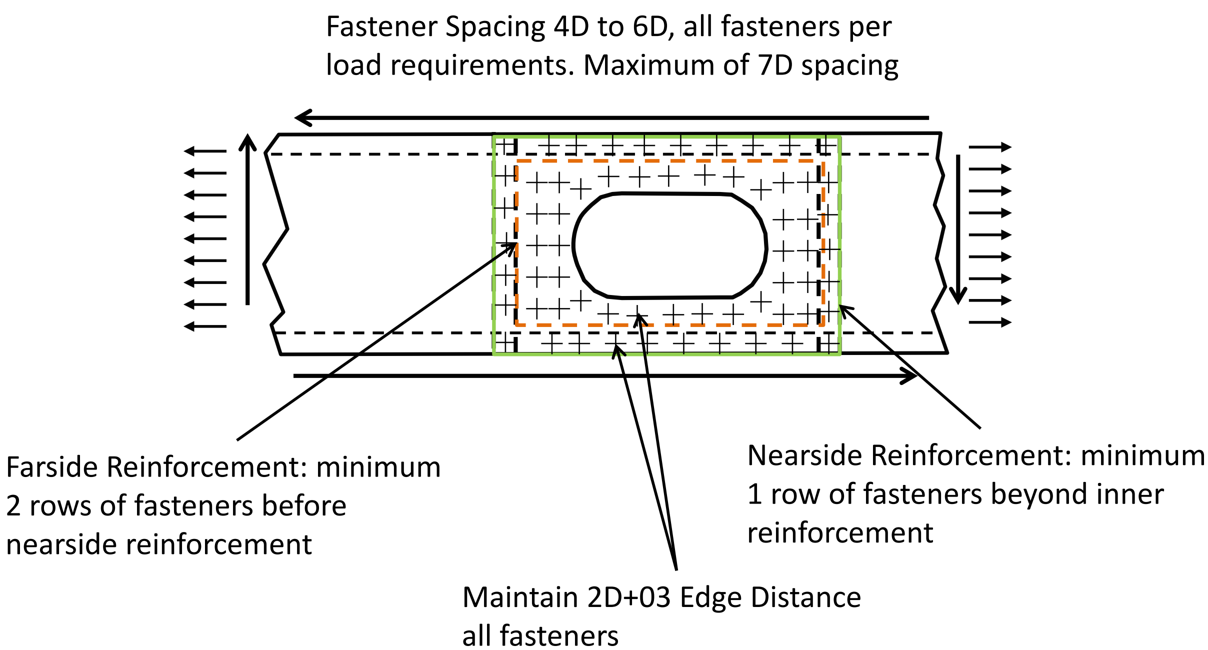
If an opening or cutout is to remain open, reinforcement of the cutout is often necessary for all but the most insignificant loading if the hole is greater than 0.75 in. in diameter. These same techniques can be used for repair of a hole or reinforcement of a panel, with no hole, to reduce the stress level. PM4057 Section 6.7 discusses how to determine, with the presence of the hole, the reduced initial buckling stress if the web is loaded in shear, as well as how to determine the reduced allowable shear stress if the web undergoes diagonal tension buckling. Section 6.7.4.2 discusses the design of ring doubler reinforcement for a circular hole.

In some cases a ring doubler is not sufficient and a larger doubler or a doubler with framing members is required. If the cutout is greater than 50% of the bay size or spans multiple bays, if a component (pump, blade antenna, etc.) is mounted to the web or skin in the area of the cutout, if the internal loads are sufficiently high, or if the shape of the hole is one of the less desirable shapes, then in addition to the doubler, framing around the hole may be necessary to support any out of plane loads, to add further reinforcement for the missing material or to lower the load level at the cutout. Guidelines for the design of the doubler and framing members are listed in Table 18.4.27-1. See Figure 18.4.27-1 for an illustration. Additionally the concepts covered in Section 18.4-26, Designing for Inspection need to be incorporated into any reinforcement repair.

Table 18.4.27-1 Cutout Reinforcement / Doubler Guidelines

Feature	Guideline	Discussion
Fasteners	Minimum 2 rows of fasteners in doubler outside of hole. This may include fasteners common to reinforcement stiffeners.	To ensure doublers are acting with structure and picking up load
	Fasteners should be interference fit or rivets. Blind fasteners shall not be used.	
	Fastener spacing minimum of 4D, maximum of 7D. Load magnitude will dictate specific spacing.	
	All fasteners 2D+0.03 edge distances (edge of part and edge of hole)	
	If reinforcement covers existing countersink fastener hole use bushing in countersink to prevent shanking of fastener	Open shank on fastener reduces strength and life.
Doubler / Cutout Reinforcement	Where possible, reinforcement should be symmetric on web. One side should extend a minimum of 1 row past the other. Material thickness should be tapered per Section 18.4.21, for thick doublers. Maximum thickness step is t/2 or 0.050 in.	Eliminate moments induced in the web. Extending one doubler past the other minimizes hard points, peaking of loads on last fastener row and improves fatigue life. Allows first row of fasteners in doubler to be visually inspected.
	If reinforcement is only on one side, extra care in tapering material per Section 18.4.21 is necessary.	Minimizes hard points, peaking of loads on last fastener row and improves fatigue life
	Material alloy and heat treat should be the same as the web/skin. Initial total reinforcement thickness should be the same as the web.	Loading/stresses will dictate if this needs to be increased.
	If doubler is external and aerodynamic smoothness or low observables require minimum thickness, use of a thin steel doubler is recommended. Titanium may also be used. See Section 18.4.21 for distribution of loads in dissimilar materials.	Minimum thickness is 0.03 in. to preclude cutting fastener with reinforcement. If rivets are used, install doubler with monel or steel rivets. Ensure adequate corrosion protections to prevent galvanic corrosion issues including fay surface sealant and wet-installed fasteners.

Feature	Guideline	Discussion
	If cutout is more than 50% of height or width of web, reinforcement should pick up adjacent stiffeners/caps.	Depending on the size of the bay, the stress level and whether or not the web/skin is buckled, consideration of adding framing members should be given.
	If a pump or antenna is mounted on web/skin, reinforcement should pick up adjacent stiffeners/caps.	These types of items attached to webs/skins impart overturning moment loads. By extending the doubler to the adjacent stiffening member, if sufficiently close, the resulting out-of-plane force couple can be reacted with minimum impact to structural integrity. If stiffeners are not sufficiently close, additional framing members should be added.
	If both an external doubler and an internal stiffener or stiffener reinforcement are required, extend the stiffener or stiffener reinforcement fasteners one row beyond the doubler.	Allows first row of fasteners in stiffener or reinforcement to be visually inspected.
Framing members	If a cutout extends more than one bay or as noted above, framing members should be added. Framing members should end on an existing stiffener, frame, or cap and not on skin/web only.	Framing members, if not ended on an existing framing member could cause fatigue issues in skin/web.



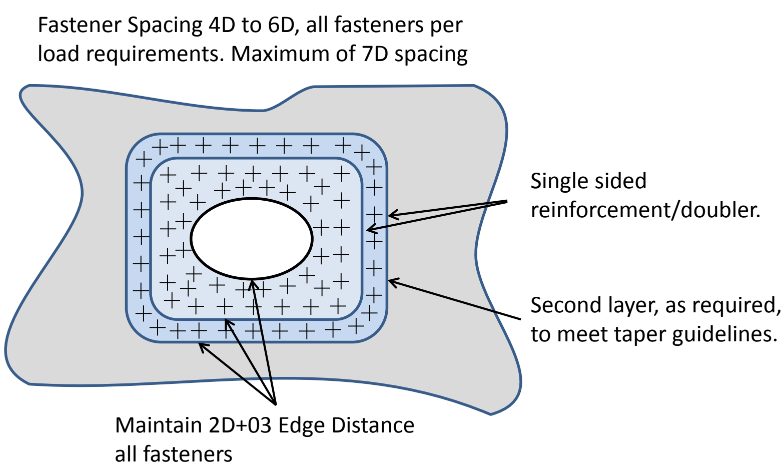


Figure 18.4.27-1 Reinforcement Recommendations for Cutouts

Sometimes a required repair or a given defect is acceptable when reviewed for static strength, but it has an unacceptable negative impact on life. In that event, one possible option would be to add a reinforcement which reduces the overall stress in the area. All of the guidelines provided above would be applicable including maintaining appropriate edge distance on all fasteners, tapering of material to reduce hard point effects or load peaking at the edge of the reinforcement, and fastener fit to ensure the reinforcement is effective.

Bonded reinforcements are also an effective means of providing reinforcement materials to reduce stress levels; however, existing fasteners should not be covered and hidden by the reinforcement. See Section 18.4.26 for further discussion on designing for inspection.

Stiff composites, such as boron-epoxy or metals such as steel can minimize thickness requirements but care must be taken to ensure galvanic corrosion is prevented. The load distribution discussion of Section 18.4.24 would also apply for composite reinforcements.

18.4.28 Repair or Reinforcement of Beams, Caps, or Stiffening Elements

When planning a repair or reinforcement of a stiffener or beam, select an arrangement that allows repair of the member as installed in the aircraft. Avoid using a single piece repair that mimics the shape of the original part such that manufacturing tolerances can either make it too small to fit over the original part or too large, requiring shims. Figure 18.4.28-1 illustrates possible repair sections as well as showing several sections which are not recommended. This set of details illustrates common cross-sections used in aircraft structure. These same approaches can be used for stiffeners machined as part of a larger integrally machined part.

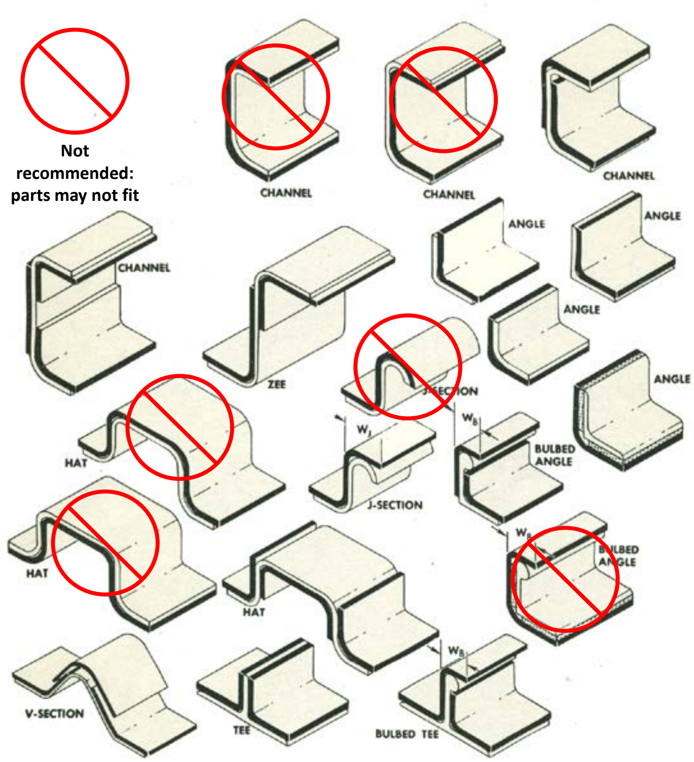


Figure 18.4.28-1 Suggested Reinforcements for Stiffeners

When a beam structure requires reinforcement due to damage, cracks, corrosion, etc., the material selected should be the same material as the damaged material and is generally one gage thicker. There must be sufficient fasteners to ensure the member load is spliced across the repair reinforcement and the reinforcement, in this case, should be sized to carry F_{tu} of the part being spliced.

The added material must restore the original cross-sectional area and stabilize any unsupported structure. Thus, for instance, if a cap and web must be repaired because of damage that severs the web, it is not sufficient to add a flat strap to the cap and a second strap to the web as the unsupported cap is not being stabilized by the repair. An example of this is shown in Figure 18.4.28-2.

While a double-sided repair is always preferred, if the depth of the affected area is sufficiently small, a single sided repair is adequate. In Figure 18.4.28-2, the depth of the crack depicted determines whether a single sided repair or a double sided repair is warranted.

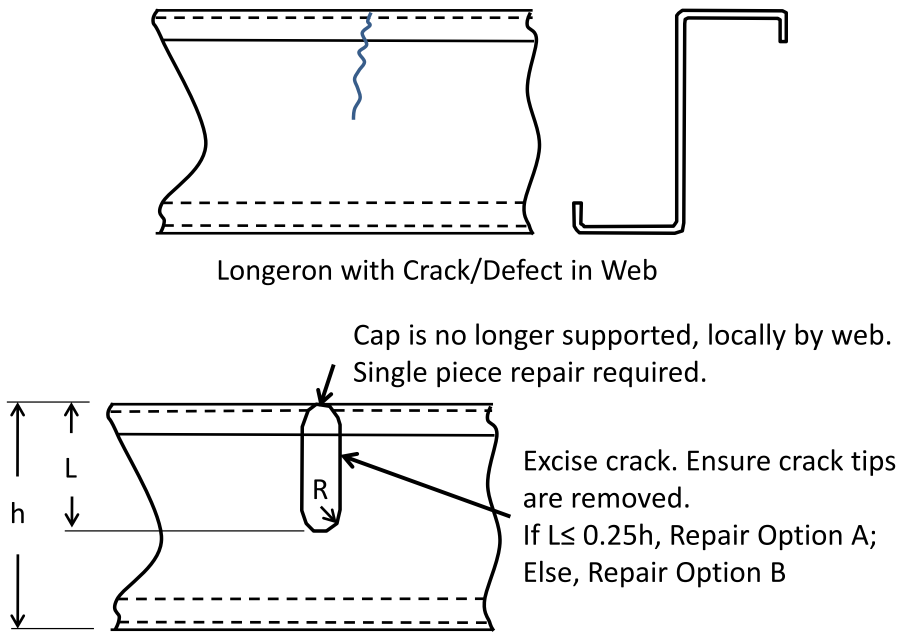


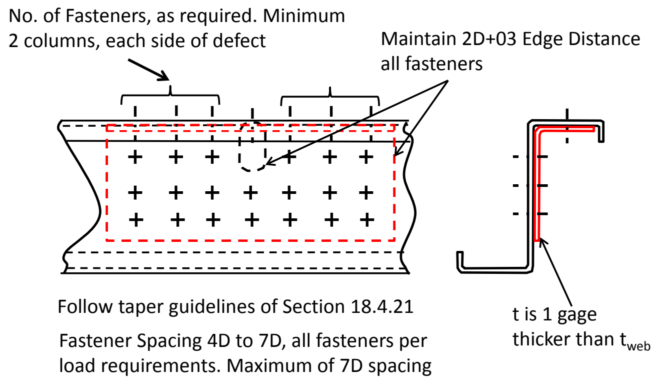
Figure 18.4.28-2 Longitudinal Member with Crack or Defect Resulting in an Unsupported Cap

Repair Option A, depicted in Figure 18.4.28-3, Top is for situations where the length of the material excised to remove the crack is less than 25% of the height of the beam. The repair angle is located on only one side of the web and is one gage thicker than the baseline part.

Option B, depicted in Figure 18.4.28-3, Bottom is a more extensive repair, required when the length of the material excised is more than 25% of the beam height. The thickness of the repair angles, located on both sides of the web are dependent on the extent of the material removed. The inner one, supporting the cap adjacent to the cracking is a minimum of the web thickness and typically one gage thicker, to provide adequate support to the cap. The reinforcement on the opposite side should be a minimum of ½ the web thickness depending on how close to the opposing cap the removed material comes to an extreme of one gage thicker than the web if the web and caps are completely severed.

Spacing of fasteners, particularly in areas spanning cutouts, needs to be 4D to 7D and inter-rivet buckling of the repair element in these areas needs to be checked. Material added should adhere to the tapering guidelines described in Section 18.4.21.

Repair Option A



Repair Option B

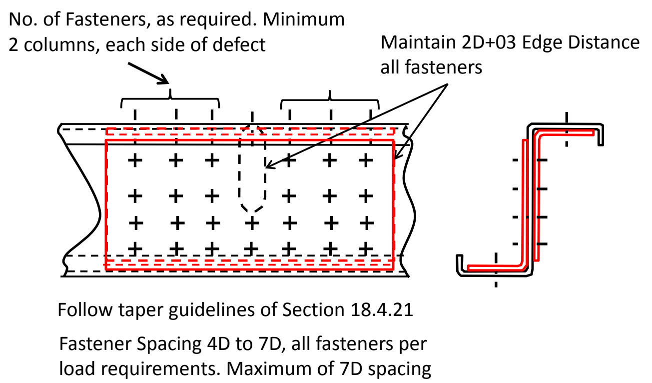


Figure 18.4.28-3 Splice Repair for Longitudinal Member with Unsupported Cap

18.4.29 Pressurized Skins and Avoiding Hard Points

Skins or webs take on a characteristic shape under pressure which is smooth and without steps or kicks. When the pressure is cycled to different levels there is a controlled change in shape and any fatigue issues typically come where the panel is attached to the substructure. If a component is mounted on the skin, either partially or fully in a bay, the shape of the deformation under pressure is impacted which can have a negative effect on the life of that skin panel because of the interaction of the panel deformations at the corners/edges of the component. Figure 18.4.29-1 illustrates the area of concern along with the pressure deformations. At the corners of pressurized bays the deformations will create a biaxial stress state which interacts with any overturning moment due to external pressure loads on the antenna. This condition can be avoided by extending the framing an additional bay.

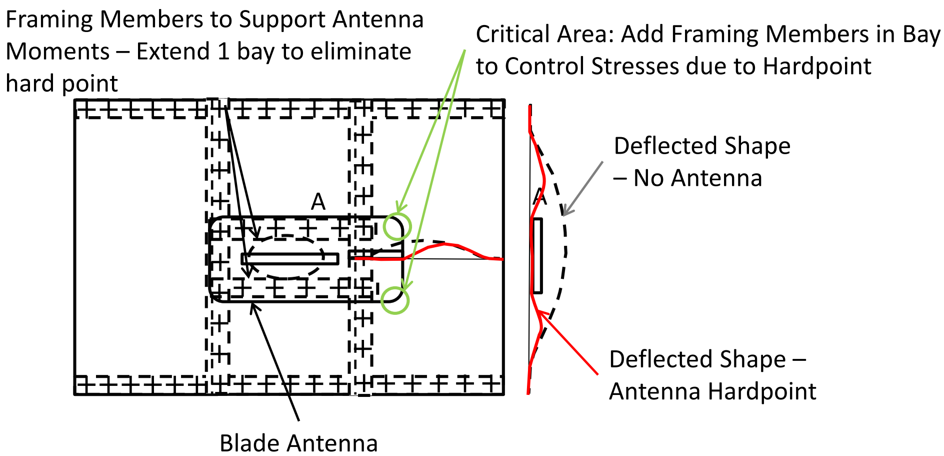


Figure 18.4.29-1 Effect of Hardpoint on Pressurized Skin Deformations

This effect can occur with any equipment mounted on pressurize bays and is not limited to shapes which have the footprint shown above.

18.5 Material Part Processing Defects

There are times when a part has been improperly processed by the material vendor and a question arises as to the impact on the structural integrity of the part. The summaries provided in this section are a high level look at this topic.

Always consult with your program Materials and Processes and/or the metallurgist prior to salvaging/dispositioning an improperly processed part.

18.5.1 Aluminum Material Processing Anomalies

18.5.1.1 Improper Heat Treat

The process by which properties are most greatly affected is heat treatment and re-heat treatment. Any operation involving changes in temperature for the purpose of altering the properties of an alloy is a heat treatment operation. By common usage, the term "heat treatment" often refers to hardening operations only, as opposed to annealing. There are two general types of heat treatment for aluminum:

- Softening operations, called annealing, for the purpose of making the alloy more formable or for removal of the effects of previous heat treatment.
- Hardening operations which involve:
  - Solution heat treatment or heating to a relatively high temperature
  - Quenching or cooling
  - Aging or holding the material at relatively low temperatures.

Here are some general facts concerning aluminum heat treatment:

- Annealing removes the effect of previous heat treatment. Therefore, if an alloy in a heat treated temper such as -T4, -T6, -T76, -T73, etc., is annealed for any reason, the part must be re-solution heat treated to restore it to a hardened condition.
- Annealing removes the effect of previous cold work. This is, of course, desirable where the intent is to soften the part for additional forming. However, in the few cases where we use alloys in the cold worked condition, *e.g.*, -T3 and -T8, annealing will lower the strength below the design allowables.

Re-solution heat treatment restores the properties to the condition before the anneal process. With the exceptions discussed below, parts can be re-heat treated, to correct an improper heat treat, after an intermediate anneal, or for any other reason, to produce a part with full properties. Furthermore, provided the operation is performed correctly, this operation can be repeated any number of times, and the final material properties will be the same. Thus, re-heat treatment is a good solution for returning the material to the design condition. It should be noted, however, once a part has been machined from thick plate or forging, there are surface residual stresses present that may cause the part to warp significantly during solution heat treat.

Re-solution heat treatment has limitations as follows:

- Each time a clad product is heated to the solution heat treat temperature, some diffusion of the cladding into the core takes place which lowers the effectiveness of the cladding in protecting the core from corrosion. Therefore, the number of reheat treatments must be restricted to one for parts up to 0.125 inch thick and two for gages over 0.125 inch thick.
- All of the heat treatable aluminum alloys are subject to eutectic melting. Eutectic melting can occur during solution heat treating if the upper temperature limit is exceeded. If for any reason the upper temperature limit is exceeded during solution heat treatment it must be assumed that eutectic melting has occurred. To confirm this, select from the heat treat furnace load a part (or parts), from the hottest zone of the furnace and have a careful metallurgical examination made of sections cut from the part. If no evidence of eutectic melting can be detected, parts have not been damaged. If evidence of eutectic melting is detected, the parts must be scrapped. Practically speaking, it can be difficult to identify eutectic melting so in most cases if the upper temperature limit has been exceeded by more than a couple of degrees, the part is generally scrapped.

Table 18.5.1-1 provides a summary of possible heat treatment anomalies that could occur in aluminum materials, rework scenarios and impact on the material properties. Materials and Processes should always be consulted to determine the best approach for rework and the final metallurgical state.

Aluminum alloys are not only hardened or strengthened by a heat treat process. They can also be strengthened by cold working or by a combination of heat treat and cold work. Cold working which results in guaranteed, uniform increase in properties can be performed only at the metal producing mill. Cold work product can be purchased, but salvage operations cannot produce the same type of cold work resulting in the same properties. Furthermore, if any product whose properties depend wholly or partially on cold work is annealed or solution heat treated, then the strength due to cold working is gone, and can't be restored.

Table 18.5.1-1 does not apply for alloys that are strengthened by cold work or cold work in conjunction with heat treatment.

Table 18.5.1-1 Discussion of Defects in Heat Treat of Aluminum Materials on Material Strength Properties

Material Defect Reported	Implication	Required Rework	Structural Implications, if Rework Accomplished
The solution soak time is too short	In this case, the alloying elements have not been fully "dissolved" in the aluminum lattice and incomplete hardening results.	Re-solution heat treat for the full time called out per specification.	No impact to final properties
The soak time is too long.	Bare: None Clad: Diffusion of clad material into the core could be a problem, as discussed. If the maximum time for clad products has been exceeded, clad re-heat treat rules apply: Number of reheat treatments must be restricted to one for gages up to.125 and two for gages over .125.	Bare: No rework required Clad: No rework if maximum heat treat limits have not been exceeded. Clad: Scrap, if clad re-heat treat limits exceeded.	No impact to final properties
The soak temperature is below the minimum specified for material grade.	The effect is incomplete solution of the hardening constituents, resulting in reduced properties after quenching.	Re-solution heat treat for the full time called out per specification.	No impact to final properties
The quenching has been performed incorrectly. • The time between removal of parts from the furnace to quenching has exceeded the maximum delay time permitted by the specification. • Parts have been quenched by the wrong method, such as spray quench where water quench only is permitted.	This may result in two effects: incomplete hardening and/or lowering of resistance to stress corrosion. Note: Parts may develop full hardness but corrosion resistance may still be impaired.	Re-solution heat treat for the full time called out per specification.	No impact to final properties
An annealed product gets aged only. The solution heat treatment is inadvertently bypassed and the parts go only to aging.	In this case, the aging has no effect on mechanical properties, nor does any diffusion of clad to core material take place because the temperatures are too low.	Solution heat treat and age per specification.	No impact to final properties

Material Defect Reported	Implication	Required Rework	Structural Implications, if Rework Accomplished
The aging temperature is too high.	Material will be over-aged, resulting in lower tensile properties.	The best rework is to re-solution heat treat and re-age, but parts may distort or result in too many reheats on clad. In such instances the best procedure is to contact the Materials and Processes group and determine from available data what the properties actually are.	If reworked, no impact to final properties. If not, material properties will be reduced and must be evaluated for static strength and possibly life. Resistance to stress corrosion is normally not seriously impaired by over-aging.
The aging time is too long: Temperature is within range, but load was left in the furnace too long.	As with over-temperature, over-aging may be the result. However, increased times are not as effective as increased temperature in causing over-aging, so there is a greater chance here that the parts may still be usable. For example, 7075-T73 stand considerable excess aging time without a reduction in properties.	Check with Materials and Processes to determine the extent of over-aging, if any. If over-aged, re-solution heat treat and re-age per specification.	If not reworked, material properties may be reduced and must be evaluated for static strength and possibly life. If reworked, no impact to final properties.
The aging time is too short and the aging temperature is too low.	This results in under-aging. In this case, not only may the tensile properties be low, but also the resistance to stress corrosion is lowered, and such parts should not be used.	It may be possible to re-solution heat treat and re-age; but parts may distort or result in too many reheats on the clad. Contact M&P Engineering for guidance. If further processing is not possible, both temperature too low and time too short: Scrap	If re-solution heat treated and re-aged, no impact to final properties. If not, do not use these parts

Material Defect Reported	Implication	Required Rework	Structural Implications, if Rework Accomplished
The aging time is too short but the aging temperature is correct.	This results in under-aging.	It is possible to add-age for the balance of the prescribed time, if the length of the first age is known. Aging is cumulative and the first short age can be added to the second age to make up the total time, provided the temperature was in range each time. It may be possible to re-solution heat treat and re-age; but parts may distort or result in too many reheats on the clad. Contact M&P Engineering for guidance.	If re-solution heat treated and re-aged, no impact to final properties. M&P should provide information on any property reduction or impacts to stress corrosion susceptibility.
The aging time is right but the aging temperature is much lower than specification.	This results in under-aging. If aging temperature is much lower, there may be no effect and parts can be add-aged with no property degradation.	It may be possible to re-solution heat treat and re-age; but parts may distort or result in too many reheats on the clad. Contact M&P Engineering for guidance.	If re-solution heat treated and re-aged, no impact to final properties. M&P should provide information on any property reduction or impacts to stress corrosion susceptibility.
The aging time is too short and the aging temperature is low but near the specification temperature.	This results in under-aging. If aging temperatures are closer to the right range, but still too low and time was correct some aging has occurred.	It may be possible to re-solution heat treat and re-age; but parts may distort or result in too many reheats on the clad. Contact M&P Engineering for guidance.	If re-solution heat treated and re-aged, no impact to final properties. M&P should provide information on any property reduction or impacts to stress corrosion susceptibility.

18.5.1.2 Improper Forming Time or Temperature – Aluminum Parts

The review of aluminum heat treat procedures in Section 18.4.1.1 may also form the basis of a discussion of the restrictions which have been placed on cold and hot forming of heat treated aluminum alloys.

All typical heat treatable aerospace-grade aluminum alloy parts may be formed hot, if maximum formability is necessary. The hot forming must be performed above a minimum temperature, below a maximum temperature, and within a maximum time at temperature.

The minimum hot forming temperatures are established with consideration of the metallurgy and the purpose of applying heat. In the cases of annealed materials, like 7075-0, already soft and formable, there is no advantage to applying heat unless it is high enough to appreciably decrease the yield strength for additional ease of forming, and in the case of a heat treated and aged product, like 7075-T6, which is strong and not so formable, the minimum temperature must be reached before the yield is low enough to permit any appreciable forming. If the forming is done below the minimum temperature, high residual stresses are formed and the potential for stress corrosion is increased. See Section 3.4.7 for a discussion of stress corrosion.

Similar considerations are used to establish the maximum temperatures. Heating annealed material above the maximum may cause some solution hardening resulting in partially heat treating the part. This results in the part after the first hot forming being less formable for a possible second cold forming. For heat treated parts, *e.g.* –T6, heating above the maximum for any appreciable length of time may cause over-aging.

Additionally, the time at temperature is very important and maximum time limits are imposed. For annealed parts, since the maximum temperatures are fairly high, too long of an exposure time may result in grain coarsening. For -T6 parts, exceeding the time limit may cause over-aging.

Thus violation of hot forming specification requirements can result in reduced properties as was the case for improper heat treatment heat and the same consideration must be given to rework and disposition.

Limitations in cold forming have been placed on the 7075 and 2014 aluminum alloys because of the susceptibility of these alloys to stress corrosion. Cold bending induces in the part residual tensile stresses. Then when the part enters service and is exposed to corrosive environments, such as salt air, the combination of residual stresses and corroding atmosphere may result in stress-corrosion cracking. This type of failure is particularly insidious since cracks propagate inward from a small area of the surface until fracturing occurs, while the exterior, visible portions of the structure appear undamaged.

The degree of susceptibility to stress corrosion in 2014 and 7075 alloys varies with the grain direction and is generally less severe in the longitudinal directions than in the transverse, or cross grain, directions. In some cases, therefore, bending in a plane perpendicular to the long axis of the part is permitted, but is prohibited in a plane normal to the long transverse or short transverse direction.

For the above reasons, it is of great importance that the restrictions on both hot and cold working be strictly maintained. Re-solution heat treatment will erase the effects of a violation of the working requirements; however, for 2014 and 7075 alloys, a reheat treat is not recommended because of the potential for severe distortion and warping resulting from quenching the finished parts. Close collaboration between Design, Stress and the Materials and Processes Engineering groups is necessary to determine the appropriate salvage/repair for improper forming operations.

Sometimes during the assembly of aircraft, cold forming using fasteners to pull up gaps between two layers of a joint is a disposition recommendation in lieu of shimming. This has the potential to induce residual stresses in the mating materials and tension stresses in the fasteners. Prior to approval of this, careful consideration must be made by the Stress and Durability and Damage Tolerance (DADT) Engineering groups on the amount of residual stresses which may result in the material.

Unfortunately this is not an easy assessment to make and it generally comes down to engineering judgment. This is a situation where walking out to see the area, touching the parts and looking at the geometry of the gaps is invaluable. If the two surfaces can be pushed together with “light hand pressure” or, more quantitatively with a series of weighted sand/shot bags, typically 0.5 to 1 pound each, for a total not-to-exceed specified weight, then the amount of residual stress may be acceptable, depending on the materials involved and the type of fastener used.

Note that typically, as part of a Program Fracture Control Plan, cold working of fracture critical and possibly durability critical parts is not permitted. Always be aware of program limitations.

18.5.2 Titanium Material Processing Anomalies

18.5.2.1 Titanium α-Case

Titanium alpha case (α-case) is the oxygen-enriched layer occurring in titanium alloys which are exposed to heated air or oxygen. It can also occur from improper drilling, which results in burning the edge of the hole in titanium parts and in laser cutting of titanium alloys. Alpha case is a brittle layer which tends to microcrack leading to a reduction in the strength and life. The only way to remove Alpha case is by removing a layer of the material through drilling, machining or chem-mill. Typically, material removal of 0.015 to 0.020 inch is sufficient.[10] For burned holes, ream the affected holes for a first oversized fastener, assuming no other clean-up is required for additional defects. For other affected parts, consult with the Materials and Processes Engineers to determine the best method for removal and the appropriate removal depth.

18.5.2.2 Hydrogen Embrittlement of Titanium Fasteners

Hydrogen embrittlement of titanium fasteners is almost always due to improper heat treat or processing during manufacture. If discovered prior to installation, these fasteners should not be used.

See Section 18.5.3.2 for further discussion of hydrogen embrittlement in fasteners and salvage approaches.

18.5.3 Steel Material Processing Anomalies

18.5.3.1 High Strength Steel Heat Treat, 220 ksi and above

High heat treat steels find limited use on aircraft, but may be found in landing gears which may be heat treated to the range of 260 - 280 ksi tensile strength. Another use of high heat treat steels is in the use of fasteners in special applications. The processing and reworking must be carefully controlled and in full conformance with the applicable specifications.

Heat treatment above 220 ksi and subsequent processing follows the same general pattern as the manufacture of steels to lower strengths, but there are some new requirements and controls necessary to insure good parts. This might include stress relieving, nital etch inspection or magnetic particle inspection and shot peening.

Most high heat treat parts and assemblies are manufactured by subcontractors and delivered in the finished condition. However, occasions arise where reworking is necessary on these assemblies after delivery. This section examines a few of the areas where high heat treat rework and salvage differ from normal steel.

[10] Affected area may be ammonia bifluoride etch-inspected to verify α-case removal. The appearance of a white or light gray area indicates residual α-case and requires further metal removal. See your M&P engineer for further details.

Full mechanical properties can always be restored by re-heat treatment, but there are some secondary effects in high strength steels which must be considered. Many high heat treat parts contain areas which are machined after heat treatment to remove all surface decarburization and provide the part with maximum fatigue properties. Surface decarburization is the loss of carbon near the surface during heat treat and while some partial decarburization is permitted by specification, total decarburization is prohibited. See pertinent program specifications for details. The loss of carbon results in a reduction in strength, thus machining after heat treatment is mandatory unless the drawing specifically spells out that certain areas can be finish-machined before heat treat. Therefore, if a finished component or assembly must be re-heat treated, and this part contains areas which are required to be machined after heat treatment, this may result in a violation of the specifications because the re-heat treatment will cause further decarburization, and there may be insufficient metal left to machine off the decarburization layer without going below minimum dimensions.

It is possible to heat treat in a controlled atmosphere to minimize the amount of decarburization. This does not totally eliminate it and actual decarburization should be verified with test specimens included in the re-heat treatment process. In addition to the controlled-atmosphere heat treat, the part may be shot peened after heat treat which to a large extent restores the loss in fatigue life due to partial decarburization.

All plating must be removed from the part prior to any re-heat treat. Examining the various steps in the heat treat and re-heat treat process:

- Normalizing is mandatory as part of the original heat treat, but may not be required on a second heat treat. Normalizing heats the steel above the critical temperature, holds for a period of time long enough for desired grain structure transformation to occur and then air cools the material. The process of normalizing steel establishes a more uniform carbide size and distribution. This facilitates later heat treatment operations and produces a more uniform final product.
- Grinding on high heat treat steel in the heat treated condition is restricted by specification. Note that these grinding restrictions do not apply to grinding of hard chrome plate or to grinding of parts in the annealed or normalized conditions. Grinding imposes high residual tensile stresses, which may lead to surface cracking unless the stresses are properly relieved. Improper grinding may also cause localized heating of the material which can result in areas of over-tempering or untempered reformed martensite (UTRM). If grinding is performed on areas not authorized by the drawing, either by accident, or where grinding is the only method possible for a rework, the parts must be stress relieved, temper-etch inspected and shot peened in accordance with the appropriate specification.
- Re-plating of high heat treat steel must be done in exactly the same way as the original plating, with all of the specification requirements and controls strictly maintained. Improper plating and improper post-plate baking can result in severe embrittlement of the parts. Embrittlement results in a loss of ductility and strength and can lead to unpredicted catastrophic failure under low or no load. Section 3.4.9 discusses hydrogen embrittlement.
- If the post plating bake has been inadvertently omitted from the processing, the parts must be returned for baking, followed by a very careful magnetic particle inspection to make sure that no surface cracks have developed. Section 2.9.1.2 discusses magnetic particle inspection.

If for any reason parts have been plated, or re-plated, without accompanying control coupons, the plating must be stripped and the parts re-plated per specification.

Any rework or salvage operation of high heat treat steels should conform to specification requirements of the original processing. When it is impossible to conform 100% to the specification, Materials and Processes engineering should play an active role in determining the proposed rework schedule which will result in the least compromise with optimum properties. In some cases, this may also result in the need for additional coupon structural testing to determine the degree of compromise.

18.5.3.2 Stress Corrosion and Hydrogen Embrittlement of Steel Fasteners

Stress corrosion and hydrogen embrittlement are issues occurring in low allow steel parts which have been heat treated to stress levels above 190 ksi and in titanium fasteners. All alloy steels are vulnerable to these types of failures, but H-11 steel was a common fastener material which was particularly sensitive. It was originally selected for steel fasteners because threads can be rolled after heat treating. Because of the severity of the problem, this alloy of fastener has been removed from aircraft service, for the most part, and should not be used for future design. In addition to the discussion below, PM4057 Section 3.4.9 discusses hydrogen embrittlement and Section 3.4.7 discusses stress corrosion.

Stress corrosion occurs in fasteners due to the presence of corrosion in a joint and high sustained tensile stresses. The cadmium plate used to protect alloy steel fasteners is sacrificial and it can be damaged on installation[11] or on older aircraft it may have been worn off. In a working joint there is no way to totally protect alloy steel bolts against environmental effects in permanent installations. This problem is exacerbated in more flexible joints. Although steel fasteners are cadmium plated and installed with sealant on the fastener and faying surface sealant in the joint, water can get into a working joint by way of something called the water pump effect.

Every time the aircraft takes off, changes in barometric pressure and temperature causes the dew point to change and moisture in the trapped air condenses on and in the structure. The air without the water leaks out while the aircraft is at altitude and the water left behind freezes and enlarges voids, moves sealant around and scratches surface finishes. When the aircraft lands, air with moisture leaks back into the voids in the structure and the cycle repeats. This mechanism is called the water pump effect. The moisture is trapped in an area where, over time, the finishes are compromised which leads to galvanic corrosion. See Section 3.4.8 for a discussion of the mechanism of galvanic corrosion.

The other necessary condition for stress corrosion is sustained tensile stresses. The sustained stresses in fasteners come from preload due to torque and secondary stresses due to imperfect installation. Tension fasteners normally have higher preload stresses than shear fasteners to maintain clamp-up of the joint under load. Section 5 discusses torque-tension relationships. Additional secondary stresses are present due to tolerance in fastener installation including fasteners not being normal to the surface and stresses due to eccentricities in the joint which can cause prying on the head and threads. The additive effect of these influences can lead to high extreme fiber stresses, due to bending and tension, at critical locations on a fastener, such as at the juncture of the head and shank and at the first thread where the cross-sectional area is minimum. Combining these stresses with the galvanic corrosion can result in stress corrosion cracking failures.

Hydrogen embrittlement occurs when atomic hydrogen diffuses into the fastener. This may occur during the manufacture of the fastener, usually during chemical cleaning, heat treat or plating operations. Oven contamination can also cause hydrogen embrittlement. In service, hydrogen embrittlement can be caused by the hydrogen migrating into the steel fastener and moving to the highest stressed location causing failure. The presence of hydrogen in service is because it is a by-product of the formation of aluminum oxide or iron oxide which results from galvanic corrosion in the joint and fastener fretting due to motion in the joint. For in-service failures, removal and replacement of the fastener and resealing the joint is typically done.

For the hydrogen embrittlement caused by the manufacture of the fasteners, closely following the specifications during manufacture can eliminate the problem. But occasionally, either inadvertently or because shortcuts were taken, a batch of fasteners are discovered to have the potential for hydrogen embrittlement. If it is discovered prior to installation, the fasteners are sent back to the vendor and not installed. Unfortunately, many times, it is only after the parts are installed, and, perhaps after the aircraft has been delivered that Lockheed Martin is notified that a batch of fasteners may have hydrogen embrittlement.

[11] If the damage is slight, the cadmium plating will still perform as a sacrificial barrier. If it has been completely breached, it may no longer serve its purpose.

When the notification is made, typically the vendor will state that a particular part number, lot number and fastener diameter were subject to an embrittling process without post process bake. Not all of the fasteners in the lot will exhibit hydrogen embrittlement but which ones do cannot be identified, since the condition can be only determined with certainty by sectioning the fastener and looking at the magnified grain structure. Further complicating matters, once fasteners are brought in-house, they are all mixed in the stock bin and any traceability of batch or lot is lost. At best the fasteners can be identified by aircraft build span and lot purchase dates.

Typically if a batch of fasteners which have already been installed on aircraft is suspected of hydrogen embrittlement, analysts must determine which fasteners of that part number and size are in safety-of-flight or critical margin locations. Only those will generally become candidates for removal and replacement and a residual strength analysis may be performed to further reduce the candidate list. The rationale behind this approach is that the potential damage to the vehicle at wholesale removal and replacement of every suspected fastener is balanced against the fact that the remaining fasteners are in locations where a single failure will not cause a catastrophic event and statistically not all of the suspected hydrogen-embrittled fasteners are indeed embrittled. Additionally all suspected stock should be eliminated. The customer is typically intimately involved with the rationale and parameters of the candidate list study and must agree to the overall approach.

The critical fasteners are then removed and replaced. In this step care must be taken that the aircraft will not shift or move while the fasteners are removed and replaced. Once the critical fasteners are removed and replaced, they should be sectioned and inspected for hydrogen precipitates.

18.6 Specific Defects and Repairs

18.6.1 Hole or Fastener Installation Defects

This section will address typical repairs, guidance and analysis requirements for defects involving defective holes and fastening systems. For hybrid composite metal joints refer to Reference 18-5 PM4056 Section 19 for necessary analysis/repairs for composite portion of the joint.

18.6.1.1 Hole Defects Repairable with Oversize Fastener or Bushing

<table>
<tr><td colspan="2">Defect/Damage: HOLE DEFECT</td></tr>
<tr><td>Description
Double-drilled hole
Elongated hole
Out-of-Round hole
Non-perpendicular hole
Holes with rifling or scratches
Burned holes</td><td>Characterization
Qualitative description of defect is provided
Maximum length and width of hole is measured
Hole perpendicularity is measured
If hole has different dimensions on top surface than on bottom surface this is quantified
Edge distance dimension is provided if it does not meet blueprint.
Hole location(s) are provided</td></tr>
<tr><th>Disposition and Repair Guidance</th><th>Reference Section</th></tr>
<tr><td>Clean up hole – round and true, center at original hole center</td><td>18.4.1</td></tr>
<tr><td>If small enough, install first or second oversize fastener. In the event that a first or second oversize fastener is not available, for solid fasteners, an Acres sleeve may be used. Retain same hole fit as blueprint fastener.</td><td>18.4.2</td></tr>
<tr><td>If larger than second oversize, bush hole to blueprint size, using interference-fit bushing</td><td>18.4.3</td></tr>
<tr><td>If short edge distance, consider peening edge of part locally, as required based on criticality</td><td>18.4.9, 18.4.10, 18.4.19</td></tr>
<tr><td colspan="2">Discussion
Hole must clean up round and perpendicular to the surface.</td></tr>
</table>

- If there are multiple defective holes in a limited area, net section tension or shear may be a problem due to loss of area.
- If hole is offset from initial blueprint location, plug repair of Section 18.6.1.2 might be applicable.

Static Strength Analysis Checklist – Oversize Fastener Option

Analysis		Section	Comments
Net Section Tension	Use outer diameter of fastener or sleeve plus hole clearance for hole size	5.2.3	Be sure to include any other hole defects in joint
Joint Bearing Strength	Use outer diameter of fastener or sleeve plus hole clearance for D in the e/D calculation. Use outer diameter of fastener or sleeve for bearing calculation.	5.2.3; 18.4.10	
Shear Tear-out	Use outer diameter of fastener or sleeve plus hole clearance for hole size	5.2.3	Could become the critical joint failure mode if e/D<1.8

Static Strength Analysis - Bushing Option

Analysis		Section	Comments
Net Section Tension	Use outer diameter of bushing for hole size	5.2.3	Be sure to include any other hole defects in joint
Joint Bearing Strength	Use outer diameter of bushing for the e/D calculation and bearing stress calculation	5.2.3; 18.4.10	For e/D<1.4, bulging of part may occur during bushing installation.
Shear Tear-out	Use outer diameter of bushing for hole size	5.2.3	Could become the critical joint failure mode if e/D<1.8
Bearing Yield	Bearing of fastener on bushing	5.2.5	
Interference fit stresses	On bushing (collapse) and joint (residual stress)	5.2.5	Typically, if standard interference values are used, this calculation is only performed if e/D<1.4 for use as a residual stress for DADT analysis.

Durability and Damage Tolerance Concerns

- Depending on load direction, peak stress at edge of part (due to interference fit) with short edge distance may be critical for bushing option. Shot peening of edge is recommended.

Repair Limitations

- Minimum sheet thickness for bushing installation is 0.050 in. thick.
- If multiple layers require bushings, bush each layer individually.
- If a sleeve is used in lieu of an oversized fastener, limit to 2 adjacent fasteners and 10% of fastener pattern per Section 18.4.2.

18.6.1.2 Hole Defects Repairable with Plug Repairs, Drilled after Installation

Defect/Damage: HOLE DEFECT

Description

- Double-drilled hole
- Elongated hole
- Out-of-Round hole
- Non-perpendicular hole

Characterization

- Qualitative description of defect is provided
- Maximum length and width of hole is measured
- Hole perpendicularity is measured
- If hole has different dimensions on top surface than on bottom surface this is quantified
- Edge distance dimension is provided if it does not meet blueprint.
- Hole location(s) are provided

Disposition and Repair Guidelines	Reference Section
This repair is <u>not recommended</u> because it is difficult to accomplish due to potential for spinning of the plug and/or potential for wall break-out. • Prior to attempting repair on-vehicle, mechanic should develop and practice the procedure on the bench. • If drill breaks through edge of plug wall, remove plug and start over • If plug spins in hole, remove plan and start over	
Clean up hole – round and true. With appropriate manufacturing development, the final hole center offset from original hole center by no more than 6%D	18.4.4
Install interference fit plug and re-center the hole to blueprint location, maintaining minimum 0.030 wall thickness. Caution plug may spin in hole and cause further damage.	**18.4.4**
If short edge distance, consider peening edge of part locally, as required based on criticality	**18.4.9; 18.4.10; 18.4.19**

Discussion

- Must maintain minimum 0.030 wall on final drill and ream.
- Hole must clean up round and perpendicular to the surface

Static Strength Analysis Checklist

Analysis		Analyze per Section	Comments
Net Section Tension	Use outer diameter of plug	5.2.3	Be sure to include any other hole defects in joint
Joint Bearing Strength	Use outer diameter of plug for the e/D calculation and bearing stress calculation	5.2.3	
Shear Tear-out	Use outer diameter of plug	5.2.3	Could become the critical joint failure mode if e/D<1.8
Bearing Yield	Bearing of fastener on bushing(plug)	5.2.5; 18.4.10	
Interference fit stresses	On bushing(plug) (collapse), after final hole drill and joint layer (residual stress)	5.2.5	Typically, if standard interference values are used, this calculation is only performed if e/D<1.4 for use as a residual stress for DADT analysis.

Durability and Damage Tolerance Concerns

Depending on load direction, peak stress at edge of hole with short edge distance may be critical. Include residual stress due to bushing interference fit.

Repair Limitations

- Minimum sheet thickness for plug installation is 0.050 in. thick.
- If multiple layers require bushings or plugs, bush or plug each layer individually.

18.6.1.3 Extraneous Holes Filled with Expanding Rivets or Plugs

Defect/Damage: GOUGE, DRILL START, EXTRANEOUS HOLES

Description	Characterization
• Deep gouge • Drill Start • Extraneous Pilot Hole • Tooling hole	• Location of defect • Depth of defect • Distance to adjacent holes or features or edge of part

Disposition and Repair Guidance	Section Reference
Drill through, clean, round and true	
Install solid expanding rivet if less than 0.25 in. diameter or plug if 0.25 in. or greater. Protruding head, if space permits	**18.4.6; 18.4.4**
If necessary, due to interference with other parts, grind flush	

Discussion

- This repair is used to fill extraneous holes and minimize their impact on the life of the part.
- If the filled hole is adjacent to a structural, loaded fastener, consideration should be given to a structural plug, *i.e.*, one made from the same material as the parent part. It will have the same bearing allowable as the parent material and any adjacent fasteners can develop their full bearing strength by transferring the load to adjacent material.
- The plug does not restore material to the basic section and net area may be critical.
- Do not use 5056 plugs in 2024 material due to galvanic corrosion concerns.

Static Strength Analysis Checklist:

Analysis	Discussion	Analyze per Section	Comments
Net Section Tension	If other holes are present in area	5.2.3	Be sure to include any other hole defects in joint

Durability and Damage Tolerance Concerns:

- By drilling through, the sharp notch at the base of a gouge or drill start is removed.
- Installation of an expanding solid rivet cold works and fills the hole.
- Depending on proximity of defect to adjacent features (fasteners, radii, steps) or the edge of part, life analysis may need to be performed; however, the installation of the solid rivet and the resulting beneficial stress state at the edge of the hole should help to mitigate the effect of the defect.

Repair Limitations:

- Rivet cannot be installed within 1D of edge of part.

18.6.1.4 Short Edge Distance Holes

Defect/Damage: SHORT EDGE DISTANCE (SED)

Description	Characterization
• Holes are drilled closer than blueprint minimum dimension to the edge of part	• Location of hole • Remaining edge distance to center of hole • Number of affected holes

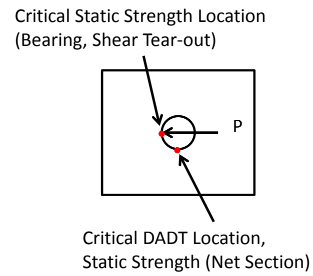
Disposition and Repair Guidance	Reference Section
Typically, after both Static (positive margin) and Durability Analysis (full life), "Use-as-Is" if $e/D \geq 1.5$	**18.4.9, 18.4.11**
If $1.2 < e/D < 1.5$, a disposition of "Use-as-Is" may still be appropriate if positive margins and full life can be shown. Consideration should be given of reducing the stresses in the parts through increasing the size of adjacent fasteners or adding a doubler, particularly if more than a few fasteners are affected or if the affected fasteners are also larger than blueprint. Cold work hole(s), if possible and shot peen edge of part.	**18.4.9, 18.4.10, 18.4.11, 18.4.18, 18.4.19**

If e/D < 1.2, consideration should be given to trimming away the discrepant hole or plugging it and abandoning it while adding additional fasteners. This assumes a single or small number of fasteners are affected. Shot peen edge of part.	**18.4.9, 18.4.18**

Discussion

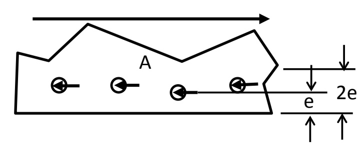
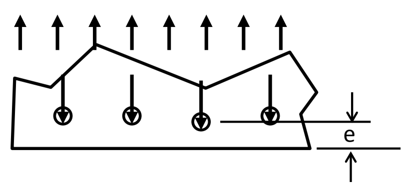
Short edge distance in the direction perpendicular with the loading is more critical for life since the peak stress is 90 degrees from the load direction. This may also be critical for Net Section Tension.

Short edge distance in the direction parallel to the load is more critical for static strength because the bearing strength and shear tear-out is affected by the edge distance in the direction of the load.



If a part has not been installed and has a large number of SED holes drilled, consideration should be given to scrapping the part.

Static Strength Analysis Checklist

Analysis	Discussion	Analyze per Section	Comments
Net Section Tension	If SED is to edge parallel to load direction in large panel, check net section using an effective width of 2e. Use actual diameter of hole for analysis checks.	5.2.3; 18.4.9	
Bearing	If SED is to edge perpendicular to load direction determine bearing allowable per Section 18.4.10. Use actual fastener diameter for bearing calculation.	5.2.3	
Shear Tearout	If SED is to edge perpendicular to load direction, this can become the critical failure mode if e/D≤1.5. Use actual diameter of hole for analysis checks.	5.2.3	
Inter-rivet Buckling	If discrepant hole is abandoned and plugged	8.6	Extremely short e/D, either load direction
Maximum Fastener Spacing		5.2.3.1.8	

Durability and Damage Tolerance Concerns

- An increased potential for cracking and a shortened life can result from a short edge distance condition. While a single or a small number of holes in a given area of the part can be defective, large numbers of defective holes in fracture critical parts should be avoided and the part scrapped if possible.

Repair Limitations

- Do not accept parts with e/D < 1.2.

18.6.1.5 Short Center-to-Center Holes

Defect/Damage: SHORT FASTENER SPACING (SHORT PITCH DISTANCE)

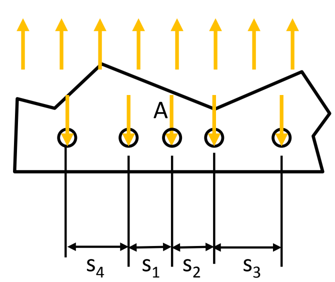
Description	**Characterization**
• Holes are drilled closer together than blueprint dimension • Holes are drilled closer together than 4D for holes added per MRB disposition • Holes are larger than blueprint, spacing is per blueprint	• Location/spacing of hole • If size is discrepant, hole diameter • Number of affected holes

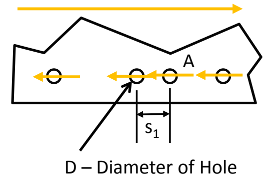
Disposition and Repair Guidance	Reference Section
Typically, after both Static (positive margin) and Durability Analysis (full life), “Use-as-Is” if $s/D \geq 3.0$	
Depending on loading, $2.5 < s/D < 3.0$, a disposition of “Use-as-Is” may still be appropriate if positive margins and full life can be shown. Consideration should be given of reducing the stresses in the parts through adding a doubler, particularly if more than a few fasteners are affected or if the affected fasteners are also larger than blueprint. Cold work hole(s), if possible.	**18.4.10, 18.4.11**
If $s/D < 2.5$, consideration should be given to plugging the discrepant hole and abandoning it. This assumes a single or small number of fasteners are affected.	**18.4.6**

Discussion

- Short fastener spacing in the direction perpendicular to the loading is critical for static strength net section tension and life since the peak stress is 90 degrees from the load.
- Short edge distance in the direction parallel to the load is more critical for static strength bearing margins because the bearing allowable is determined using an e/D of one-half the fastener spacing.
- If a part has not been installed and has a large number of short fastener spacing holes drilled, consideration should be given to scrapping the part.

Static Strength Analysis Checklist

Analysis	Discussion	Reference Section	Comments
Net Section Tension	If short spacing direction is perpendicular to load direction, check net section using a width half the distance to each of the adjacent holes. For hole A: $w=½(s_1+s_2)$ Use actual diameter of hole for analysis checks.	**5.2.3; 18.4.9**	
Shear Tearout	If short spacing is to edge perpendicular to load direction, this can become the critical failure mode if edge distance is also short. Otherwise, no check is required. Use actual diameter of hole for analysis checks.	**5.2.3**	
Analysis	**Discussion**	**Reference Section**	**Comments**
Bearing	If short spacing direction is parallel to load direction, determine bearing allowable, at A, per Section 18.4.10 using an edge distance of $(s_1\text{-}D/2)$. Use actual fastener diameter for bearing calculation.	**5.2.3; 18.4.10**	

Maximum Fastener Spacing	If fastener spacing exceeds 7D, structure will not develop full strength	**5.2.3.1.8**	

Durability and Damage Tolerance Concerns
- An increased potential for cracking and a shortened life can result from a fastener spacing condition.

Repair Limitations
- Do not accept parts with s/D < 2.5.

18.6.1.6 Burned Holes

Defect/Damage: BURNED HOLES – METAL STRUCTURE

Description	**Characterization**
• Holes are burned due to dull drill bits or other causes (typically Titanium) • Composite – See PM4056 Section 19.6.18	• Location of Defective holes • Hole Diameters • Number of affected holes

Disposition and Repair Guidance	**Reference Section**
Clean up hole – round and true, center at original hole center. If burned hole is only defect, a first oversize should remove sufficient material to remove Titanium Alpha Case	**18.5.2.1**
If small enough, install first or second oversize fastener. In the event that a first or second oversize fastener is not available, for solid fasteners, an Acres sleeve may be used. Retain same hole fit as blueprint fastener.	**18.4.2**
If larger than second oversize, bush hole to blueprint size, using interference-fit bushing	**18.4.3**
If short edge distance, shot peen edge of part locally	**18.4.9, 18.4.10, 18.4.19**

Discussion
- Burned holes in Titanium results in a layer of Titanium alpha case. See Section 18.5.2 for discussion.
- For burned holes in Graphite Composite see PM4056 Section 19

Static Strength Analysis Checklist

Analysis		Section	Comments
Net Section Tension	Use outer diameter of fastener or sleeve plus hole clearance for hole size	5.2.3	Be sure to include any other hole defects in joint
Joint Bearing Strength	Use outer diameter of fastener or sleeve plus hole clearance for D in the e/D calculation. Use outer diameter of fastener or sleeve for bearing calculation.	5.2.3; 18.4.10	
Shear Tear-out	Use outer diameter of fastener or sleeve plus hole clearance for hole size	5.2.3	Could become the critical joint failure mode if e/D<1.8

Durability and Damage Tolerance Concerns
If nominal edge distance and spacing, no DADT concerns

Repair Limitations
If a sleeve is used in lieu of an oversized fastener, limit to 2 adjacent fasteners and 10% of fastener pattern per Section 18.4.2.
If nominal edge distance and spacing, no limitations

18.6.1.7 No Destack and Deburr

Defect/Damage: NO DESTACK AND DEBURR	
Description • Per design, parts were intended to be destacked and deburred and were not	**Characterization** • Location of holes • Number of affected holes
Disposition and Repair Guidance	**Reference Section**
Typically, rework to blueprint, i.e. destack and deburr	**18.4.12**
If a significant number of permanent fasteners have been installed, analyze joints using program approved destack and deburr factor for DADT analysis. If acceptable life, attempt to use a chip chaser to clean out debris from faying surface. All faying surfaces must be in contact.	**18.4.12**
Discussion • None	
Static Strength Analysis Checklist • None	
Durability and Damage Tolerance Concerns • An increased potential for cracking and a shortened life can result from burrs at the edge of the hole and swarf in the faying surface due to potential damage to hole and fastener from this debris. See discussion in Section 18.4.2.	
Repair Limitations • Acceptance of no destack and deburr should be balanced by the risk of collateral damage of disassembly of joint if fasteners have been installed.	

18.6.1.8 Shanked Fastener

Defect/Damage: SHANKED FASTENER	
Description • Fastener is too long for stack-up and gap exists between nut/collar or formed tail and surface of joint	**Characterization** • Location of fasteners • Number of affected fasteners • Amount of gap
Disposition and Repair Guidance	**Reference Section**
Remove and replace fasteners with proper grip length. Most fastener installation specifications allow for the installation of washers to adjust grip length.	**--**
Discussion • Fasteners which are too long can move back and forth along their axis in the hole and cause damage to the hole and the surface of the hole, causing fatigue damage. This can also allow the fastener to rotate in the hole causing wear and fretting of the joint layers. It can also limit the tension capability. • It is especially important to ensure that blind fasteners are correctly gripped so that there is sufficient material to properly form the tail bulb. If not, the fastener has no tensile capability and reduced shear strength.	
Static Strength Analysis Checklist No analysis required. Condition is unacceptable and must be repaired.	
Durability and Damage Tolerance Concerns No analysis required. Condition is unacceptable and must be repaired.	
Repair Limitations Do not use washers on blind fasteners or rivets to adjust grip length.	

18.6.1.9 Spinning Nutplates, Removable Panels/Doors

Defect/Damage: SPINNING NUTPLATE (REMOVABLE PANEL)	
Description • Installed bonded nutplate is spinning due to bond failure	**Characterization** • Location of nutplate(s) • Number of affected nutplate(s)
Disposition and Repair Guidance	**Reference Section**
Drill out fastener, remove panel and replace nutplate. Because FOD can develop due to the nutplate removal it must be captured and removed.	**PM4056 Section 19.6.21**
Discussion • If the panel is a removable panel for equipment access, then the nutplate must be replaced. • If the panel is a fixed, close-out panel where later access is not required, see Section 18.6.1.10.	
Static Strength Analysis Checklist • No analysis required	
Durability and Damage Tolerance Concerns • No analysis required	
Repair Limitations • None	

18.6.1.10 Spinning Nutplates, Permanent Installations

Defect/Damage: SPINNING NUTPLATE (PERMANENT PANEL INSTALLATION)	
Description • Installed bonded nutplate is spinning due to bond failure	**Characterization** • Location of nutplate(s) • Number of affected nutplate(s)
Disposition and Repair Guidance	**Reference Section**
Drill out fastener, replace with program-approved blind fastener. Retain same hole fit as blueprint fastener. Because FOD can develop due to the nutplate removal it must be captured and removed or encapsulated in sealant or by some other means.	**PM4056 Section 19.6.21**
Discussion • This approach is only acceptable for fixed panels.	

Static Strength Analysis Checklist

Analysis		Section	Comments
Fastener Shear/Tension Capability	Check the shear/tension strength of the fastener. Retain 15% margin on fastener shear.	5.2.3	If margin is negative, use an alternative blind fastener with increased strength, increase fastener diameter (perform appropriate analysis for bearing and net section), or remove the panel and replace the nutplate.
Fastener Bending Strength	Check the bolt bending strength of the joint if bolt bending can develop.	5.2.3	If total stack-up exceeds 2D or the fastener-to-hole clearance is greater than 0.004.

Durability and Damage Tolerance Concerns
- No analysis required

Repair Limitations
- The seating surface for the blind bolt tail should be free of adhesive and any part of the nutplate so that the tail can form properly.
- Inspect the tail side of the fastener to ensure it is properly formed.
- Repair is limited to 2 adjacent fasteners and no more than a total 10% of the fasteners in the panel.
- The blind fastener tension strength should equal or be greater than the tension strength of the joint

18.6.2 Surface Defects, Interferences, Blend and Smooth

This section addresses the repair, guidance and analysis associated with trim and blend dispositions.

18.6.2.1 Scratches, Gouges or Other Shallow Surface Defects

<table>
<tr><td colspan="2">Defect/Damage: SHALLOW SCRATCH, GOUGE, DRILL START or OTHER SURFACE DEFECT</td></tr>
<tr><td>Description
• Shallow Gouge
• Shallow Drill Start
• Shallow Scratch
• Rough Surface Finish</td><td>Characterization
• Location of defect
• Depth of defect
• Radius at depth
• Thickness of part at defect
• Measurement of Surface Finish</td></tr>
<tr><td>Disposition and Repair Guidance</td><td>Reference Section</td></tr>
<tr><td>Blend and Smooth</td><td>18.4.18</td></tr>
<tr><td>If blend requires reducing thickness below minimum blueprint thickness, and analysis indicates a negative margin, a doubler repair may be necessary.</td><td>18.4.21, 18.4.24, 18.4.26, 18.4.27, 18.4.28</td></tr>
<tr><td colspan="2">Discussion
• This repair is used to blend out shallow surface defects with minimum removal of material
• If gouge or drill start is deep, see Section 18.6.1.3.</td></tr>
<tr><td colspan="2">Static Strength Analysis Checklist
Analyze critical margins using actual thickness if material thickness is below minimum blueprint thickness,</td></tr>
<tr><td colspan="2">Durability and Damage Tolerance Concerns
• Sharp notch at the base of scratch, gouge or drill start must be removed or it will serve as a crack-start feature.
• Depending on proximity of defect to adjacent features (fasteners, radii, steps) or the edge of part, life analysis may need to be performed using minimum thickness after blend</td></tr>
<tr><td colspan="2">Repair Limitations : Remove minimal material during blend and retain required blueprint surface finish.</td></tr>
</table>

18.6.2.2 Radii Mismatch

<table>
<tr><td colspan="2">Defect/Damage: SURFACE IMPERFECTION</td></tr>
<tr><td>Defect Description:
• Radius mismatch</td><td>Characterization:
• Location of Defect
• Length/Depth
• Actual Surface Finish (if not per Blueprint)</td></tr>
<tr><td>Disposition and Repair Guidance:</td><td>Reference Section</td></tr>
<tr><td>Blend and smooth to blend radius mismatch</td><td>18.4-18, 18.4-19</td></tr>
<tr><td colspan="2">Defect Discussion:
• This repair is used to blend out the cusp of two adjacent radii.
• Care should be used to not decrease the radius of the smaller radii or to remove material thickness.</td></tr>
<tr><td colspan="2">Static Strength Analysis Checklist:
If part thickness is maintained, no analysis is required. If reduced thickness results from this operation, then affected area must be reanalyzed with reduced thickness.
<u>Beware of failure modes that do not scale linearly with thickness such as bending and stability.</u></td></tr>
<tr><td colspan="2">Durability and Damage Tolerance Concerns:
• If part thickness is maintained and the smaller of the two radii is not decreased, no analysis is required. If reduced thickness results from this operation or if the radius is reduced, then life calculations of the affected area may need to be performed.
• Life analysis examining remaining multiple stress concentrations should be performed.</td></tr>
<tr><td colspan="2">Repair Limitations: Care must be taken to ensure part thickness is not affected and no sharp radii are generated.</td></tr>
</table>

18.6.2.3 Structural Interference with Fastener/Nut

Defect/Damage: FASTENER/NUT INTERFERENCE WITH STRUCTURE

Defect Description:
- Fastener riding radius
- Fastener interference with step
- Fastener installed on sloped surface
- Fastener interference with adjacent structural features

Characterization:
- Measure of Interference
- Magnitude of surface slope
- Fastener perpendicularity

Disposition and Repair Guidance:	Reference Section
First choice: Fasteners on a sloped surface, use a tapered washer or self-aligning collars	
For fasteners where a special radius block could be used, this would be the best choice	**18.4.16**
If a radius block cannot be used to resolve the problem, as a last resort and in consultation with DADT engineering, touch spotface or counterbore to a specified depth.	**18.4.15**

Defect Discussion:
- For fasteners on a sloped surface, perpendicularity of hole to backside surface (if not tapered) should be reported. Fastener perpendicularity to a non-sloped surface is required.
- The small radius/sharp corner on the periphery of the counterbore is the predominant concern, so making it as large as possible is desirable. A minimum radius of 0.13 in. is recommended.

Static Strength Analysis Checklist:
- If a tapered washer or radius block is used, no analysis is required.
- If reduced thickness results because of touch spotface or counterbore, check section for bearing or net section tension with reduced thickness.

Durability and Damage Tolerance Concerns:
- If a tapered washer or radius block is used, no analysis is required.
- In shear joints, with spotface or counterbore, a conservative approach is to analyze using the diameter of the counterbore as the diameter of a hole in the structure.
- In tension joints where bending across the spotface/counterbore/hole exists, it is recommended that a detail FEA model of the specific geometry of the area be constructed for use in determination of the stress concentration.

Repair Limitations:
Use of spotface / counterbore in primary structure is not recommended

18.6.2.4 Rough Surface Finish

Defect/Damage: ROUGH SURFACE FINISH NOT PER BLUEPRINT

Defect Description:
- Surface finish which does not meet blueprint requirements

Characterization:
- Estimation of surface finish
- Location of defect

Disposition and Repair Guidance:	Reference Section
Blend and smooth to obtain blueprint surface finish or better, minimize material removal	**18.4.18**
If remaining thickness has been reduced below blueprint minimum, analysis must be conducted and the area may require reinforcement.	**18.4.21, 18.4.24, 18.4.26, 18.4.27, 18.4.28**

Defect Discussion:
- Surface finish on structural parts should, in general be RA 125 or better. Rougher surfaces have been demonstrated to cause fatigue cracking and reduced life.

Static Strength Analysis Checklist:
- If material thickness is reduced below minimum blueprint thickness, analyze area for same failure modes as design margins using actual material thickness.

  Beware of failure modes that do not scale linearly with thickness such as bending and stability.

Durability and Damage Tolerance Concerns: If material thickness is reduced below minimum blueprint thickness, analyze area using actual material thickness.
Repair Limitations: None

18.6.3 Other Defects

This section will address miscellaneous other defects which can occur.

18.6.3.1 Part Too Thin

<table>
<tr><td colspan="2">Defect/Damage: PART IS BELOW MINIMUM BLUEPRINT THICKNESS</td></tr>
<tr><td>Defect Description:
• Part has areas which are below blueprint thickness</td><td>Characterization:
• Location and actual thicknesses</td></tr>
<tr><td>Disposition and Repair Guidance:</td><td>Reference Section</td></tr>
<tr><td>Analyze for critical failure modes with actual thickness</td><td>18.2.1</td></tr>
<tr><td>If reduced thickness results in lower than acceptable margins either scrap and replace or reinforce using doubler or reinforcement member.</td><td>18.4.21, 18.4.24, 18.4.26, 18.4.27, 18.4.28</td></tr>
<tr><td colspan="2">Defect Discussion:
• None</td></tr>
<tr><td colspan="2">Static Strength Analysis Checklist:
• If material thickness is reduced below minimum blueprint thickness, analyze area for same failure modes as design margins using actual material thickness.
<u>Beware of failure modes that do not scale linearly with thickness such as bending and stability.</u></td></tr>
<tr><td colspan="2">Durability and Damage Tolerance Concerns: If material thickness is reduced below minimum blueprint thickness, analyze area using actual material thickness.</td></tr>
<tr><td colspan="2">Repair Limitations: None</td></tr>
</table>

18.6.3.2 Improper Grain Orientation

<table>
<tr><td colspan="2">Defect/Damage: PART IS INCORRECTLY ORIENTED IN PLATE OR BLOCK FORGING</td></tr>
<tr><td>Defect Description:
• Part has been incorrectly machined and grain direction is not per blueprint</td><td>Characterization:
• Actual grain orientation</td></tr>
<tr><td>Disposition and Repair Guidance:</td><td>Reference Section</td></tr>
<tr><td>If part is a Class I part per Section 2.2, scrap</td><td></td></tr>
<tr><td>Analyze for critical failure modes with actual grain orientation</td><td></td></tr>
<tr><td>If incorrect grain orientation results in lower than acceptable margins either scrap and replace or reinforce using doubler or reinforcement member.</td><td>18.4.21, 18.4.24, 18.4.26, 18.4.27, 18.4.28</td></tr>
<tr><td colspan="2">Defect Discussion:
• Short transverse grain orientation in aluminum material typically has lower material properties than L or LT. Concentrated loads applied in this direction can result in premature failures.</td></tr>
<tr><td colspan="2">Static Strength Analysis Checklist:
• Analyze critical areas based on material properties for actual grain orientation for same failure modes as design margins. Inspect geometry to see if additional analysis may be required because reduced material properties make other areas more critical.</td></tr>
<tr><td colspan="2">Durability and Damage Tolerance Concerns: Analyze critical areas based on material properties for actual grain orientation for same geometries as blueprint analysis. Inspect geometry to see if additional analysis may be required because reduced material properties make other areas more critical.</td></tr>
<tr><td colspan="2">Repair Limitations: None</td></tr>
</table>

18.6.3.3 Excessive Gaps

Defect/Damage: EXCESSIVE GAPS BETWEEN LAYERS

Defect Description:	**Characterization:**
• Adjacent parts have gaps due to mismatches on assembly	• Magnitude of gap • Location of gap • Extent of gap • Taper, if applicable

Disposition and Repair Guidance:	**Reference Section**
Gaps should be shimmed with non-structural, structural or a combination of structural and non-structural shims	**18.4.13, 18.4.14**
For structural shims, taper guidelines should be considered	**18.4.21**

Defect Discussion:

- Gap pull-up always results in residual stresses which in some alloys causes stress corrosion cracking.
- Shimming is strongly recommended. See reference sections for guidelines on the use of structural versus non-structural shims.
- If gap is large, investigate the possibility of repositioning various parts/assemblies to improve the situation. This will involve manufacturing and tooling engineering.
- If a large, thick, structural shim is required, load redistribution to and within the joint may need to be investigated. Additionally an increase in bolt diameter may also be required to keep t/D ratios reasonable, *i.e.*, less than 3.0, to preclude fastener bending or head failures.
- If fastener is blind, shear head, or has aluminum nut or collar consider going to a stronger fastener/titanium or steel nut to preclude tension or bending failure of the fastener.

Static Strength Analysis Checklist:

Analysis		Section	Comments
Fastener Shear/Tension Capability	Check the shear/tension strength of the fastener. Retain 15% margin on fastener shear.	5.2.3	If margin is negative, use an alternative fastener with increased strength, increase fastener diameter (perform appropriate analysis for bearing and net section).
Fastener Bending Strength	Check the bolt bending strength of the joint if bolt bending can develop.	5.2.3	If total stack-up (including shim) exceeds 3D, depending on loading direction relative to shim.

Durability and Damage Tolerance Concerns:

- Analyze hole for bearing peaking with non-structural shim
- Analyze for residual stresses if gap is pulled up.

Repair Limitations:

- Limitation on non-structural shim thickness to 15% to 25% of fastener diameter
- Recommended limitation on total joint stack-up (all layers, including shims) 4D.

18.6.3.4 Bent Lug or Flange Due to Gap Pull-up

Defect/Damage: PERMANENT DEFORMATION RESULTING FROM CLAMP UP OR IMPROPER SHIMMING

Defect Description:	**Characterization:**
• Part has been permanently deformed due to pull-up.	• Description of deformation or visual indication of defect

Disposition and Repair Guidance:	**Reference Section**
Fastener(s)/pin should be removed and the part inspected.	**18.4.13**
If permanent deformation exists, part should be removed and scrapped.	
If no permanent deformation exists, then part should be inspected for cracks using dye penetrant inspection. If uncracked, reinstall hardware with correct bushings/washers/spacers or shims.	**18.4.13, 18.4.14, 18.6.3.3**

Defect Discussion:

- This is typically found on lug/clevis fittings where clamp-up bushings were inadvertently left out or washers were not installed. Clevis is visibly bent.
- This can also occur in shear or tension clip (integral or fastened) attachments to structure

Static Strength Analysis Checklist:

- None, if part scrapped and replaced or if no permanent deformation. If additional shims are added, then

Analysis		Section	Comments
Fastener Shear/Tension Capability	Check the shear/tension strength of the fastener. Retain 15% margin on fastener shear.	5.2.3	If margin is negative, use an alternative fastener with increased strength, increase fastener diameter (perform appropriate analysis for bearing and net section).
Fastener Bending Strength	Check the bolt bending strength of the joint if bolt bending can develop.	5.2.3 or 5.4.5	If total stack-up (including shim) exceeds 3D or if lug has large gaps.

Durability and Damage Tolerance Concerns: None, if part scrapped and replaced or if no permanent deformation.

Repair Limitations: Do not use a part with permanent deformation present.

18.6.3.5 Web Deformation Due to Residual Stresses

Defect/Damage: WEB PERMANENT DEFORMATION OR "OIL CANNING"

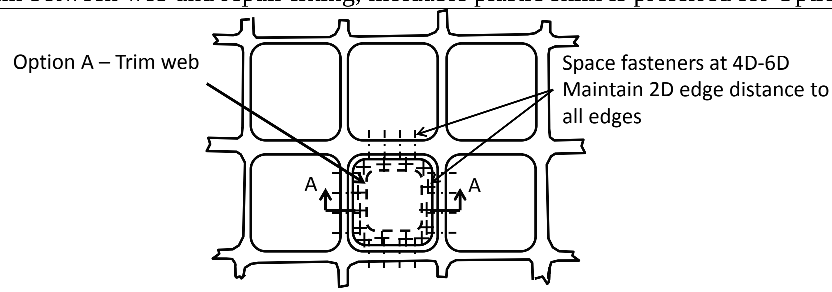
Defect Description:	**Characterization:**
• The thin web of part has permanently deformed into a sinusoidal shape as result of residual stresses and machining	• Description of deformation • Location • Depth of wave

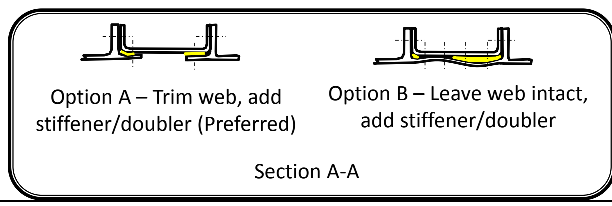
Disposition and Repair Guidance:	**Reference Section**
Trim web and add fitting to web area, attaching to adjacent stiffeners. Shim gaps with solid shim or moldable plastic shim. DO NOT PULL UP GAPS.	**18.4.27, 18.4.29**
An alternative approach, if the bay is too small to trim web and still have fasteners common to web and fitting, do not trim web. Add fitting, shimming gaps with moldable plastic shim and attach to stiffeners and also through web. See figure, below.	**18.4.27**

Defect Discussion:

- This defect is typically found on an integrally machined part with caps and webs such as a frame, bulkhead, spar or longeron. It is a result of a combination of residual stresses in the material due to forming or rolling and the machining operation.
- It is important that the issue be resolved for future parts by changing the processing of the parts. Consult with Materials and Processing Engineering and Producibility to determine the best approach.

- For a limited number of parts, if acceptable to DADT, this condition may be repaired as follows:
  - If the web is pressurized or post-buckled, it is important to stabilize it so that it cannot pop from one deformed state to a different deformed state under operational loading.
  - Stabilize web in the deformed state rather than attempting to flatten and further increasing the stresses. Trimming out the center of the web, as shown in Option A of figure below, can relieve some of the residual stress and relax the deformation. This is the preferred repair.
  - A machined fitting which is attached through the stiffeners as well as the periphery of the web, if trimmed, can replace the defective web. If the web is not trimmed, the repair part should pick up fasteners across the width and height of the web at 4D-6D spacing.
  - Shim between web and repair fitting, moldable plastic shim is preferred for Option B.





Static Strength Analysis Checklist:

Analysis		Section	Comments
Fastener Shear/Tension Capability	Check the shear/tension strength of the fasteners common to integral stiffener/repair fitting.	5.2.3	These fasteners must react all pressure loads and in-plane shear to integral stiffeners. Retain 15% margin on fastener shear.
Fastener Shear/ Tension Strength	Fasteners common to web/repair fitting	5.2.3	Depending on the side of the web the repair fitting is located; the fasteners may have to react all pressure loads as tension loads combined with in-plane shear to integral stiffeners. Retain 15% margin on fastener shear.
Flange Bending	Repair Fitting	5.3.5	Depending on the side of the web the repair fitting is located; flange bending may be critical for the repair fitting
Stability of Repair Fitting Web	Check initial buckling of repair fitting web, assume simply supported edge conditions. Panel size is fastener line to fastener line. Allow no buckling to ultimate load.	10.3.2	The residual stresses from the deformed shape of the web and the added complexity of the repair fitting dictate conservatism relative to load redistribution.
Pressure loading of the Repair Fitting Web	The repair fitting should be of sufficient thickness that it acts as a simply supported flat plate in bending, *i.e.* $\delta \leq t/2$	10.2.2	

Durability and Damage Tolerance Concerns:
- Residual stresses in deformed web.
- With the added repair fitting, fasteners will be added to stiffeners. Although this is typically undesirable for DADT, this is necessary to obtain the proper continuity to transfer the applied loads.

Repair Limitations:
- This repair should not become a “standard repair” for a specific part. Other means should be used to find a long term solution, including, alternative heat treat/quench, more controlled machining, and thickening the web.
- Do not use blind fasteners for this repair

18.6.3.6 Cracked Part – During Aircraft Manufacture

Defect/Damage: PART CRACKED DURING MANUFACTURE

Defect Description:	**Characterization:**
• Part has developed a crack during the manufacturing process	• Description of crack location • Length of crack, both surfaces • Orientation of crack

Disposition and Repair Guidance:	**Reference Section**
Crack should be removed from the part. Ensure that the crack tip has been completely eliminated.	**18.4.18, 18.4.22**
Add doubler/reinforcement as necessary	**18.4.21,18.4.24, 18.4.27**

Defect Discussion:
- This is typically the result of abuse of the part.
- It can occasionally occur due to the installation of interference fit bushings or cold work of a short edge distance hole.
- In a production environment, if the part can be removed and replaced without risk of significant collateral damage (damage to adjacent parts) that is the best alternative. If that is not practical, then excising the crack is the next best solution.

Static Strength Analysis Checklist:
- None, if part scrapped
- Analysis is dependent on the final design of the repair

Durability and Damage Tolerance Concerns: None, if part scrapped.

Repair Limitations: A crack SHALL not be left in a part during initial production of the aircraft.

18.6.3.7 Cracked Part – Post Production Field Repair

Defect/Damage: PART CRACK DISCOVERED DURING FIELD INSPECTION	
Defect Description: • Part has developed a crack during operation	**Characterization:** • Description of crack location • Length of crack, both surfaces • Orientation of crack
Disposition and Repair Guidance:	**Reference Section**
With customer approval, part may be stop drilled. The decision to stop drill depends on customer goals, location of crack and length of crack. Post repair inspection is always required.	**18.4.23**
If not stop drilled then crack should be removed from the part. Ensure that the crack tip has been completely eliminated.	**18.4.18, 18.4.22**
Add doubler/reinforcement as necessary	**18.4.21, 18.4.24, 18.4.26, 18.4.27, 18.4.28**
Defect Discussion: • This is typically the result of cyclic fatigue and is discovered during maintenance or inspection operations in the field.	
Static Strength Analysis Checklist • Analysis is dependent on the final design of the repair	
Durability and Damage Tolerance Concerns: Analysis is dependent on the final design of the repair. Areas of concern include ensuring that the repair is appropriately tapered such that a new critical area does not result. Additionally, the repair should be designed to allow for inspection of the crack to determine if the stop drill has stopped the growth.	
Repair Limitations: Customer approval is required.	

18.7 Repair Validation Testing

For many of the repairs performed and analyzed on a daily basis, no additional testing is required. However, occasionally there is a repair which so significantly affects the load paths that a proof test, test to limit load, a repeat of loads calibration testing or a fatigue test may be required. Rather than a single large repair the cumulative effect of a significant number of adjacent repairs may also result in requirements for testing. The tests required may be of a single structural element such as a horizontal tail, flap or leading edge or it may be of a whole aircraft.

Additionally, significant repairs to control surfaces, landing gear, and control system actuator attachment back-up structure would be possible candidates for additional validation testing such as ground vibration testing or proof loading. Any repairs to these items should be done in consultation with the Flutter and Dynamics group.

Extensive repairs sometimes performed on post production aircraft, such as spar insertions or replacing wing skins, may also trigger a need for validation testing.

The first step in the process of determining how a repair of large magnitude might affect the internal loads distribution would be to modify the air vehicle finite element model to reflect the changes. If significant redistribution of loads occurs, testing may be required. Engineering judgment and experience play a role in the final decision and any conclusions need to be coordinated with the customer.

A second level of repair validation testing may involve testing a new type of repair such as bonded patches or straps, a room temperature cure adhesive, or a bolted/bonded repair to determine the ultimate strength of the repair. If a unique repair or class of repairs have to be developed to address a particular defect/anomaly, then validation testing at a coupon, element or subcomponent level is likely. Typically this type of repair develops point design allowables for the specific configuration in question. Depending on the repair scenario, sufficient articles need to be tested to adequately represent the scatter in strength due to inherent defects, allowed production anomalies, material, etc. Testing should only be accomplished to develop the strengths used for disposition after the final process is defined in a process specification and all materials are identified and have material specifications.

18.8 Computer Tools

See PM4056 Section 19.10 for a discussion of Composite Material Review IDAT Tools.