3 Materials

The purpose of this chapter is to provide generic guidance on metallic structural materials and fasteners. For some aircraft programs specific guidance may be offered for some or all of these topics. In that event program guidance would govern the analysis approach.

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3.1.1 List of Symbols and Nomenclature

Symbol	Description	Units
σ	material stress	psi
E	Modulus of Elasticity	psi
e/D	edge distance / fastener hole diameter	
E_c	Compression Modulus of Elasticity	psi
E_{sec}	Secant Modulus	psi
E_{tan}	Tangent Modulus	psi
e	material strain	in/in
e_o	material elongation	in/in
e_p	plastic strain	in/in
e_{rup}	material rupture strain	in/in
e_u	material Strain at ultimate stress	in/in
$f_{0.1ys}$	0.1%-offset yield stress	psi
$f_{0.2ys}$	0.2%-offset yield stress (F_{ty})	psi
$f_{0.7}$	0.70E Secant Intercept of stress-strain curve	psi
$f_{0.85}$	0.85E secant intercept of stress-strain curve	psi
F_{bry}	material bearing yield stress	psi
F_{bru}	material bearing ultimate stress	psi
F_{cmax}	material ultimate stability stress cutoff	psi
F_{cy}	material compression yield stress	psi
F_{cu}	material ultimate compression stress	psi
F_{rup}	material rupture stress	psi
F_{su}	material shear ultimate strength	psi
F_{tu}	material tensile ultimate stress	psi
F_{ty}	material yield stress	psi
F_{tp}	material proportional limit in tension	psi
G	Shear Modulus	psi
G_{tan}	Shear Tangent Modulus	psi
IDAT	Integrated Detail Analysis Tool	

Symbol	Description	Units
k_{bry}	bearing yield allowable stress reduction factor for edgewise orientation in thick aluminum plate	
k_{bru}	bearing ultimate allowable stress reduction factor for edgewise orientation in thick aluminum plate	
k_{wpb}	bearing allowable stress reduction factor due to wet pin installation	
L	material longitudinal grain direction	
LS	material longitudinal-short direction	
LT	material longitudinal-transverse grain direction	
n	Tension Ramberg-Osgood parameter	
n_c	Compression Ramberg-Osgood parameter	
n_t	modified Ramberg-Osgood parameter	
S	material short grain direction	
ST	material short-transverse grain direction	
T	material transverse grain direction	
TS	material transverse-short grain direction	

Greek Symbols

Symbol	Description	Units
γ	Shear Strain	in/rad
ν	Material Poisson's Ratio	--
σ	Stress	psi
τ	Shear stress	psi

3.2 Material Behavior

This section includes various aspects of material behavior deemed relevant to the practice of detailed metallic stress analysis. This section is not intended to be a balanced or comprehensive treatment of the subject of metallic material behavior (see open literature, such as Reference 3-7). In addition to the open literature on material behavior in general, heritage structural analysis texts, handbooks, manuals, and reports (e.g., References 3-1 through 3-4, 3-8, and 3-9) may also be cited as acceptable reference documents for material behavior aspects of LM Aero structural analyses not covered in this Process Manual.

3.2.1 Strain Softening Issues in Stress Analysis

Figure 3.2.1-1 shows typical full-range and idealized metallic stress-strain responses. Common nomenclature is defined on the curve. The idealized curve is an example of a Ramberg-Osgood-based non-full range stress-strain curve, which is found in the MMPDS for all materials. Full-range curves are given in the MMPDS only for certain alloys. It is important to realize that the vast majority of aluminum, steel, and titanium structural alloys exhibit little reduction in strength between ultimate stress and rupture. Thus, it is convenient to simplify common usage: (a) refer to strain at ultimate stress, e_u , and rupture strain, e_{rup} , interchangeably; and (b) assume that the Ramberg-Osgood stress-strain idealization provides all necessary information regarding material response. This common usage of terms implies that material elongation relates to rupture strain and strain at ultimate stress as:

$$e_u = e_{rup} = e_o + F_{rup} / E \qquad \text{Equation 3.2.1-1}$$

where
F_{rup} is the stress at rupture (psi)
e_o elongation at ultimate stress (psi)
E material elastic modulus (psi)

Since the F_{rup} / E term is negligible for most steel, aluminum, and titanium alloys when $e_o > 5\%$, material (plastic) elongation, e_o , is also often equated to strain at ultimate stress, e_u , and rupture strain, e_{rup}. Nonetheless, the distinctions between strain at ultimate stress, e_u (an important point in stress analysis), rupture strain, e_{rup} , and material (plastic) elongation, e_o (an easily measured and reported quantity found for all alloys in the MMPDS), are occasionally important. A few alloys/material forms, such as those listed in Table 3.2.1-1, exhibit significant strain-softening behavior prior to rupture, *i.e.*, $e_u << e_{rup}$, $e_u << e_o$, and $F_{rup} << F_{tu}$. Examples of these sorts of full-range stress-strain curves are shown in Figure 3.2.1-2. For these materials it is thus important to discriminate between strain-at-ultimate-stress, rupture strain, and material elongation.

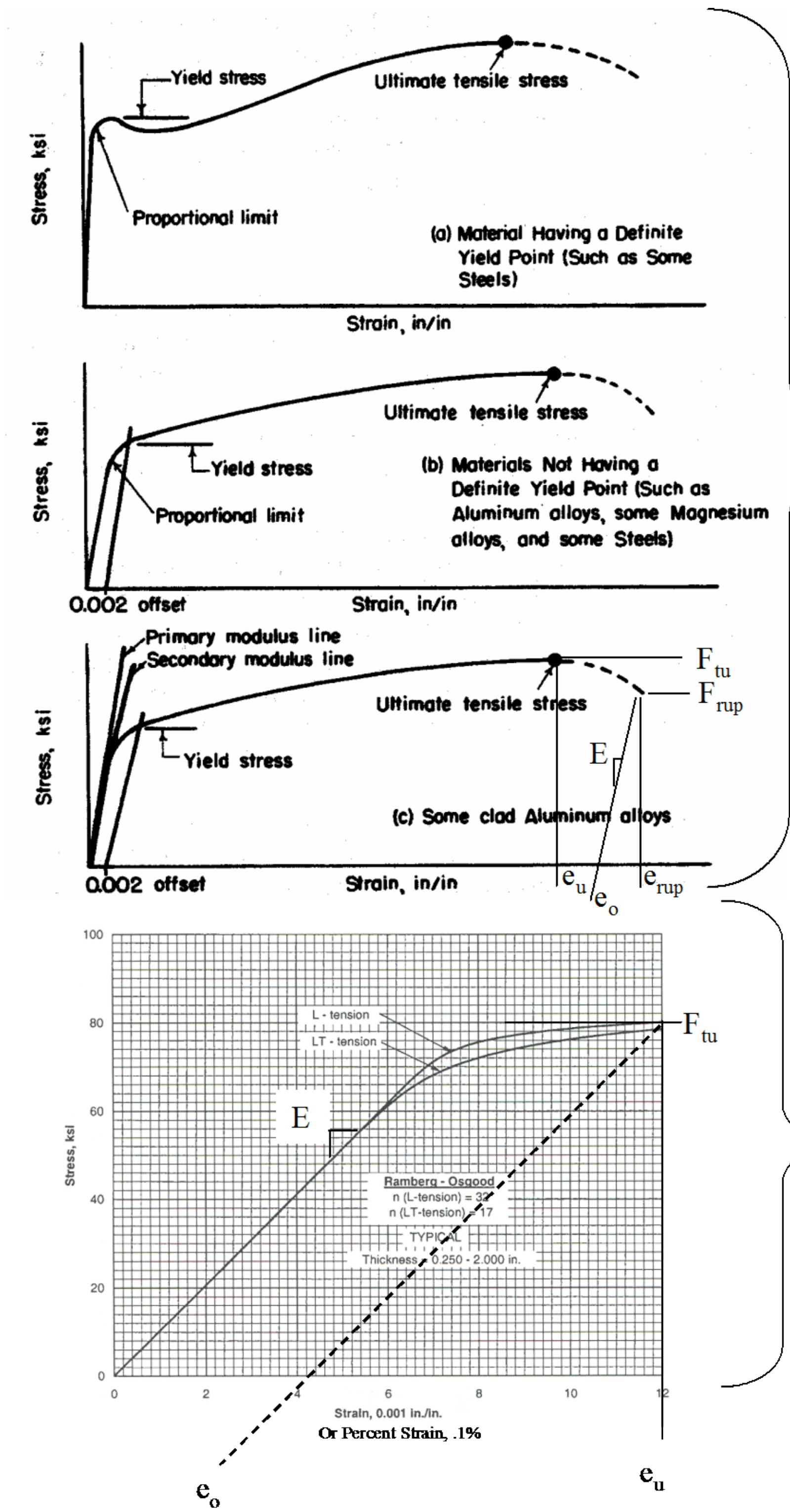
For details regarding the proper usage of various strain-based properties with strain-softening materials, refer to the section of this process manual dealing with the specific analysis technique of interest (e.g., Section 5.4 for lug analysis, 6.3 for plastic bending, 10.2 for plate buckling, etc.). Depending both on the type of analysis and on whether or not it has recently been updated, certain differences in terminology and usage of strain-based properties should be expected. The differences relating to various Ramberg-Osgood formulations are addressed in Section 3.3.1.

Table 3.2.1-1 Typical Properties of Strain-Softening Materials

Material	Condition	e_u (%)	F_{tu} (ksi)	e_o (%)	e_{rup} (%)	F_{rup} (ksi)	F_{rup} / F_{tu}
9Ni-4Co-0.30C Intermed. Alloy Steel forging	Quench/temper	4.6	230	15.4	15.9	150	0.65
18 Ni 280(300) High Alloy Maraging Steel bar	Maraged 900F	1.8	285	10.4	11	170	0.60
AerMet 100 (280-300 ksi) High Alloy Steel bar	Sol'n treat/age	3.6	285	14.2	16.8	160	0.56
AerMet 100 (290-310 ksi) High Alloy Steel bar	Sol'n treat/age	3.8	303	14.2	14.9	185	0.61
PH13-8Mo Stainless Steel bar	H950	2.0	229	9.6	10.1	147	0.64
PH13-8Mo Stainless Steel bar	H1000	1.4	215	9.2	9.7	135	0.63
PH13-8Mo Stainless Steel bar	H1050	1.6	184	10.6	11.0	104	0.57
PH13-8Mo Stainless Steel bar	H1100	6.6	174	16.6	17.0	106	0.61

Notes:
1. All data longitudinal-orientation typical values at 70F.
2. This table does not include all conditions, temperatures, and orientations. See the MMPDS (Reference 3-5) for specific material application.

All of these materials exhibit an interesting phenomenon in that 75-85% of their elongation occurs after their ultimate strength has been reached. For this reason, caution must be used in applying the standard Ramberg – Osgood formulations to predict the material behavior and additional component testing may be required to accurately predict failure. For these materials, the strain at ultimate stress from a full range stress-strain curve is generally used to determine the practical e_u of the material for analysis purposes.

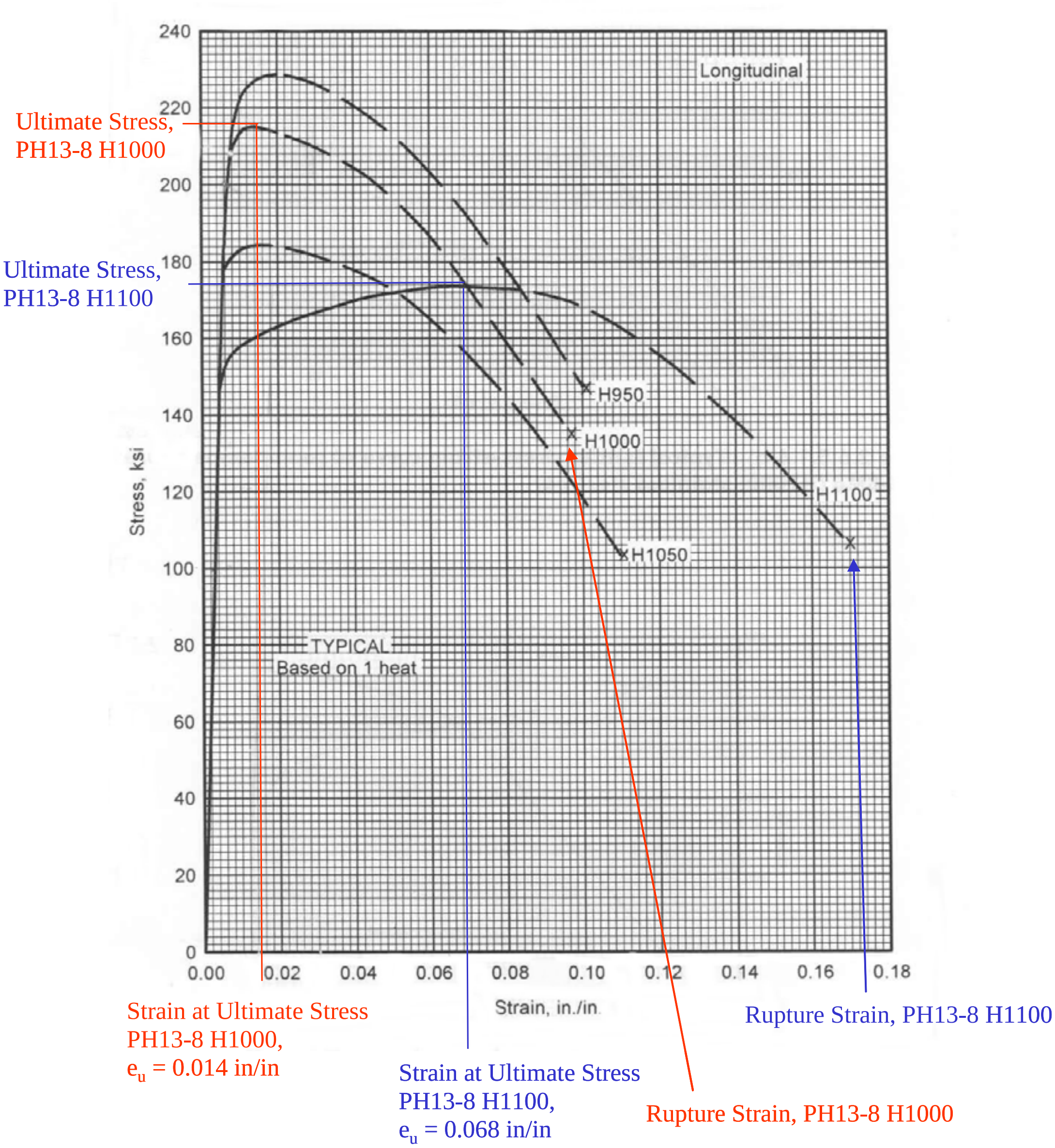


•Actual Material Behavior full-range stress-strain curve
•Includes rupture stress and strain
• Based on test data points.

•Idealized material behavior, non-full range stress-strain curve.
•Rupture stress and strain not shown.
•Based on Ramberg-Osgood formulation.

from MMPDS Reference 3-5

Figure 3.2.1-1 Typical Metallic Stress-Strain Response



From Figure 2.6.5.1.6c, MIL-HDBK-5H, Reference 3.3-4

Figure 3.2.1-2. Metallic Stress-Strain Response with Strain-Softening

3.2.2 Modulus of Elasticity, Tangent and Secant Modulus

The modulus of elasticity or Young's Modulus describes the slope of the stress-strain curve in the elastic region; *i.e.*, below the proportional limit where the curve is linear. It is determined from the ratio stress/strain or f/e. Beyond the linear region, there are other mathematical formulations which can be more useful for engineering analysis.

The tangent modulus is the slope of a tangent line to the stress-strain curve at any stress and represents the rate of change of stress with strain. In the elastic region it is the same as the modulus of elasticity. However, once the proportional limit is reached, the tangent modulus starts to decrease as the stress-strain curve starts to flatten out.

This is shown in Figure 3.2.2-1. At ultimate stress, the tangent modulus goes to zero. Section 3.3.1 provides equations for the calculation of tangent modulus.

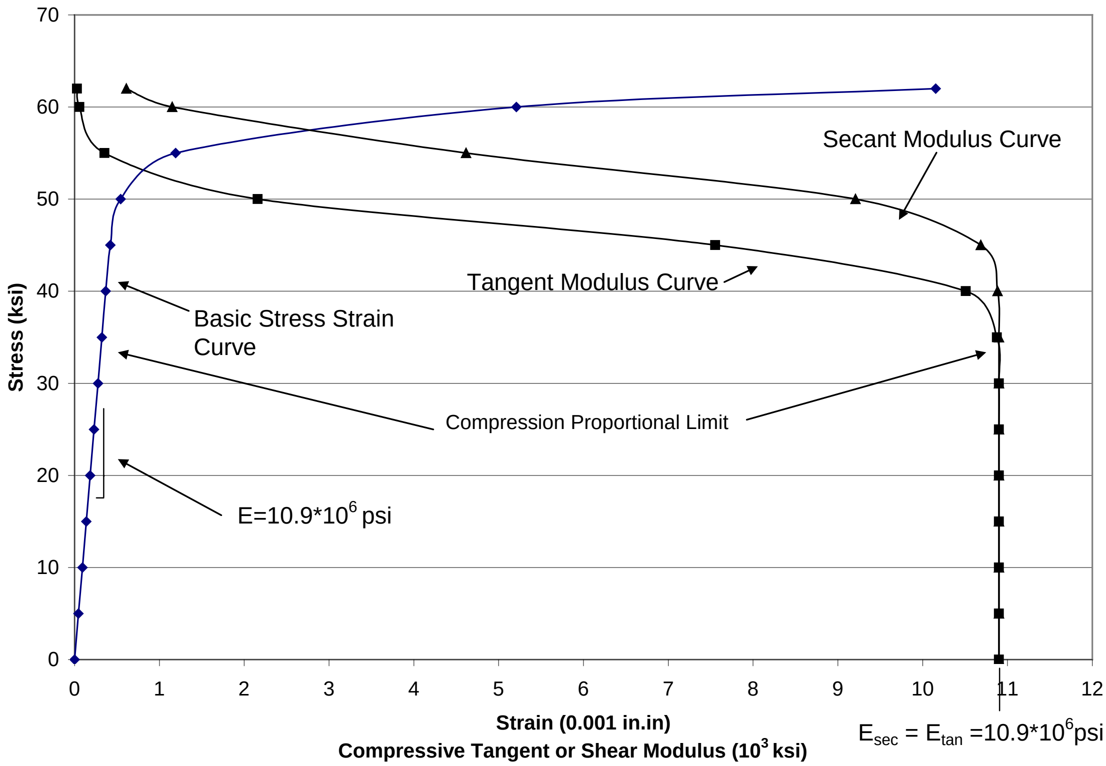


Figure 3.2.2-1 Elastic Modulus and Tangent Modulus Curves for 2024-T62 plate

The tangent modulus is primarily used for column buckling calculations as experimental results have shown it represents the loss of stiffness seen in inelastic column behavior.

The secant modulus is the slope of a line from the origin of the stress-strain curve to a specific point on the stress-strain curve. Below the proportional limit of the material, the value of the secant modulus is the same as the tangent modulus and the elastic modulus. Above the proportional limit the secant modulus is generally reducing but not as rapidly as the tangent modulus. This is illustrated in Figure 3.2.2-1. Equations for the calculation of secant modulus are provided in Section 3.3.1.

The secant modulus or a linear combination of the secant and tangent moduli would be used for buckling calculations depending on loading and edge restraint and buckling behavior. These values are called reduced moduli since their value is below the elastic modulus. Reference 3-10 provides a tabular summary of the range of reduced moduli and their application. This summary is provided in Table 3.2.2-1. The highest value among the reduced moduli is the secant modulus and this applicable if there is negligible longitudinal bending as occurs in a simply supported flange with axial loading only which buckles by twisting. The lowest value is the tangent modulus which is applicable when bending is predominant over other distortions as would be the case for long column buckling.

Further discussions on the correct use of these equations can be found in Sections 8 and 10.

Table 3.2.2-1 Summary of Reduced Modulus Values for Buckling

Structural description	Reduced Modulus	Comments / Equation Number
Loaded flange, one unloaded edge, simply supported, one free	E_{sec}	**Equation 3.2.2-1**
Long flange, one unloaded edge clamped, one free	$E_{\sec}\left(0.330+0.670\sqrt{\left(0.25+0.75\frac{E_{\tan}}{E_{\sec}}\right)}\right)$	**Equation 3.2.2-2**
Long plate, both unloaded edges simply supported	$E_{\sec}\left(0.50+0.50\sqrt{\left(0.25+0.75\frac{E_{\tan}}{E_{\sec}}\right)}\right)$	Stowell Modulus **Equation 3.2.2-3**
Long plate, both unloaded edges clamped	$E_{\sec}\left(0.352+0.648\sqrt{\left(0.25+0.75\frac{E_{\tan}}{E_{\sec}}\right)}\right)$	**Equation 3.2.2-4**
Short plate loaded as a column (L/b<<1)	$0.25E_{sec} + 0.75\ E_{tan}$	**Equation 3.2.2-5**
Long Column (L/b >>1)	E_{tan}	**Equation 3.2.2-6**

3.2.3 Modulus of Rigidity or Shear Modulus

In the case of pure shear such as the torsion of tubes or deflection of shear webs, a relationship between shear stress and shear strain can be developed which is similar to the relationship between axial stress and axial strain. Shear stress and shear strain curves also have an elastic portion of the curve where the relationship is expressed by a straight line. The slope of this line represents the elastic shear constant. It is referred to as the modulus of rigidity or modulus of elasticity in pure shear and is given the symbol G. The latter term is sometimes shortened to shear modulus. It is defined as

$$G=\tau/\gamma$$ **Equation 3.2.3-1**

where
τ is the shear stress (psi)
γ is the shear strain (radians)

From the Mohr's circle relationship between shear and axial loading, an expression for G in terms of the modulus of elasticity, E can be derived[2] as

$$G=\frac{E}{2(1+\nu)}$$ **Equation 3.2.3-2**

where
E is the modulus of elasticity or Young's modulus of the material (psi)
ν is the Poisson's ratio of the material

[2] Reference 3.2-5

In the plastic range, the tangent shear modulus which, is used in shear buckling and torsional instability calculations, can be expressed as

$$G_{\tan} = \frac{E_{\tan}}{2(1+\nu)}$$ **Equation 3.2.3-3**

where
E_{tan} is the tangent modulus given by Equation 3.3.1-3 or 3.3.1-8(psi)

As with the tangent modulus, the tangent shear modulus represents the slope of the tangent to the shear stress-strain curve at a specific stress or the rate of change of stress with strain.

3.3 Design Mechanical and Physical Properties

The purpose of this section is to provide generic guidance on design mechanical and physical properties for metallic structural materials, and serve as the source document for the metallic material properties database used in the Integrated Detailed Analysis Tools (IDAT) suite of quality-controlled structural analysis software. Additional guidance and properties are found in MIL-HDBK-5 (Reference 3-4) or its successor MMPDS (Reference 3-5), the AFRL preliminary material properties handbook (Reference 3-12), and heritage documents such as LMAS Stress Memos 61m and 77a (Reference 3-1), LR31445 (Reference 3-13), the GD Structures Analysis Manual (Reference 3-2), and LTV Structures Manual (Reference 3-3).

3.3.1 Design Stress-Strain Curves

In certain metallic airframe stress analyses, particularly panel buckling and plastic bending, it is necessary to capture the physics of post-yield material response. In order to model this type of material response, several generic functional forms of the metallic stress-strain response curve are used, depending on application. In this section, three of these methods – the original Ramberg-Osgood and Hill approaches, and a modified version of Hill's formulation (commonly termed the "Modified Ramberg-Osgood" formulation) - are documented, in order to clarify terminology and relate the currently-preferred equations to legacy methods. Table 3.3.1-1 lists which version was used by various common structures texts and manuals over the past 60 years.

Table 3.3.1-1. Stress-strain Formulations in Common Use

NACA-TN-902 (Ramberg-Osgood) , Reference 3-14	**NACA-TN-927 (Hill),** Reference 3-15
Peery, Reference 3-8 Bruhn, Reference 3-9[2] LTV Structures Manual, Reference 3-3 GD Structures Analysis Manual, Reference 3-2[2]	MMPDS, Reference 3-5 LMAS Stress Memo 77a, Reference 3-1[1] PM-4057 MSAM, Section 6.3[3]
Notes: 1. Shows figure with TN-902 terminology and nomenclature, including E_{tan} in terms of $f_{0.7}$ but uses the TN-927 offset-based equation for compressive "n" and a modification thereof for tension. 2. "3/7" coefficient shown in Equation 3.3.1-1 omitted in this reference, through typographical errors. 3. Modified to better fit yield-to-ultimate region of stress-strain response.	

3.3.1.1 Ramberg-Osgood Formulation

The most common functional form of stress-strain approximation is the original Ramberg-Osgood relationship, Reference 3-14. This formulation was originally intended to accurately predict the nonlinear stress-strain response (either tensile or compressive) between the proportional limit and the 0.2%-offset yield stress, for use in nonlinear beam and plate buckling analysis (see Reference 3-16, or LTV Structures Manual, Sections 3 and 4, Reference 3-3 for details).

For the purpose of this process manual, the Ramberg-Osgood equation for strain as a function of stress is written in dimensional terms as

$$e = \frac{\sigma}{E}\left(1 + \frac{3}{7}\left(\frac{\sigma}{f_{0.7}}\right)^{n-1}\right)$$ Equation 3.3.1-1

where the Ramberg-Osgood number is given by

$$n = 1 + \frac{\log\left(\frac{17}{7}\right)}{\log\left(\frac{f_{0.7}}{f_{0.85}}\right)}$$ Equation 3.3.1-2

Equation 3.3.1-1 is also often seen in terms of non-dimensional stress and strain (References 3-2, 3-14). The stresses denoted $f_{0.7}$ and $f_{0.85}$ are experimentally-determined 0.70E and 0.85E secant intercepts of the stress-strain curve. It is important to realize that these secant intercepts may be determined for either typical (mean value) or reduced stress-strain curves (equivalent to A- or B-basis statistical reductions), and separately for both tension and compression. For aluminum in tension, $f_{0.7}$ and $f_{0.85}$ fall near and below the 0.2% yield stress, F_{ty}, respectively.

Of most direct use in buckling analyses is an expression for reduced compressive tangent and secant moduli, given as

$$E_{\tan} = \frac{E}{\left(1 + \frac{3}{7}n\left(\frac{\sigma}{f_{0.7}}\right)^{n-1}\right)}$$ **Equation 3.3.1-3**

$$E_{\sec} = \frac{E}{\left(1 + \frac{3}{7}\left(\frac{\sigma}{f_{0.7}}\right)^{n-1}\right)}$$ **Equation 3.3.1-4**

In this case, it is also convenient to solve for $f_{0.7}$ using the relation in Reference 3-3,

$$f_{0.7} = F_{cy}\left(214.3\frac{F_{cy}}{E_c}\right)^{1/(n-1)}$$ **Equation 3.3.1-5**

where F_{cy} and E_c are reduced, or basis, values but the Ramberg-Osgood parameter, n, is determined from typical compression data. Note that 3.3.1-3 may also be used for typical stress-strain curves and for tensile as well as compressive response (given appropriate $f_{0.7}$ and n values), but 3.3.1-4 in its current form cannot. An analogous expression to Equation 3.3.1-4 for use in tension applications can be derived where F_{ty} and E are used in lieu of F_{cy} and E_c however, it does not have as widespread an application.

The $f_{0.7}$ and $f_{0.85}$ intercept stresses found in the above equations are not readily available from source material such as the MMPDS, but are tabulated for many older materials along with the exponent, n, in legacy sources such as the General Dynamics and LTV structures manuals Reference 3-2 and 3-3. However, care should be taken in choosing a value from sources such as these heritage structures manuals or the MMPDS, since it is often unclear whether the parameters are derived from tension or compression, typical or reduced stress-strain curves. Table 3.3.1-2 illustrates the types of parameters favored by various heritage documents. Thus, the MMPDS is the preferred reference for typical values of both the Ramberg-Osgood coefficient, *n*, and graphical presentations of tangent modulus, E_{tan}, with these values being provided for every alloy in the MMPDS. However, it is important to note that the derivation used in the MMPDS to derive these values is that of Hill (Reference 3-15), which uses 0.1% and 0.2% off-set stresses rather than the secant intercepts of the original Ramberg-Osgood formulation (Reference 3-14). Thus, if the functional forms of either strain (Equation 3.3.1-1) or tangent modulus (Equation 3.3.1-3) need to be programmed for use with alloys not previously tabulated in legacy manuals (*i.e.*, no $f_{0.7}$ data), the Hill formulation may be used as an alternative to the equations shown in this section. It is believed that in the case of all reasonably well-behaved metallic materials, the coefficient *n* is identical to at least two significant figures, whether derived using the original Ramberg-Osgood equations or the Hill formulation.

Table 3.3.1-2. Types of Ramberg-Osgood Shape Parameters Reported in Various Sources

Source Document	Typical or Reduced Values	Tension or Compression Properties
LMAS Stress Memo Manual, Reference 3-1	Reduced	Both[1]
GD Structures Analysis Manual, Reference 3-2	Reduced	Compression
LTV Structures Manual, Reference 3-3	Reduced	Compression
MMPDS, Reference 3-5	Typical	Both
Notes: 1. SM77a also includes shape parameter and design curves for bearing.		

Reference 3-5, Section 9.8.4.1.3 has proposed an extension of the Ramberg-Osgood formulation (n_1, n_2 and K) to better model the behavior of certain newer alloys in the initial yield region of the stress-strain curve. At this time, the analysis methods presented in this manual, which have been verified by component and full scale testing, are based on the original formulation of Reference 3-14. For all materials presented in MMPDS, the Ramberg-Osgood parameters for both formulations are presented. The traditional single parameter value, n, should be used in analysis for all materials.

3.3.1.2 Hill Formulation

As noted above, Hill (Reference 3-15) proposed, and the MMPDS adopted, a modified version of Equation 3.3.1-1, using 0.1% and 0.2% off-set rather than secant-intercept stresses. This Hill formulation then takes the form

$$e = \frac{\sigma}{E} + 0.002\left(\frac{\sigma}{f_{0.2ys}}\right)^n \qquad \text{Equation 3.3.1-6}$$

where

$f_{0.2ys}$ is the 0.2%-offset yield stress, generally referred to as F_{ty} in tension or F_{cy} in compression (psi)

The Ramberg-Osgood number is given by

$$n = \frac{\log 2}{\log \frac{f_{0.2ys}}{f_{0.1ys}}} = \frac{\ln 2}{\ln \frac{f_{0.2ys}}{f_{0.1ys}}}$$

Equation 3.3.1-7

where
$f_{0.1ys}$ is the 0.1% offset yield stress and may be tension or compression, as appropriate (psi)

And the tangent and secant moduli are given as

$$E_{\tan} = \frac{1}{\frac{1}{E} + 0.002\left(\frac{n}{f_{0.2ys}}\right)\left(\frac{\sigma}{f_{0.2ys}}\right)^{n_c - 1}}$$

Equation 3.3.1-8

$$E_{\sec} = \frac{1}{\frac{1}{E} + \left(\frac{0.002}{f_{0.2ys}}\right)\left(\frac{\sigma}{f_{0.2ys}}\right)^{n_c - 1}}$$

Equation 3.3.1-9

As with the Ramberg-Osgood formulation, the Hill formulation may be used with either typical or reduced, and tensile or compressive, offset stresses.

3.3.1.3 Modified Ramberg-Osgood Formulation

In contrast to nonlinear buckling analyses, where the region of interest lies above the proportional limit but below the 0.2% offset compressive yield stress, plastic bending analysis requires accurate approximation of the stress-strain response as it approaches the ultimate tensile strength, F_{tu}, in order to determine engineering strain at ultimate. Refer to MSAM section 6.3 for the details of this analysis method. Of interest in this materials section of the MSAM is the exact manner in which the tensile stress-strain response between yield and ultimate is approximated. A simple modification to the Hill formulation is used (traditionally referred to as a "modified Ramberg-Osgood" formulation), substituting yield and ultimate stresses for 0.1%- and 0.2%-offset yield values in order to determine the shape parameter, n_t. The subscript "t" is used for "tension," since the original parameter is generally used as and understood to be a compressive value for inelastic plate buckling:

$$n_t = \frac{\log\left(\frac{e_u - \frac{F_{tu}}{E}}{0.002}\right)}{\log\left(\frac{F_{tu}}{F_{ty}}\right)}$$

Equation 3.3.1-10

As with the traditional Ramberg-Osgood parameter used for plate buckling, the modified value used in plastic bending analysis is most often calculated and used as a reduced A-, B-, or S-basis, rather than typical value.

3.3.1.4 Tensile Proportional Limit Stress, F_{tp}

The tensile proportional limit is the highest stress level in which the stress remains proportional to strain. The point where the stress curve departs from the linear is difficult to define and is generally done so in terms of a small degree of plastic strain. The MMPDS, Reference 3-5, defines the proportional limit as the point which corresponds to a plastic strain of 0.0001 in/in or a 0.01% deviation from linear. From Equation 3.3.1-6, the total strain is given by the sum of the elastic strain, σ / E, and the plastic strain, $0.002\ (\sigma / f_{0.2ys})^n$.

An equation for the proportional stress can then be derived as follows, by substituting the plastic strain and solving for the resulting stress, which is F_{tp}.

$$e_p = 0.0001 = 0.002\left(\frac{\sigma}{f_{0.2ys}}\right)^n$$

$$0.05 = \left(\frac{\sigma}{f_{0.2ys}}\right)^n$$

$$\sigma = f_{0.2ys}(0.05)^{\left(1/n\right)}$$

But $\sigma = F_{tp}$; $f_{0.2ys} = F_{ty}$

$$F_{tp} = F_{ty}(0.05)^{\left(1/n\right)}$$ **Equation 3.3.1-11**

where
σ_{tp} is the stress at the given strain level, in this case, proportional limit (psi)
$f_{0.2ys}$ is the 0.2%-offset yield stress or F_{ty} (psi)
n is the Ramberg-Osgood number in tension given by Equation 3.3.1-7

3.3.1.5 Compressive Proportional Limit Stress, F_{cp}

The compression proportional limit is the highest compression stress level in which the stress remains proportional to strain. As was discussed with the tension proportional limit, it is difficult to define the point of departure from the linear stress-strain curve. For purposes of practical analysis, the same value of plastic strain of 0.0001 in/in as in the tension case is used for determining the compression proportional limit stress as given by the following equation:

$$F_{cp} = F_{cy}(0.05)^{\left(1/n_c\right)}$$ **Equation 3.3.1-12**

where
F_{cy} is the 0.2%-offset compression yield stress (psi)
n_c is the Ramberg-Osgood parameter in compression given by Equation 3.3.1-7

For the purposes of iterative buckling solutions performed by computer, it is useful to define a compression proportional stress which is significantly smaller than is generally used in practical analysis. This value provides a smoother solution for these iterative buckling problems. For this purpose, the proportional limit is defined as the point which corresponds to a plastic strain of 0.00001 or a 0.001% deviation from linear. Thus, using Equation 3.3.1-6, the total strain is given by the sum of the elastic strain, σ / E, and the plastic strain in terms of compressive yield, $0.002(\sigma/F_{0.2cys})^n$.

An equation for the compression proportional stress can then be derived as follows, by substituting the plastic strain and solving for the resulting stress, which is F_{cp}

$$e_p = 0.00001 = 0.002\left(\frac{\sigma}{f_{0.2cys}}\right)^{n_c}$$

$$0.005 = \left(\frac{\sigma}{f_{0.2cys}}\right)^{n_c}$$

$$\sigma = f_{0.2cys}(0.005)^{\left(1/n_c\right)}$$

But $\sigma = F_{cp}$; $f_{0.2cys} = F_{cy}$

$$F_{cp} = F_{cy}(0.005)^{\left(1/n_c\right)}$$

Equation 3.3.1-13

where
σ is the stress at the given strain level (psi)
$f_{0.2cys}$ is the 0.2%-offset yield stress in compression or F_{cy} (psi)
n_c is the Ramberg-Osgood number in compression given by Equation 3.3.1-7

3.3.1.6 Generation of Basis or Reduced Stress-strain Curves

If a Basis or Reduced stress-strain curve is needed, the most straightforward approach is the use of Equation 3.3.1-6 for compression where the 0.2% yield stress, $f_{0.2ys}$, is replaced with the A or B-basis F_{cy}, and typical values of E_c and the compression Ramberg-Osgood number are used.

$$e = \frac{f}{E_c} + 0.002\left(\frac{f}{F_{cy}}\right)^n$$

Equation 3.3.1-14

where
f is the stress at which the strain is to be calculated (psi)
E_c is the typical compression modulus (psi)
F_{cy} is the A or B Basis compression yield stress (psi)
n is the typical compression Ramberg-Osgood number from Reference 3-5

To generate a curve, uniform incremental values of stress between 0 and Fty are selected and the strain calculated per the above equation. These are then plotted with strain on the x-axis and stress on the y-axis.

To generate a Basis or Reduced stress-strain curve for tension, again Equation 3.3.1-6 is used where the 0.2% yield stress, $f_{0.2ys}$, is replaced with the A or B-basis F_{ty}, and the typical value of E is used. For tension, either the typical Ramberg-Osgood number or the Basis n_t, calculated from Equation 3.3.1-10 can be used. Using n_t results in a small difference in the calculated strain values in the region from the proportional limit to the tensile yield of the material from the values calculated using the typical value for n. This difference is usually less than 5%. Figure 3.3.1-1 shows a sample tension stress-strain plot for 7050 T7451 Aluminum Plate. The line with the X symbol is a digitized version of the typical stress-strain curve from the MMPDS, Reference 3-5. The curve with the solid squares represents the calculated Basis stress-strain curve using the typical value for the Ramberg-Osgood number in tension. The curve with the open triangles represents the calculated stress-strain curve using the Basis n_t Ramberg-Osgood number. The latter two curves are B-Basis stress-strain curves, while the digitized curve is the typical stress-strain curve.

Since the slope of the tension curve is not used for calculations, the differences between the curves calculated from the typical and the basis Ramberg-Osgood numbers is inconsequential. Because the slope of the compression curve, E_c, is used in stability calculations, a number calculated using the formulation for n_t but with compression values substituted should not be used.

If a temperature-reduced Basis curve is desired, then E or E_c, F_{ty} or F_{cy} and n_t or n are adjusted per guidance in Section 3.3.2.1 and the curve constructed using the temperature adjusted values and Equation 3.3.1-11.

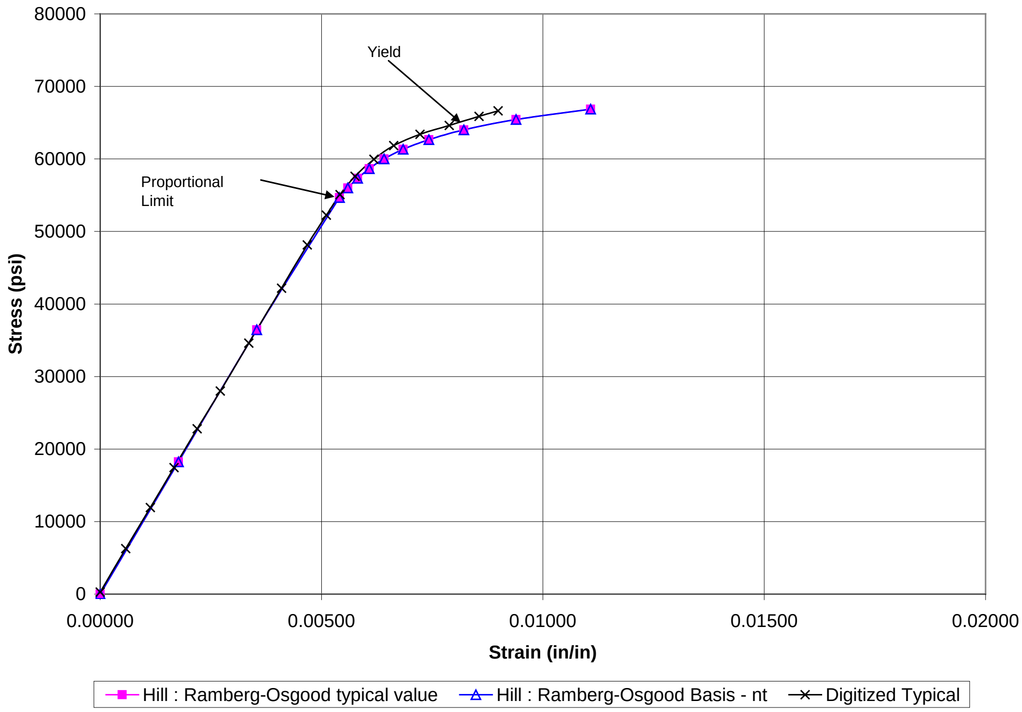


Figure 3.3.1-1 Sample B-Basis Tension Stress-Strain Plot

3.3.1.7 Generation of Non-Linear Material Curves for Use in Finite Element Analysis

In material non-linear finite element analysis, the user must supply material stress-strain data to failure. This section describes how that data can be formulated. The best result occurs when a full range stress-strain plot of the material in question is available and the first step involves digitizing the full range stress-strain plot. Generally this can be done by selecting 12 or so points from the curve: the origin, the proportional limit, several points at the knee of the curve, yield, several points along the flatter part of the curve including the point of maximum stress and then failure. This is illustrated in Figure 3.3.1-2.

The full range stress-strain curve is given in terms of engineering stress versus engineering strain[3]. This is the most commonly used form of stress and strain used in engineering applications. Engineering stress and strain are given by

$$\sigma = P/A_o$$
$$e = \Delta L / L_o$$

where
P is the applied load (lbs)
A_o is the unstressed cross-section area (in^2)
ΔL is the change in length (in)
L_o is the unstressed length (in)

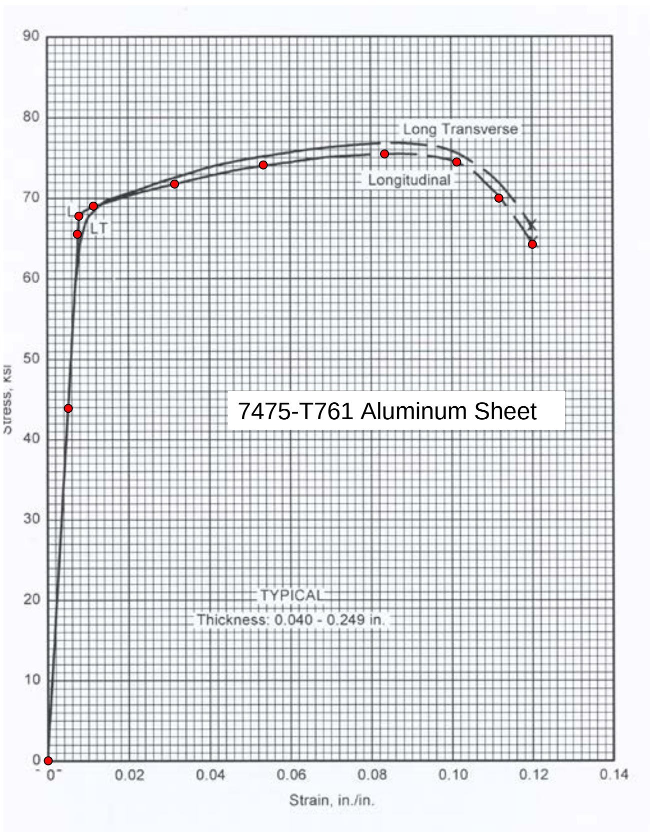


Figure 3.3.1-2 Sample Full Range Stress-Strain Curve from MMPDS (Reference 3-4)

Most FEA codes use either true stress and true strain[4] or true stress and true plastic strain[5]. To convert from engineering stress and strain to true stress and strain the following equations are used.

$$\sigma_{true} = (e+1)\sigma \quad \textbf{Equation 3.3.1-15}$$

[3] Engineering strain is the change in distance between the gage marks for a given load divided by the original spacing. Engineering normal stress is the load divided by the original area. True strain is integral of the length increments, dL, each divided by the associated value of total length that existed just prior to the increment. True normal stress is the total load divided by actual sectional area associated with them. This accounts for the transverse contraction under axial load (Poisson's effect).

[4] NASTRAN non-linear material properties require true stress-true strain
[5] ABAQUS non-linear material properties require true stress-true plastic strain

$$e_{true} = ln(e+1)$$ **Equation 3.3.1-16**

where
e is the engineering strain (in/in)
σ is the engineering stress (in/in)

If the true plastic strain is required, it can be obtained from true strain by the following

$$e_{true-plastic} = e_{true} - \frac{\sigma_{true}}{E}$$ **Equation 3.3.1-17**

where E is the Modulus of Elasticity or Young's Modulus (psi)

For many materials the full range stress-strain curve is not available. A good approximation of the curve can be generated using the material elongation, Ramberg-Osgood number and material ultimate and yield strengths. The procedure outlined in Section 3.3.1.6 is used to generate the portion of the curve below yield.

The ultimate strain is calculated from

$$e_u = e_o + \frac{F_{tu}}{E}$$ **Equation 3.3.1-18**

where
e_o is the material elongation [6] (in/in)
F_{tu} is the material ultimate stress (psi)

Figure 3.2.1-1 and Figure 3.2.1-2 depict ε_u, e_o, and ε_{ptu}. The plastic strain at ultimate stress, ε_{ptu}, is calculated from

$$e_{ptu} = e_u - \frac{F_{tu}}{E}$$ **Equation 3.3.1-19**

where
E is the Modulus of Elasticity or Young's Modulus (psi)

The strain at any stress level between yield and ultimate can then be calculated from

Equation 3.3.1-20
$$e = \frac{f}{E} + e_{ptu}\left(\frac{f}{F_{tu}}\right)^{n_t}$$

where
f is the stress (psi)
e_{ptu} is the plastic strain at ultimate stress given by Equation 3.3-18 (in/in)
n_t is the modified Ramberg-Osgood parameter given by Equation 3.3-10

Equations 3.3.1-17 through 3.3.1-19 use engineering strains and the stress used in Equation 3.3.1-20 is an engineering stress. These can be converted to true stress and true strain using Equations 3.3.1-14 through 3.3.1-16. An example is given to illustrate the process. Note that if a compression stress-strain curve is desired, F_{cy} is used in lieu of F_{ty} and the compression Ramberg-Osgood number and Modulus of Elasticity are used.

[6] For materials that exhibit significant strain softening, refer to discussion in Section 3.2.1. For these materials, using the strain at ultimate stress is recommended in lieu of material elongation. In Reference 3.4, elongation is given as e, while in this manual material elongation is designated as e_o to distinguish it from strain.

3.3.1.7.1 Example Problem – Nonlinear Material Properties for FEA Analysis

Given the Material shown in Figure 3.3.1-2, 7475-T761 Aluminum Sheet
1) Generate a Table of True Stress vs True Strain and True Stress vs. True Plastic Strain values from the full range stress-strain curve provided
2) Assume there is no full range stress-strain curve available for this material and generate a Table of True Stress vs True Strain and True Stress vs. True Plastic Strain values using the approach outlined with Equations 3.3.1-17 through 3.3.1-19

Part 1: In examining the stress-strain curve, there is significant strain softening at strains greater than 0.10 in/in. When digitizing the curve, stop at 0.10 in/in. which is about a 1% drop in stress from the maximum value.

The values obtained from the curve are in terms of engineering stress and engineering strain.
$E = 10.0 \times 10^6$ psi

Strain	Stress
0	0
0.0058	50400
0.0076	65400
0.0080	67600
0.0115	68900
0.0313	71700
0.0542	73900
0.0831	75400
0.1009	74500

Part 1: Convert engineering stress and strain to true stress and strain and true plastic strain.

Sample Calculation: $\varepsilon = 0.0058$ in/in $\sigma = 50400$ psi
$e_{true} = \ln(e+1) = \ln(0.0058+1) = 0.005783$in/in
$\sigma_{true} = (e+1)\sigma = (0.0058+1)(50400) = 50692$ psi
$e_{true\text{-}plastic} = e_{true} - \sigma_{true}/E = 0.005783 - 50692/(10.0 \times 10^6) = 0.0007$
Figure 3.3-3 (Top) shows the resulting curves

True Strain $e_{true} = \ln(e+1)$	True Stress $\sigma_{true} = (e+1)\sigma$	True Plastic Strain $e_{true\text{-}plastic} = e_{true} - \sigma_{true}/E$
0	0	0
0.005783	50692	0.0007
0.007571	65897	0.0010
0.007968	68141	0.0012
0.011434	69692	0.0045
0.030820	73944	0.0234
0.052782	77905	0.0450
0.079827	81666	0.0717
0.096128	82017	0.0879

Part 2: Assuming there is no full range stress-strain curve available, create a full range stress-strain curve. Allowables provided in Reference 3-5 are generally basis allowables. The published full range stress-strain curves are typical or average values, thus the maximum stress levels shown on the full range stress-strain curves are higher than the ultimate stress shown in the Design properties tables.
For instance, $F_{tu} = 71000$ psi and Fty = 61000 psi per Table 3.7.15.0(b), MMPDS-04 while ultimate strength from Figure 3.3.1-2 is 75400. To show that this method does provide a reasonable match to the full range stress-strain curve, adjust the design properties by a ratio of 75400/71000 = 1.061.

Material properties are then:
$F_{tu\text{-}avg} = 71000(1.061) = 75331$ psi
$F_{ty\text{-}avg} = 61000(1.061) = 64721$ psi
$e = 0.09$ in/in
$E = 10.0 \times 10^6$ psi
$n = 26$

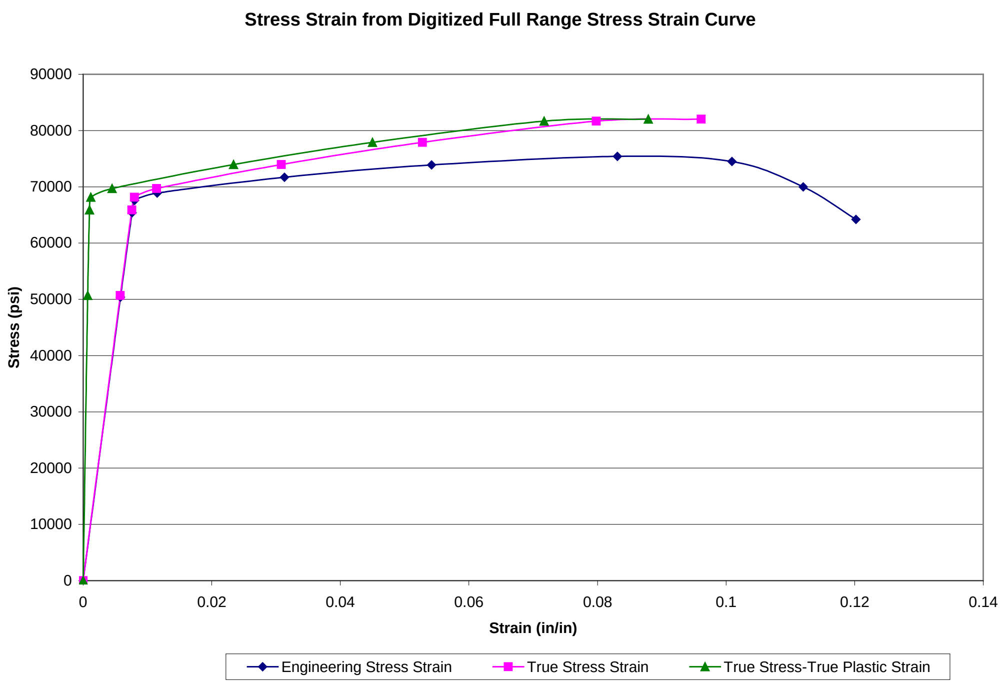
Calculate
$e_u = e_o + F_{tu}/E = 0.09 + 75331/(10 \times 10^6) = 0.09753$ in/in
$e_{ptu} = e_u - F_{tu}/E = 0.09753 - 75331/(10 \times 10^6) = 0.09$
$n_t = \log\left((e_u - F_{tu}/E) / 0.002 \right) / \log\left(F_{tu} / F_{ty} \right) = \log(0.09/0.002)/\log(75331/64721) = 25.08$
$F_{pl} = F_{ty}(0.05)^{(1/n)} = 64721(0.05)^{(1/26)} = 57677$ psi

For stresses less than F_{ty}

Stress (assumed)	Strain $e = f/E + 0.002\,(f/F_{ty})^n$	True Strain $e_{true} = \ln(\varepsilon+1)$	True Stress $\sigma_{true} = (e+1)\sigma$	True Plastic Strain $e_{true\text{-}plastic} = e_{true} - \sigma_{true}/E$
0	0	0	0	0
10000	0.00100	0.00100	10010	0
20000	0.00200	0.00200	20040	0
30000	0.00300	0.00300	30090	0
40000	0.00400	0.00399	40160	0

50000	0.00500	0.00499	50250	0
60000	0.00628	0.00626	60377	0.00022
62000	0.00685	0.00683	62425	0.00059
For stresses equal to or greater than F_{ty}				
Stress (assumed)	Strain $e = f/E + e_{ptu}(f/F_{tu})^{nt}$	True Strain $e_{true} = \ln(\varepsilon + 1)$	True Stress $\sigma_{true} = (e + 1)\sigma$	True Plastic Strain $e_{true\text{-}plastic} = e_{true} - \sigma_{true}/E$
64721	0.00847	0.00843	65269	0.00190
66000	0.00987	0.00982	66651	0.00315
68000	0.01370	0.01361	68932	0.00672
70000	0.02128	0.02106	71490	0.01391
72000	0.03615	0.03551	74603	0.02805
74000	0.06495	0.06293	78806	0.05505
75331	0.09753	0.09306	82678	0.08479

The results from steps 1 and 2 are shown below. Plotted are the engineering stress-strain curves, the true stress-strain curves and the true stress – true plastic strain curves.



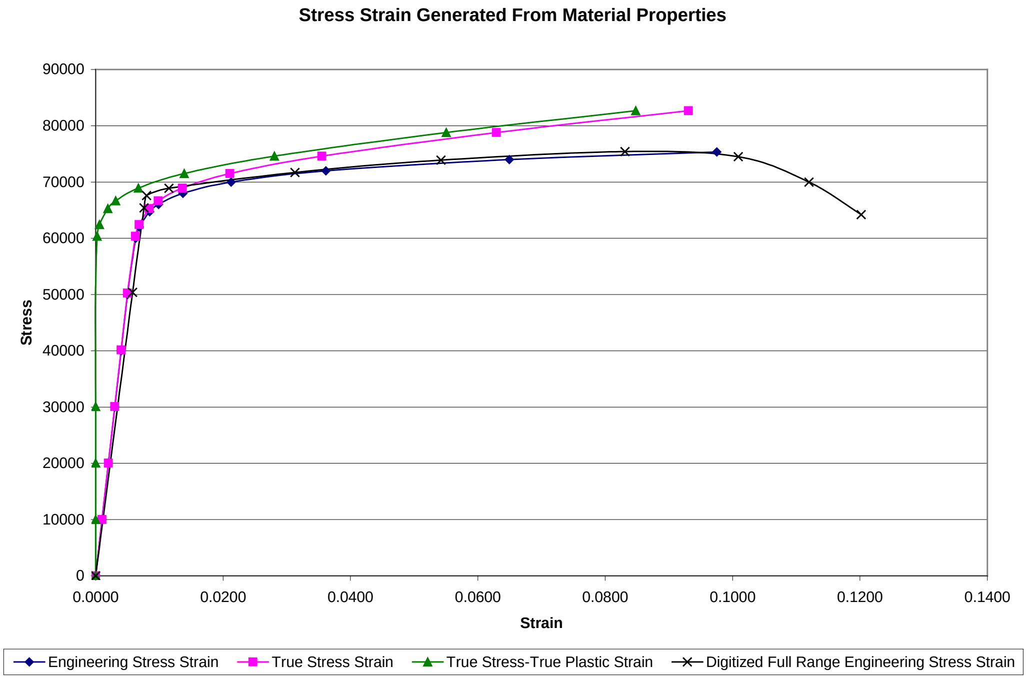


Figure 3.3.1-3 Results from Example 3.3.1.7.1 Parts 1 (Top) and 2 (Bottom) Stress-Strain Calculations

3.3.2 Basic Physical and Elastic Properties

Refer to the MMPDS, Reference 3-5, the AFRL preliminary material properties handbook, Reference 3-7, the LM Aeronautics Integrated Detail Analysis Tools (IDAT) metallic material properties database, Program data reports, or other Program-approved data sources.

For clad aluminum sheet and plate products, it should be noted that the MMPDS provides both “primary” and “secondary” modulus values. The initial or primary modulus represents an average of the aluminum and cladding elastic moduli, and applies only up to the proportional limit of the cladding; *i.e.*, approximately 6 ksi for 2024-T3 and 12 ksi for 7075-T6 (Reference 3-4). Thus, secondary modulus values shall be used for all analysis of clad materials, except low amplitude high frequency fatigue.

Some reference materials and text books suggest the use of a cladding reduction factor for stability analyses such as plate buckling, crippling, etc. The methods described in Section 8 and Section 10, when used in conjunction with secondary moduli and statistically based clad material properties, require no further reduction. For the purpose of preliminary design analysis, where statistically based clad material properties are not available, the clad reduction factor described in Reference 3-28 shall be used.

3.3.2.1 Temperature Reduction Factors

Temperature effects require additional considerations for static, fatigue and fracture toughness properties. Temperatures above room temperature usually cause a decrease in the strength properties of metallic alloys. This decrease is dependent on many factors, such as temperature and the time of exposure which may degrade the heat treatment condition, or cause a metallurgical change.

When strength properties are required at temperatures other than room temperature, these can usually be obtained using temperature reduction (material property knockdown factor) curves provided in the MMPDS (Reference 3-5). In the MMPDS, the effect of temperature on static mechanical properties is shown by a series of graphs of property as percentages of the room temperature allowable property versus temperature. Typical exposure times for the curves are ½, 10, 100, and 1000 hours. The product of the percentage, obtained from the curve data at the desired condition, and the room temperature statistical property value will provide the “at-temperature” design allowable. This “at temperature” allowable is considered to have the same statistical basis (A, B, or S) as the room temperature property. For temperatures between those available in published properties, interpolation may be used to calculate properties. Extrapolation to estimate properties outside the range of published properties shall not be used.

In instances where related properties (tensile ultimate and yield strengths, compressive yield strength, shear ultimate strength, and bearing ultimate and yield strengths) differ in their response to temperature, additional curves are provided and are labeled to indicate specific properties and forms to which they apply. The effect of temperature on the mechanical properties of most heat treat conditions for a material are shown as individual curves and these curves must not be used for other heat treat conditions. The modulus of elasticity at elevated temperature is not normally influenced by the heat treat condition of the material. There are some exceptions, however, such as Ti-6Al-6V-2Sn and 301 SS.

The elastic modulus may vary with test direction and product form. The percentage curve for modulus of elasticity is a best-fit smooth curve drawn through the average of all percentages at each temperature. Caution should be exercised in using these static property curves at very high temperatures, particularly if the strain rate intended in design is much less than that stated with the graphs. The reason for this concern is that at very low strain rates or under sustained loads, plastic deformation or creep deformation may occur to the detriment of the intended structural use.

The temperature reduction factors for Modulus of Elasticity, E, can be found for many materials in Reference 3-4 and 3-5, however there are no temperature reduction factors given for the Shear Modulus, G. If a temperature reduction factor for the shear modulus is needed, a reasonable assumption is that a material’s Poisson’s ratio is temperature independent and thus the same temperature reduction factor given for the Modulus of Elasticity may be used for the Shear Modulus.
There are two distinct types of temperature curves presented in MMPDS: “Strength at Temperature” curves where the MMPDS figure title will start with “Effect of Temperature” and “Strength at Room Temperature” curves where the MMPDS figure title will start with “Effect of Exposure”. These curves look very similar; therefore make sure to note the label on the graph before use. Normally in design, a particular mechanical property is desired for a material being strained while exposed to a temperature and time condition. For this condition, the curves labeled “Strength at Temperature”, illustrated in Figure 3.3.2-1 must be used. The “Strength at Room Temperature” data, Figure 3.3.2-2, is useful in determining requirements for hot forming and straightening procedures or where the strength property after exposure to a heating cycle is desired. In this case the material being tested is allowed to cool to room temperature prior to static tests.

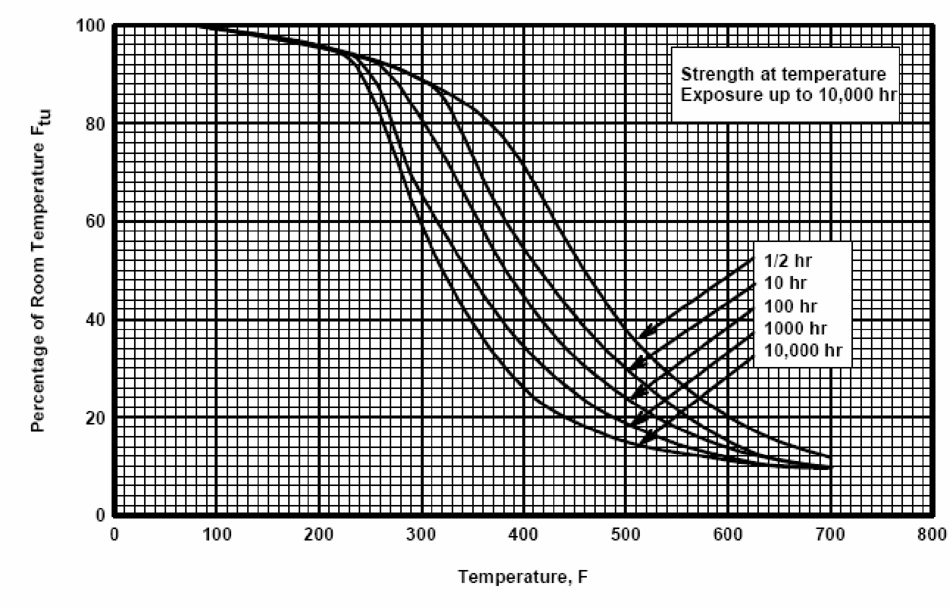


Figure 3.3.2-1 Example Strength At Temperature Curve From the MMPDS, Reference 3-5

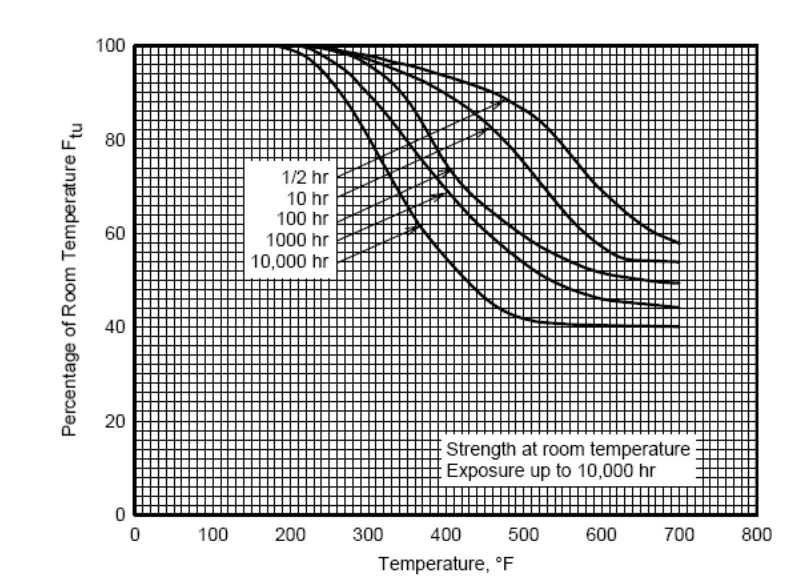


Figure 3.3.2-2 Example of Strength at Room Temperature After Exposure Curve, From the MMPDS, Reference 3-5

In the case of simple exposure, exposure temperature and test temperature are assumed to be identical – these curves will be labeled "Strength at Temperature". For complex exposure, exposure temperature and test temperature need not be the same. A sample complex-exposure curve is illustrated in Figure 3.3.2-3. An example problem is worked below to illustrate the usage of the complex exposure curves.

Table 3.3.2-1 Example Problem for the Use of Complex Exposure Temperature Curves

Example Problem: A part is exposed for 1 hour to 400 degrees Fahrenheit, followed by 1000 hours at 300 degrees Fahrenheit and then tested at 350 degrees Fahrenheit. Using Figure 3.3.2-3, determine what the reduction to the room temperature value of F_{ty} would be.		
Step	Discussion	Discussion
1	Enter curve at first exposure time of 1 hour (A) and draw horizontal line to the appropriate temperature curve of 400 degrees (B)	
2	Draw vertical line from point B to new exposure temperature at C	
3	Draw Horizontal Line from point C to Exposure Time Axis at D – 120 hours	This is the equivalent exposure time for 1 hour at 400 degrees in terms of exposure at 300 degrees.
4	Enter curve at combined exposure time for the second temperature: 120 hours + 1000 hours = 1120 hours (E) and draw horizontal line to the appropriate temperature curve of 300 degrees (F)	Add the equivalent exposure time at 300 degrees from step 3 to the actual exposure time at 300 degrees
5	Draw a vertical line to the test temperature curve (G).	If there is no curve at the test temperature, interpolate between curves. NEVER extrapolate.
6	Draw a horizontal line to the Percentage of Room Temperature – 71%	The reduction to the room temperature allowable for the given exposure times when tested at 350 degrees is 71%.

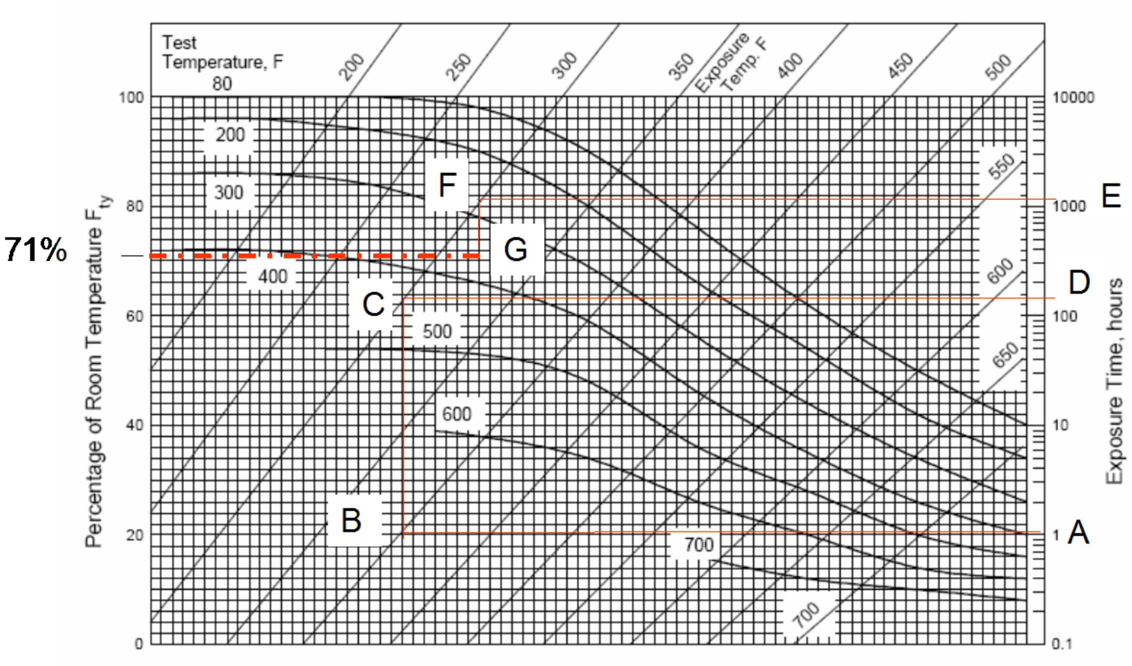


Figure 3.3.2-3 Example of Complex Exposure Curve From the MMPDS, Reference 3-5

The "at temperature" reduced material properties for some metallic materials may also be obtained from the METDB IDAT tool. METDB does not currently account for cumulative elevated temperature exposure.

For aluminum alloys, thermal exposure history may result in cumulative damage to the material properties in addition to the at-temperature affect. The total effect of temperature on material properties is a function of the at-temperature degradation due to maximum/minimum operating temperatures plus the cumulative degradation due to repeated exposure to normal operating temperatures. This "cumulative damage" can be taken into account by use of the modified Larson-Miller technique. This approach only works with aluminum and should not be used for other materials.

The basic approach of the Larson-Miller technique is to reduce multiple time/temperature combinations over an aircraft's lifetime to equivalent time at a single temperature which can then be easily used to determine the effects of the complex thermal exposure on material strength. This method is only applicable to aluminum alloys and has been incorporated into MMPDS for certain tempers of 2024 and 7075 aluminum alloys. For a given exposure time t_2 at temp T_2, the equivalent time t_1 at temperature T_1 can be calculated if the applicable constant C is known. The parametric equation is:

$$T_1(C+Log(t_1)) = T_2(C+Log(t_2))$$

where
T_1, T_2 are temperatures in degrees Rankine ($T_{Rankine}=T_{Fahrenheit} + 459.69$)
t_1, t_2 are time in hours
C is a material dependent constant
C = 16.5 (for Aluminum 7075 and 7050 alloys);
C = 16.0 (for Aluminum 2024 and 2124 alloys)[7]

The calculation of equivalent time at a single temperature is performed for each time/Temperature combination and added together to give the total time at the single temperature. This equivalent total time at a given temperature can then be used with the applicable MMPDS single exposure temperature reduction curves to estimate the strength remaining after exposure.

It should be noted that where the calculated equivalent time at a given temperature exceeds the maximum hours associated with the temperature reduction curves (e.g., typically 10,000 hours), this approach is not valid. The LM Aero approach to determining the effects of complex thermal exposures on the mechanical properties of certain aluminum alloys has been proven to be reasonable, based on comparison with test data on legacy programs and as verified recently in limited tests.

For materials other than aluminum, one approach that provides a conservative assessment of the reduction in material property due to exposure at multiple temperatures is to determine the individual temperature reduction factors for each exposure time-temperature combination being considered. The cumulative temperature reduction factor is then the product of all of the individual factors.

3.3.2.2 Threshold and Maximum Exposure Temperatures

There are threshold temperatures below which no significant change in property is recorded after 10,000 hours of exposure time. Thus, any exposures to temperatures below this point would not be included in the calculations of equivalent time at a single temperature because the exposure would not add to the damage. Some threshold temperatures are provided in Table 3.3.2-2.

Table 3.3.2-2 provides some material maximum temperature usage guidelines which may be used in the absence of specific program direction.

Table 3.3.2-2 Recommended Maximum Usage Temperatures and Selected Threshold Temperatures

[7] For 2024 and 7075, Reference 3.3-16, report by D.R. Apodaca. For 7050, limited testing was performed and documented in Fort Worth Materials & Processes Lab report MLPR-2783 dated 30 Sept 2004 but the calculated temperature reduction values are unpublished

Material	Nominal Maximum Temperature	Threshold Temperature
2XXX Aluminum	<300ºF	245 ºF: 2024,2124 aged products
7XXX Aluminum	<250ºF	215 ºF: 7050T74 180 ºF: 7075T6XX
Steel, CRES	<600ºF	--
Steel, Stabilized CRES	<1200ºF	--
Titanium[8]	350-400ºF	--
Sealant	<300ºF	--
Paints	<275ºF	--

3.3.3 Basic Mechanical Strength Design Properties

The purpose of this sub-section is to provide generic guidance on basic mechanical strength properties for metallic structural materials. Subsections include material forms not available in the MMPDS, MMPDS assumptions and derived properties, shear ultimate and yield strengths, short-transverse yield and ultimate strength estimates/reductions, static bearing ultimate strength reduction, and IDAT metallic material property database control.

Material static strength allowables should be statistically based, and are traditionally identified by the following categories listed below in order, from the least statistical confidence to the highest statistical confidence:

- Typical Basis - A typical property value is an average value and has no statistical assurance associated with it.
- S-Basis - This designation represents the minimum value specified by the governing Federal Military or industry specification. S-basis values established since 1975 may be viewed as estimated A-basis values
- B-Basis - This designation indicates that at least 90 percent of the population of values is expected to equal or exceed the statistically calculated mechanical property value with a confidence of 95 percent.
- A-Basis - The lower value of either the statistically calculated number T-99, or the specification minimum (S-basis). The statistically calculated number indicates that at least 99 percent of the population is expected to equal or exceed the statistically calculated mechanical property value with a confidence of 95 percent.

The use of design allowables is program specific; therefore refer to your program manual or structural design criteria document for direction. Some general guidelines for the use of design allowables are listed below.

The aircraft model specifications generally will provide guidelines on which basis allowables are to be used for what category of structure and would govern the design. Typically A-Basis Allowables are used for single load path, safety-of-flight parts where safety-of-flight parts are defined as parts whose failure would cause direct loss of the air vehicle or loss of stiffness leading to divergence or flutter which will result in loss of air vehicle or unrecoverable loss of control, weapons/store carriage/suspension parts whose failure would result in release of a weapon or store, or components of pressurized compartments whose failure would result in an explosive decompression, while B-Basis Allowables are often used for redundant structure, in which the failure of individual elements would result in applied loads being safely distributed to other load carrying members

[8] Most alloys. Some titaniums are targeted for improved performance in specific high temperature bands. For specific high temperature applications, consult the Materials and Processes organization.

3.3.3.1 Material Forms Not Available in the MMPDS

Refer to Program-approved data sources; the IDAT Metallic Material Database, Reference 3-26; LMAS Stress Memo 61m, Reference 3-1, Table III; and LR31445, Reference 3-13 if a particular material is not available in the MMPDS.

In some cases, on new programs, new materials may be under development for use on the program. It is often the case that estimated properties must be used in lieu of published A and B basis numbers during the early part of the program. These estimated properties may be generated by a smaller sample size or with fewer lots of data than will ultimately be used to generate the true basis material properties. As result, it is sometimes the case that the material properties are lower than estimated when they become available.

3.3.3.2 MMPDS Assumptions and Derived Properties

In the MMPDS, statistical basis values are directly determined only for a portion of the reported properties, typically F_{tu} and F_{ty} in one primary testing direction. The rest of the tabulated A-, B-, or S-basis values are derived from a limited amount of actual test data, plus the assumption that statistical distributions are the same as those of F_{tu} and F_{ty}. Details of these assumptions and statistical computations are found in section 9.2.10 of the MMPDS, Reference 3-5. Until recently, bearing yield and ultimate strength properties, F_{bry} and F_{bru}, were implied to be the minimum of the three orthogonal grain directions, when, in fact, for most existing alloys they were only the minimum of the L- or LT-orientations. Thus, ST-direction bearing strengths could be, and often are, lower than those values tabulated in the MMPDS. This point is addressed in more detail in Section 3.3.3.6. For new alloys added to the MMPDS after 2005, the guidelines require the applicable grain direction to be explicitly stated. While it may be the case that the data for ST direction is still not available, the analyst will be able to determine the applicability of the data that is present.

Occasionally, it is desirable to have an estimate of typical material properties for use in the correlation of component or full scale test results or for use in damage tolerance calculations. Reference 3-4 states that the average yield and ultimate tensile material property may be obtained by multiplying the B-Basis material property times a factor of 1.029. This was obtained by examining the average material property data compared to published B-Basis values for multiple alloys of aluminum, steel and titanium materials. This factor shall not be used to create a pseudo B-Basis F_{tu} or F_{ty} material property from a small sample pool of test data for a material lacking sufficient data to generate a proper B-basis value.

3.3.3.3 Ultimate Strength

3.3.3.3.1 Ultimate Shear Strength

Heritage guidance in SM61m, Reference 3-1, required the use of the lower of (a) the MMPDS F_{su} value, or (b) the theoretical limit, $0.577F_{tu}$, due to concerns regarding the validity of the MMPDS data. Following a detailed study of this issue, described in FZM-8839, Reference 3-17, the MMPDS F_{su} data are found to be relatively accurate in most cases (A286 steel data were removed from the MMPDS, due to this review), and thus should be used as-published for future LM Aero stress analyses.

Note that care should nonetheless be taken, since F_{su} data in the MMPDS are (a) assumed to be independent of grain orientation (except for hand forgings); and (b) derived from limited testing, plus F_{tu}-based statistics, as described in section 3.3.3.2. A specific LM Aero-approved alloy which does exhibit grain-orientation-dependent F_{su} design values that must be used properly by the analyst is the 2297 aluminum-lithium plate product.

3.3.3.3.2 Ultimate Compression Strength

Values for ultimate compression strength properties are not published in Reference 3-1 because the proper use of compression strength material properties is dependent on the type of analysis being performed. If the analysis is related to compression stability, the member is considered to have failed when its average stress reaches F_{cmax}. F_{cmax} is the minimum of the ultimate tensile strength of the material or the stress at which the column has lost 95% of its initial stiffness. Thus, F_{cmax} is given by

$$F_{cmax} = Minimum[F_{tu}, F_{0.05T}] \qquad \textbf{Equation 3.3.3-1}$$

$$F_{0.05T} = F_{cy}\left[\left(\frac{1}{0.05}-1\right)\frac{F_{cy}}{0.002E_c n_c}\right]^{\frac{1}{n_c-1}} = F_{cy}\left(9500\frac{F_{cy}}{E_c n_c}\right)^{\frac{1}{n_c-1}} \qquad \textbf{Equation 3.3.3-2}$$

where
$F_{0.05T}$ is the stress at which the column has lost 95% of its initial stiffness, *i.e.*, the ratio of the tangent modulus to the elastic modulus is 0.05. Refer to Section 3.2.2 for a discussion of tangent modulus.
F_{tu} is the ultimate tensile strength of the material (psi)
F_{cy} is the compression yield strength of the material (psi)
E_c is the modulus of elasticity in compression (psi)
n_c is the compression Ramberg-Osgood parameter

If the analysis is an ultimate compression check where stability is not a concern, for example the check of the maximum compression bending stress in a section, F_{cu} is given as

$$F_{cu'} = \frac{F_{tu}}{F_{ty}}F_{cy}$$

$$F_{cu} = minimum[F_{tu}, F_{cu'}] \qquad \textbf{Equation 3.3.3-3}$$

Finally, if the analysis is related to a localized surface compression such as might be found with direct contact stresses, the failure is typically a shear failure which occurs below the surface of the material. In this case, a reasonable estimate of the compression allowable, F_{cu} is given as

$$F_{cu} = 2F_{su} \qquad \textbf{Equation 3.3.3-4}$$

where
F_{su} is the ultimate shear strength of the material (psi)

3.3.3.4 Shear Yield Strength

Shear yield is not a measured value. Per Reference 3-5, an estimate of the shear yield stress in the in-plane direction can be obtained from

$$F_{sy} = \left(\frac{2F_{su}}{F_{tu-L}+F_{tu-LT}}\right)\left(\frac{F_{ty-L}+F_{cy-L}+F_{ty-LT}+F_{cy-LT}}{4}\right) \qquad \textbf{Equation 3.3.3-5}$$

Where
F_{su} is the ultimate shear stress of the material from Reference 3-5 or other suitable reference. (psi)
F_{ty-L} is the yield tensile stress of the material in the L direction from Reference 3-5 or other suitable reference. (psi)
F_{ty-LT} is the yield tensile stress of the material in the L-T direction from Reference 3-5 or other suitable reference. (psi)
F_{cy-L} is the yield compressive stress of the material L direction from Reference 3-5 or other suitable reference. (psi)
F_{cy-LT} is the yield compressive stress of the material L-T direction from Reference 3-5 or other suitable reference. (psi)
F_{tu-L} is the ultimate tensile stress of the material in the L direction from Reference 3-5 or other suitable reference. (psi)

$F_{tu\text{-}LT}$ is the ultimate tensile stress of the material in the L-T direction from Reference 3-5 or other suitable reference. (psi)

If the short transverse shear yield stress is needed, the above equation should be re-formulated appropriately using the short transverse ultimate and yield stress values. Additionally, if the shear ultimate values are known in multiple material orientations, as with aluminum lithium alloys, the appropriate orientations should be used in lieu of the $2F_{su}$ term.

3.3.3.5 Short-Transverse Strength Estimates

If aluminum short transverse (ST) mechanical strength properties are not available in the MMPDS, or other appropriate reference, the ST properties shall be estimated as shown in Table 3.3.3-1.

Table 3.3.3-1. Estimated Aluminum Short Transverse (ST) Properties[1] , Reference 3-17

Material	F_{tu} *ST* (ksi)	F_{ty} *ST* (ksi)	F_{cy} *ST* (ksi)
2xxx-hand forging[2]	$0.97\ F_{tu}\ LT$	$0.93\ F_{ty}\ LT$	$1.00\ F_{cy}\ LT$
7xxx-plate	$0.92\ F_{tu}\ LT$	$0.91\ F_{ty}\ LT$	$0.97\ F_{cy}\ LT$
7xxx-hand forging	$0.95\ F_{tu}\ LT$	$0.92\ F_{ty}\ LT$	$0.98\ F_{cy}\ LT$
7xxx-extrusion	$0.94\ F_{tu}\ LT$	$0.92\ F_{ty}\ LT$	$0.93\ F_{cy}\ LT$

Notes:
1. There is no distinct trend in the ST/LT ratio for percent elongation, *e*. Thus, if it is necessary to estimate *e ST*, either choose the published value for the closest alloy to that for which a value is desired (and document the assumption), or conservatively use 1%.
2. Do not use for 2xxx aluminum-lithium alloys.

3.3.3.6 Thick Plate Bearing Strength Reductions

Bearing strengths for alloys added before 2005 are generally given in the MMPDS without reference to grain direction, and are assumed to be the same in all directions. Previously, 2000 and 7000 series thick plate aluminum were thought to be the only alloys for which bearing strength was affected by grain direction. However, a recent survey of legacy materials undertaken by MMPDS has indicated that Titanium 6AL-4V plate exhibits a similar directionality as do aluminum lithium alloys. The results of bearing tests on LS- and TS-loaded specimens taken edgewise from these materials have shown that edgewise bearing strengths are substantially lower than those of flatwise-oriented specimens on which most MMPDS bearing data were generated. Fatigue and crack growth behavior are also degraded. Thus the reduction factors shown in
Table **3.3.3-2**shall be used for all fasteners in thick 2000 and 7000-series aluminum plate, aluminum lithium plate and thick 6AL-4V titanium plate oriented other than flatwise that is not subsequently heat-treated[9]. Figure 3.3.3-1 illustrates the orientations noted in
Table 3.3.3-2. For off-axis orientation and loading, apply the
Table 3.3.3-2 knockdowns if geometry is in the orientation shown in Figure 3.3.3-1. This reduction factor is independent of any other factors (fitting, dry-pin, etc). It does not apply to material properties other than bearing yield and ultimate strength.

[9] These knockdowns do NOT apply to hand or die forgings, even though they also exhibit edgewise bearing strengths that are less than flatwise-orientations, because hand- and die-forged bearing strength data published in the MMPDS are taken from edgewise-oriented specimens, thus the lower values are published in the MMPDS.

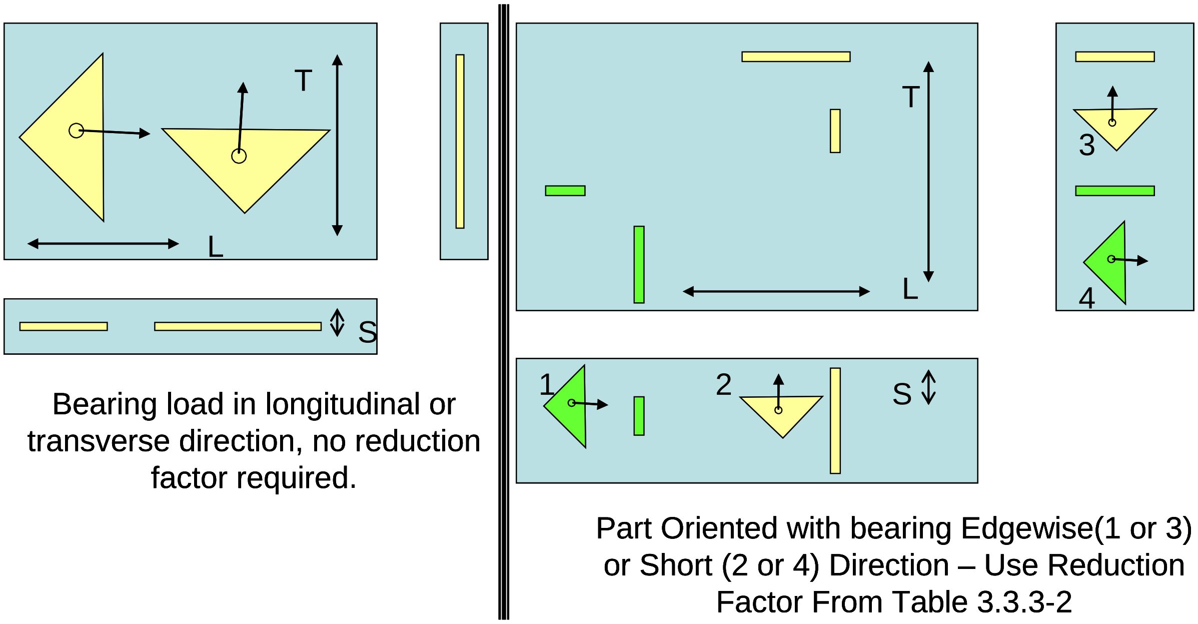


Figure 3.3.3-1 Illustration of Flatwise and Edgewise Part Orientation

Table 3.3.3-2. Bearing Property Reductions for Edgewise-Oriented Thick Plate, References 3-17 and 3-5[10]

		Bearing Property Reduction Factor, k_{br}				
Material and Alloy Family	Thickness (in)	1.0-2.0	2.0-4.0	4.0-6.0	6.0-8.0	8.0-10.0
2000 Series Aluminum excluding Al-Li Alloys	F_{bru} (e/D<3.0)	k_{bru}=0.10(e/D) + 0.70			--	--
	F_{bry} (e/D<3.0)	k_{bry}=0.95			--	--
All Aluminum Lithium Alloys	F_{bru} (e/D<3.0)	k_{bru}=0.06(e/D) + 0.65		k_{bru}=0.06(e/D) + 0.68		--
	F_{bry} (e/D<3.0)	k_{bry}=0.91		k_{bry}=0.04(e/D) + 0.86		--
7000 Series Aluminum	F_{bru} (e/D<3.0)	k_{bru}=0.10(e/D) + 0.70		k_{bru}=0.10(e/D) + 0.65		k_{bru}=0.08(e/D) + 0.72
	F_{bry} (e/D<3.0)	k_{bry}=0.95		k_{bry}=0.08(e/D) + 0.82		
6AL-4V Titanium	F_{bru} (e/D<3.0)	--	k_{bry}=0.84			
	F_{bry} (e/D<3.0)	--	k_{bry}=0.84			

3.3.3.7 Static Bearing Strength "Wet-Pin" Reduction

As noted in the MMPDS, Reference 3-5, sections 1.4.7 and 3.1.2.1.1, published values for bearing yield, F_{bry}, and ultimate, F_{bru}, strength can be unconservatively high for design purposes. This drawback is due to the fact that

[10] Reduction factors for aluminum lithium and 6AL-4V Titanium approved for publication in MMPDS05, June 2011.

MMPDS properties are usually generated with hard, ultrasonically-cleaned, tight-tolerance pins in accordance with ASTM E238, Reference 3-18, while production fasteners are usually installed wet – either lubricated or with sealant – and are not as hard as the E238 pins, and manufacturing hole tolerances are less stringent. The MMPDS recommends that "designers should consider a reduction factor in applying these values to structural analyses." Quantitative evidence of this "dry-pin" to "wet-pin" strength knockdown is found in a paper by Stickley and Moore, Reference 3-21, and in several NADC reports, References 3-22 through 3-25. As developed in FZM-8839, Reference 3-17, the recommended bearing strength reductions of the MMPDS dry-pin data are shown in Table 3.3.3-.

F_{bru} and F_{bry} should be linearly interpolated over the ranges $0.5 < e/D < 1.5$, $1.5 < e/D < 2.0$, and $2.0 < e/D < 2.5$. Note that an e/D = 0.5 is assumed to have a bearing strength of 0 psi, since it would be breaking out at the edge of the part. Ratios of e/D below 1.5 should not be used for design, only for the disposition of discrepant parts, and e/d ratios below 1.0 should not be used at all.

Table 3.3.3-3. Bearing Strength Reductions for ASTM E238-Generated Dry-Pin Allowables

Material	Reduction Factor, k_{wpb}[1]
All Aluminum Alloys	0.82
All Other Materials	0.90

Notes:
1 Applicable to all material forms, orientations and thicknesses; both e/D = 1.5 and 2.0 (but not e/D ≥ 2.5); and both yield (F_{bry}) and ultimate (F_{bru}) bearing strengths, when denoted as dry-pin data in the MMPDS.

3.3.3.8 IDAT Metallic Material Property Database

Structural Analysis Core Engineering (6E5) shall exercise change control authority over the static metallic material property database in the Integrated Detailed Analysis Tool (IDAT) and approval of static analysis software suites for all non-F-35 programs. The F-35 SDI Methods, Policies and Procedures group shall exercise change control authority over the static metallic material property database in the IDAT software suite for the F-35 program. Structural Analysis Core Engineering (6E5), in conjunction with a material allowables working group, will ensure that the active IDAT data file meets the material requirements set forth in section 3 of this Process Manual and that data integrity exists between the electronic database and original source. A spreadsheet version of the current database may be viewed via Reference 3-26.

3.4 Prevention of Corrosion

The purpose of this section is to define various types of corrosion and to outline available corrosion control techniques, which when implemented during the design, development and manufacture process, will prevent many common corrosion problems from occurring. Field experience has continued to identify corrosion of aircraft structural components as a continuing problem. All aircraft experience some form or degree of corrosion damage. In many cases entire sections of aircraft have suffered severe attack and have required complete component replacement.

Stress and Materials and Process (M&P) engineering are responsible for reviewing the drawings and certifying that adequate preventive procedures have been incorporated in the design to mitigate conditions which may become conducive for corrosion initiation so that the specified strength and rigidity requirements are satisfied for the life of the vehicle. The Stress and M&P Engineers approve the methods adopted for corrosion protection of a part or structure when signing the Engineering drawings of these items. The responsible Materials and Process Engineer should be consulted when the proposed method for corrosion prevention is being selected or further information on a specific type of corrosion is required.

Many factors contribute to the susceptibility of a metal to corrosion. Generically, metallic corrosion consists of chemical interactions of a metal with its environment. Water, with its dissolved salts and other chemicals, constitutes the single most corrosive agent known and causes the majority of all corrosion. The three most common corrosive agents are acids, alkalis and salts.

The problems most associated with corrosion are derived from:

- Water intrusion into structural joints from the environment
- Insufficient or inadequate protective coatings
- Corroded fasteners
- Pitting of exterior skins
- Exfoliation
- Contaminated fuel and fluids
- Stresses in high strength alloys in the short transverse grain direction
- Dissimilar metal couples
- Hydrogen embrittlement in high strength steels

Although stress corrosion is generally considered paramount due to its catastrophic implications, other types of corrosion can create major problems as well. Corrosion can vary from superficial discoloration to deep pitting and intergranular corrosion to overall degradation of the structure's integrity. The severity depends upon the previously mentioned exposure to environmental factors and the degree of preventive measures utilized along with the judicial application of good corrosion design practices.

Table 3.4.0-1 describes the deleterious impact that different types of corrosion can have on structural integrity. Sections 3.4.2 through 3.4.9 describe each of these forms of corrosion in more detail.

Table 3.4.0-1 Summary of Negative Effects of Various forms of Corrosion

Corrosion Type	Effect	Discussion
Surface Corrosion	Cosmetic	Accelerates more corrosion and pitting
	Reduces Static M.S.	Reduces cross-sectional area
	Reduces Stability M.S.	Parts are no longer in intimate contact; changes support assumptions
	Reduces Fatigue Life	Reduces joint preload and increases movement
Pitting Corrosion	Reduces Fatigue Life	Pits are notches Can be the start of intergranular corrosion
Intergranular Corrosion	Reduces Static M.S.	Reduces cross-sectional area
	Reduces Static M.S.	Leads to redistribution of internal loads
	Reduces fatigue life	Separations of grain structure acts as a notch
	Reduces fatigue life	Separations of adjacent grain layers acts as a crack and is a tearing initiation location
	Leads to Stress Corrosion Cracking	Under sustained stress
	Can start of Exfoliation Corrosion	
Exfoliation Corrosion	Reduces Static M.S.	Compression – due to layer separation; Poisson effect accelerates short transverse cracking and access to moisture
	Destroys Material	Rapid destruction of the structural capability of the aluminum

3.4.1 Corrosion Prevention Design

The most effective method to prevent or minimize corrosion is to exclude those external agents which can promote or accelerate corrosion. Control of corrosion by preventing water and other corrosive fluids from being entrapped within the aircraft structure through environmental sealing continues to be the most effective preventive.

Other general corrosion preventive design concepts include:

- Avoid depressed areas in integral fuel tanks where drainage is not available.
- Avoid the use of absorbent or hydroscopic materials (*i.e.*, felts, tapes, fabrics) in contact with metallic surfaces.
- Provide adequate ventilation and drainage to minimize the accumulation of condensed vapors and moisture.
- Provide easy access for the purpose of corrosion inspection and part replacement.
- Provide permanent joints with additional protection from corrosion by assembling with faying surface sealant and with fasteners and bushings that are installed wet with sealant. The sealant provides a barrier and fills the voids to prevent entrance of moisture and fluids which could promote corrosion.
- Use aluminum alloys with increasingly higher purity. Instead of 7075, use 7175 or 7475. Similarly, use 7149 instead of 7049 or use 7249.
- Aluminum 7050 is considered to have the best combination of strength and corrosion resistance.
- When possible, use ALCLAD sheet.
- Use caution and appropriate barrier methods when placing aluminum in contact with graphite epoxy and graphite bismaelimide composites.
- For new design, do not use aluminum materials that have a stress corrosion rating of C or D for structural applications. Reference 3-4 Section 3.1.2.3 provides a listing of stress corrosion ratings.

3.4.2 Surface Corrosion

This type of corrosion is visually uniform and is objectionable from an appearance viewpoint. Dulling of a bright or polished surface, etching by acid cleaners, or oxidation (*i.e.,* discoloration) of steel are examples of surface corrosion. Corrosion resistant and stainless steels can become tarnished or oxidized in corrosive environments. Surface corrosion can indicate a breakdown in the protective coating system and should be examined closely for more advanced attack. If surface corrosion is permitted to continue, the location may become a precursor to more serious types of corrosion, thinning of metal may occur and the load-carrying capability diminished.

Protective coatings such as paint or primers containing chromates prevent corrosion by shielding the metal surface from moisture. Metallic coatings or plating on steel alloys and cladding on aluminum alloys protect the base metal by sacrificial corrosion. Chromium plating applied directly to steel as on landing gear piston surfaces is used primarily as a corrosion resistant coating.

Stainless steel alloys, nickel alloys and titanium can be protected by inducing a thin, tightly adhering complex oxide film at the surface which keeps moisture away from the active base metal. The process associated with the formation of this film requires the presence of oxygen and is called passivation. This film, as long as it remains intact or is permitted to reform after minor abrasions or scratches, will protect the metals from corroding. In certain instances where oxygen is not available, such as under washers or on faying surfaces, the protective film will not form and corrosion can initiate.

Figure 3.4.2-1 shows several examples of surface corrosion on in-service aircraft. The figures to the upper left and right show the characteristic bubbling paint indicative of corrosion underneath. The lower figure shows the coatings gone and the corrosion of the parent material, as evidenced by the white powdery residue of oxidized metal.

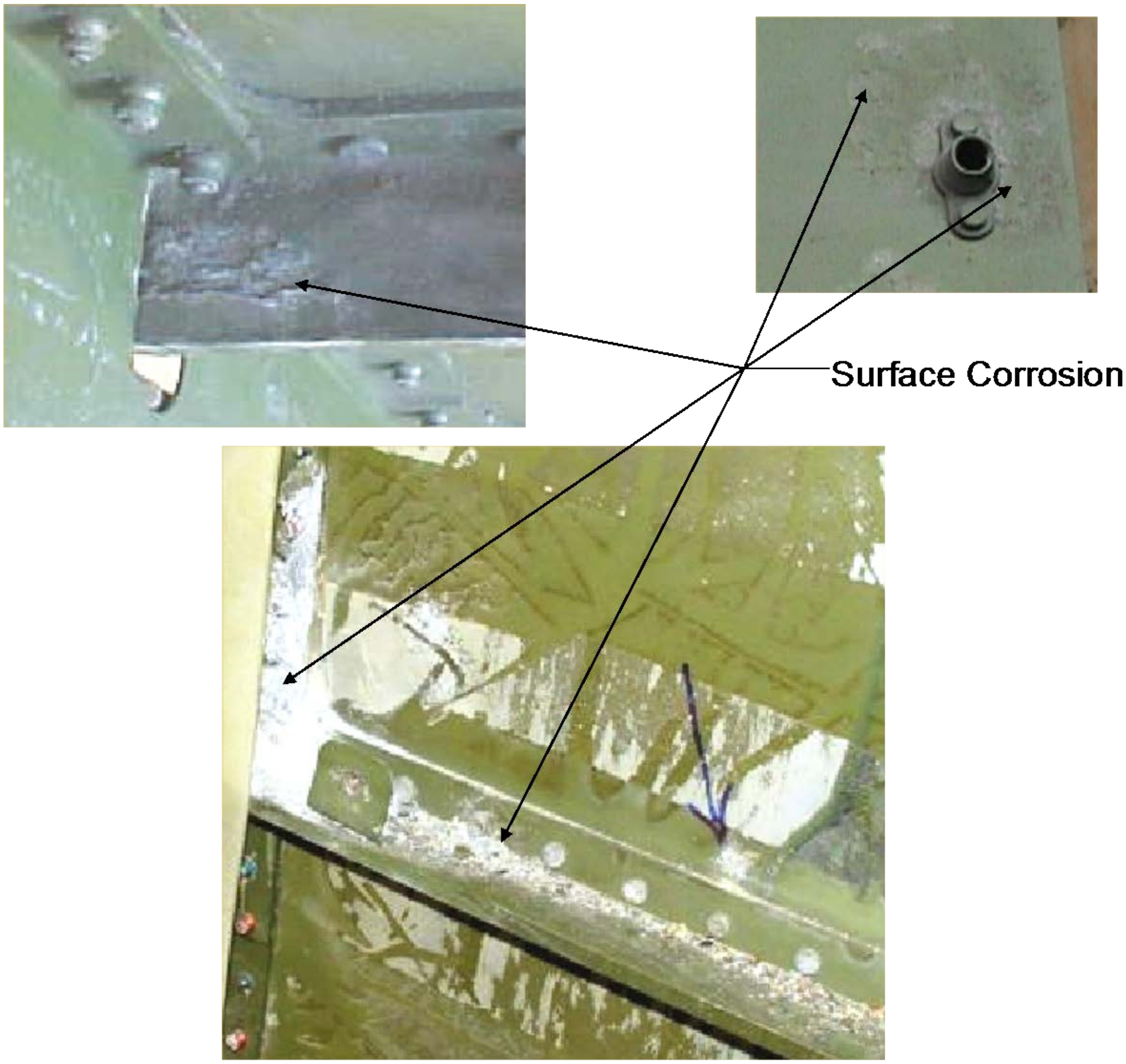


Figure 3.4.2-1 Examples of Surface Corrosion

3.4.3 Pitting Corrosion

Pitting occurs locally on the surface of a metal and is generally characterized by the formation of cavities and the presence of loose corrosion products. On aluminum and magnesium parts these corrosion products appear white or gray. Most metals and their alloys are subject to pitting corrosion. A cross-section through a pitted surface would show shallow to deep depressions and may show evidence of undercutting. These can be considered as potential initiating points for more serious corrosion and fatigue since the surface is irregular and may have sharp edges. Removal of corrosion products will reveal minute pits or holes in the surface. Pitting corrosion is more serious than general surface corrosion because of its localized or concentrated nature. Figure 3.4.3-1 shows an example of surface pitting found on an airplane in service.

Protective coatings such as chromate paint and primers prevent corrosion by shielding the metal surface from moisture

Figure 3.4.3-1 Surface Pitting

3.4.4 Intergranular Corrosion

Intergranular corrosion proceeds along grain boundaries in a metal alloy and can penetrate through a section in a short period. It is normally initiated by impurities at or near grain boundary areas. Precipitation of particles is produced along grain boundaries in an aluminum or steel alloy, especially if the alloy has undergone an improper heat treatment. The grain boundaries become anodic to the much larger adjacent cathode grains. The precipitation particles produce less corrosion resistant zones as they corrode rapidly in the presence of an electrolyte. Intergranular corrosion is more aggressive on exposed short transverse grain. This condition can exist at the end of a plate, bar or extrusion, at the parting plane of forgings, and at lap joints, seams and fastener holes. Figure 3.4.4-1 shows a crack resulting from intergranular corrosion at the edge of a fastener hole. This was taken from an aircraft in service.

Techniques available to inhibit the initiation of intergranular and exfoliation corrosion:

- Avoid exposure of the short transverse grain structure.
- Use a cold working process on the surface grain structure (*i.e.*, shot peening, rolling).
- Use a protective film such as plating, cladding, anodizing or a sealing compound.
- Use alloys and heat treat conditions which are less susceptible to intergranular corrosion (*i.e.*, T76, T74 and T73 tempers for the 7xxx aluminum alloy series and 6xxx alloys).

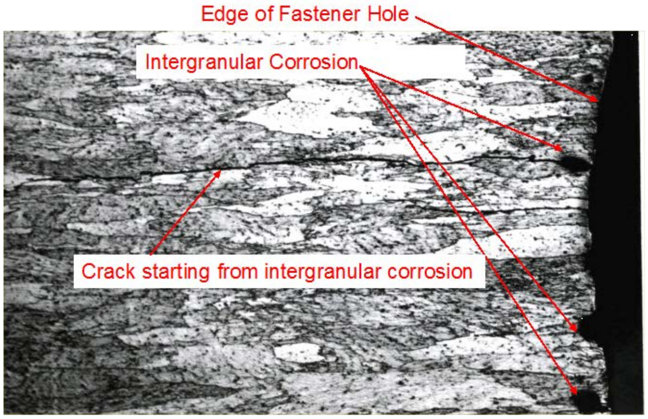


Figure 3.4.4-1 Cracking Resulting from Intergranular Corrosion in a Loaded Fastener Hole

3.4.5 Exfoliation Corrosion

This type of corrosion occurs in the high strength aluminum alloys and is a specific form of intergranular corrosion. It is prevalent in extruded or other heavily worked shapes in which the grains or metal have been extruded in length and flattened. Corrosion products along these grain boundaries exert pressure between the grains and the result is a lifting or leafing effect. This type of corrosion usually initiates at grain ends as in a machined edge, groove, chamfer or machined hole and can progress through an entire section. Exfoliation is characterized by leafing of the corroded section of metal away from the rest of the part as shown in Figure 3.4.5-1. Exfoliation, being a more severe destructive form of intergranular corrosion, should be prevented by using the same techniques described in Section 3.4.4 to inhibit intergranular corrosion initiation.

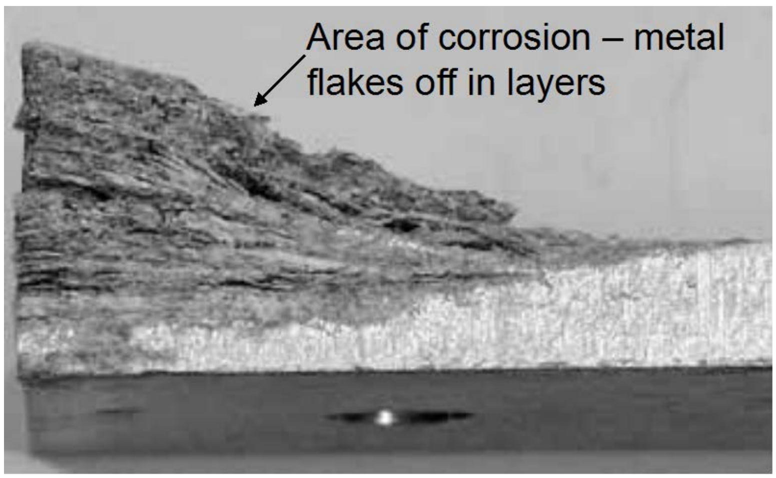


Figure 3.4.5-1 Exfoliation Corrosion

3.4.6 Fretting Corrosion

Fretting corrosion can exist at the faying area between two adjacent contacting surface members. Unlike a true electrochemical corrosion process, the deterioration of one or both contacting surfaces is created by the relative mechanical displacement motion of the surface particles. An abrasive corrosion product forms when the metallic particles created by the fretting process become oxidized. As this process continues, the amount of abrasive product formed increases and the surface damage (gouges, scratches, nicks etc.) will become more severe by the abrasive action itself. The damaged area can then become the origin of corrosion and cracks.

Techniques available to inhibit the initiation of fretting corrosion:

- Use a lubricant or sealant on the contact or faying surfaces.
- Design the joint with a hard metal in contact with a soft metal. The two metals should be galvanically compatible.
- Fill the faying surface of the joint with sealant to prevent entrance of a corrosive agent (moisture). Sealing solely around the edges will not work. Do not trap air.
- Consider adhesive bonding plus fillet sealing in addition to mechanical attachments for vital fatigue critical parts.
- Shot peening provides a work hardened surface that retards the onset of wear by fretting and the compression surface stresses can inhibit crack formation and growth.
- Limit the use of large bolt-to-hole clearances which allow for joint motion.

3.4.7 Stress Corrosion Cracking (SCC)

Stress corrosion or stress corrosion cracking (SCC) results from the combined effect of stress, a corrosive agent and a susceptible material. This action can result in cracking of structure and, in the worst case, premature structural failure. If any of these three contributing factors is absent the risk for stress corrosion cracking becomes negligible. Good design practices result in designing out each of these factors through choice of material, best practices for sealing and corrosion prevention and minimizing or eliminating residual sustained tensile stresses in a part.

A survey of aluminum SCC failures (Reference 3-34) in-service indicates the culprit for SCC is tensile residual stresses particularly in the short transverse grain direction in thick material where through-machining or hole drilling grain ends were exposed. This situation can exist in forgings, thick plate and thick extrusions that are final machined after heat treatment.

Not all materials are susceptible but many aircraft high strength alloys are. Stress corrosion cracking can occur in aircraft grade aluminums, low alloy steels, including stainless steels, some brasses and some titanium alloys. It can proceed either along grain boundaries or across the grains and can penetrate through a section in an extremely short period of time. For aluminum alloys, it predominantly proceeds inter-granularly.

3.4.7.1 Discussion of SCC Threshholds

As discussed above, in order for stress corrosion cracking to occur, three elements have to be present:

- Susceptible Materials
- Sustained Tensile Stresses
- Corrosive Environment

Remove any one of these and the risk for SCC is virtually eliminated. Unfortunately, a corrosive environment is a real-world element of aircraft exposure. While aircraft structure can be protected, if the protection system fails or is compromised, the environment again becomes a factor.

The SCC rating from Reference 3-4, MMPDS only addresses part of the first contributing element, material, and does not include such factors as manufacturing process or variation in environmental conditions. While this A-D rating system is helpful in selecting a material which is less susceptible to SCC, it does not incorporate all the parameters, which ultimately determine the likelihood of SCC occurring. Under this system, different materials, product forms and grain orientations are tested in environments to determine their susceptibility to stress corrosion cracking. Those with a rating of A are considered least susceptible while it is recommended that those with a D rating should not be used. Unfortunately, many times a material may be rated A in one grain direction and a C or D in a different grain direction within the same part.

There is not an SCC threshold stress material property. Reference 3-4 uses a threshold level based on laboratory testing to classify material/grain orientation into the A-D categories. But that data is based on laboratory conditions, moisture levels, and specimen configuration and size. Figure 3.4.7-1 illustrates the variation of exposure times and failure rates for the same material exposed to 5 different real-world environments. All are stressed at the 45 ksi level. Also shown in the figure, with the dashed line, is the laboratory test condition result on which the A-D ranking is based.

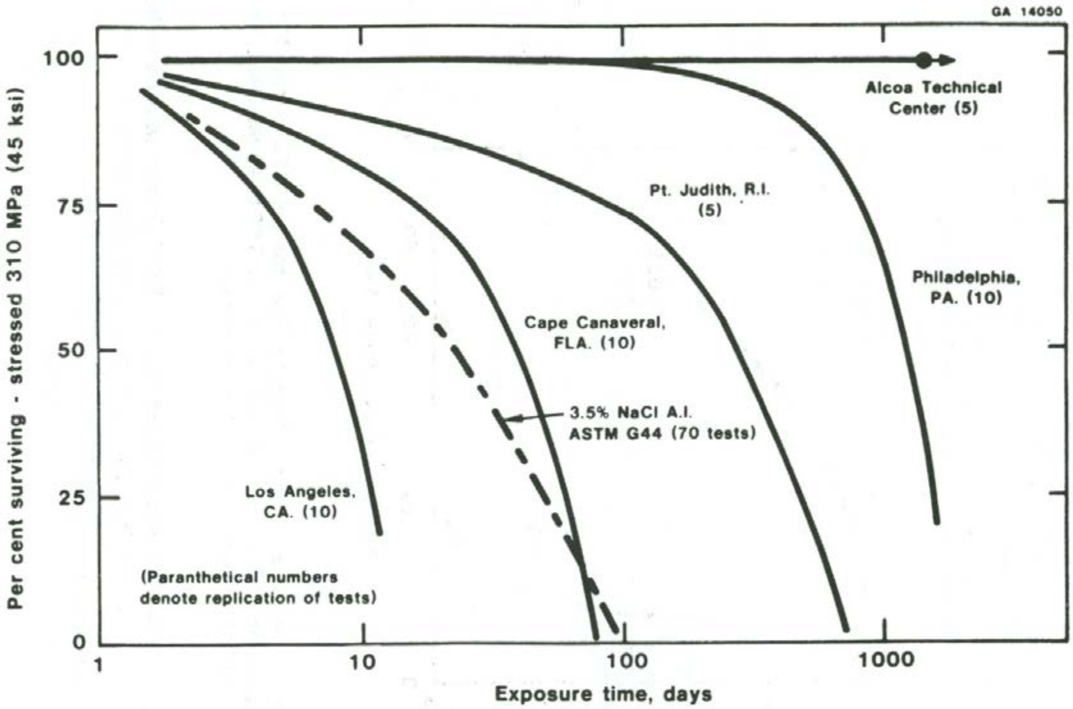


Figure 3.4.7-1 Variations in Atmospheric Environments on the Probability and Time to Failure by Stress Corrosion Cracking of 7075-T7651 Plate in the Short Transverse Grain Direction (Reference 3-37)

So while the testing and resulting A-D categories provide a relative ranking systems, they do not represent an absolute threshold. Reference 3-34 indicates that it is “not advisable to design for a sustained tensile stress just beneath the threshold stress.”

As a general rule, the design should focus on eliminating the risk of SCC through the choice of material and temper, surface treatments such as shot or laser peening which are discussed below, and eliminating sustained tensile residual stresses through good assembly practices such as shimming. However, if necessary, Table 3.4.7-1 provides some recommendations for maximum sustained surface stresses which are based on 75% of the category cutoffs of Table 3.1.2.3.1 of Reference 3-4. They are applicable to rolled plate, rod and bar, extruded shapes and forgings. Sheet material under 0.110 in thick is not susceptible to SCC particularly if it is in the CLAD condition. Sheet material is not susceptible primarily because it is difficult if not impossible to build up residual stresses in the short transverse grain direction. But note, plate or other product forms machined to sheet thicknesses are still susceptible to SCC.

Reference 3-4, Table 3.1.2.3.1(b) through (e) also provide information on corrosion resistance. This provides the maximum stress at which ST test specimens will not fail, usually in terms of percent LT or L tension yield strength. These also should not be used directly as threshold stresses. For all material in these tables, assume a “B” rating for the short transverse direction and use Table 3.4.7-1, if a threshold calculation must be made.

Residual stresses used for comparison to the values in Table 3.4.7-1 should include any stress concentration factors from radii or local details.

Table 3.4.7-1 Recommended Maximum Sustained Surface Stress

Stress Corrosion Rating Reference 3-4 Section 3.1.2.3	Allowable Sustained Surface Stress Due to Part Manufacture, Cold Straightening, and Part Assembly
A	56% $F_{ty\text{-}minimum}$
B	38% $F_{ty\text{-}minimum}$
C	19% $F_{ty\text{-}minimum}$
D	10% $F_{ty\text{-}minimum}$

If the part is durability or fracture critical, additional evaluation may be performed by the Durability and Damage Tolerance Group using program guidelines. In the absence of program guidelines, Reference 3-6, SLM-9a discusses SCC and life.

3.4.7.2 Material Alloys and Temper and Stress Corrosion Cracking Susceptibility

Higher purity metals exhibit less susceptibility to SCC and more highly alloyed metals exhibit a higher susceptibility. This is particularly an issue with 2000 and 7000 series aluminum alloys primarily when loaded in the short transverse grain direction, although for some older alloys, the transverse direction is also susceptible.

For 7000 series alloys, the T6 temper is the most susceptible to SCC. By overaging the material, which slightly reduces the ultimate strength, the T7 temper is achieved which has much better resistance to SCC. The –T73 temper is the most resistant and has been in field use for many years with no reported incidences of SCC. The –T76 temper has moderate resistance to SCC and high resistance to exfoliation corrosion. Figure 3.4.7-2 illustrates the difference in SCC resistance as a function of temper. While this example is for 7075 the temper effect also extends to other 7000 series alloys.

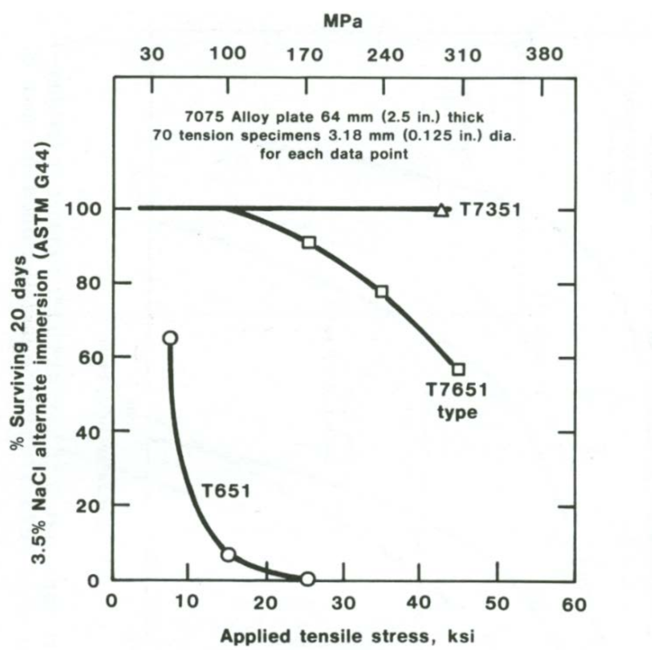


Figure 3.4.7-2 Effect of Temper of 7075 Alloy Plate on its Stress Corrosion Cracking Performance when Stressed in the Short Transverse Direction (Reference 3-37)

Several other 7000 series alloys offer combinations of resistance to SCC, strength and improved fracture toughness. These include 7049-T73 and –T76; 7149-T73 and –T76, 7249-T73, 7050-T73, -T736 and –T76, 7175-T73 and –T736 and 7475-T73 and –T76. The 7050 alloy was developed specifically for superior performance in thick sections. For the new alloy 7085, the –T7451 provides better resistance than the –T7651 temper.

Additionally, the use of stress relieved tempers, such as -TX51X (stretch relieved plate) or -TX52, are a good way to avoid stress corrosion cracking issues.

For the 2000 series alloys, using the –T8 tempers ensure good resistance to SCC. Some examples of these alloys and tempers are rolled plate 2024-T851, 2124-T851, and 2219-T851 and –T87. Also 2024-T852 forgings have good SCC resistance.

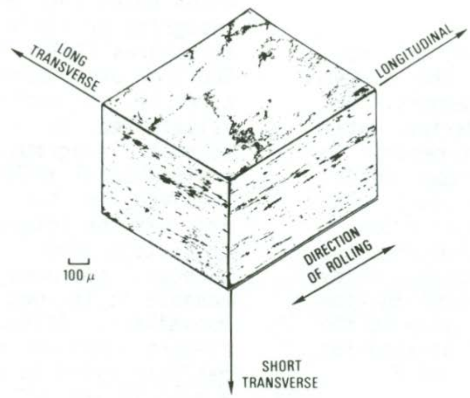
Table 3.4.7-2, taken from Reference 3-29 provides a qualitative rating resistance to stress corrosion cracking in aluminum alloys in the short transverse grain direction.

Table 3.4.7-2 Rating For Resistance to Stress Corrosion Cracking in Aluminum Alloys in the Short Transverse Grain Direction

Alloy and Temper	Rolled Plate (>0.25 in thick)	Rod and Bar	Extruded Shapes	Forgings
2014-T6	Low	Low	Low	Low
2024-T3*, -T4*	Low	Low	Low	Low
2024-T6		High		Low
2024-T8	High	Very High	High	Intermediate
2124-T851	High			
2219-T351X,-T37	Very High		Very High	Very High
2219-T6	Very High	Very High	Very High	Very High
6061-T6	Very High	Very High	Very High	Very High
7049-T74	Very High		High	High
7049-T76			Intermediate	
7149-T74			High	High
7050-T74	High		High	High
7050-T76	Intermediate	High	Intermediate	
7075-T6*	Low	Low	Low	Low
7075-T736				High
7075-T74	Very High	Very High	Very High	Very High
7075-T76	Intermediate		Intermediate	
7175-736			High	
7475-T6	Low			
7475-T73	Very High			
7475-T76	Intermediate			
* Do not use for new design per Reference 3-29				

3.4.7.3 Grain Direction

Stress corrosion cracking susceptibility is highly correlated to grain direction. This is illustrated in Figure 3.4.7-3, taken from Reference 3-34 for 7075-T651 rolled plate.



Directional Grain Structure of 7075-T651 Hot Rolled Plate

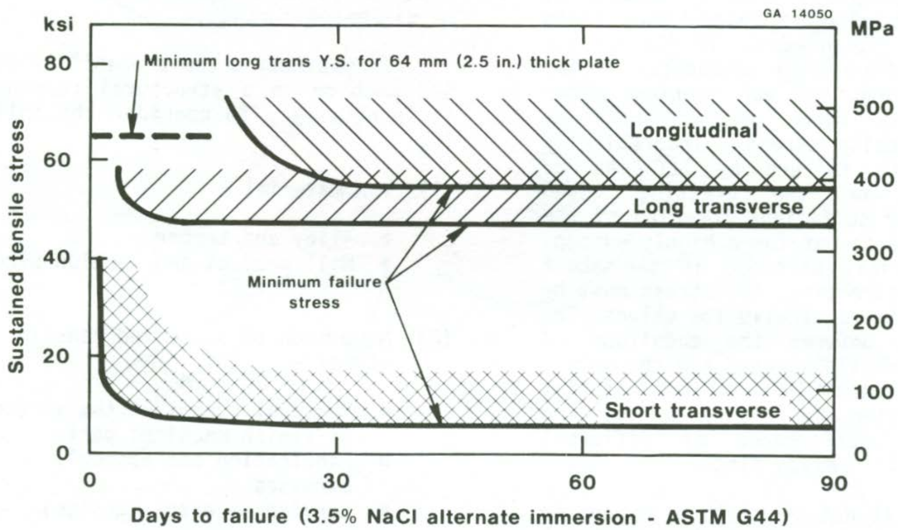


Figure 3.4.7-3 Effect of Magnitude of Sustained Tensile Stress and Grain Orientation on the Resistance to Stress Corrosion Cracking of a Metallurgically Susceptible Material (Reference 3-37)

Most stress corrosion cracking occurring in the field have been a result of sustained tensile residual stresses in the short transverse grain direction. These are usually parts machined down from thick product forms such as plate, forging or extrusion, because that provides the opportunity for residual stresses to exist in that direction.

Figure 3.4.7-4 shows the grain orientation in standard wrought products. Forgings are a function of the type of forging and how the die parting plane is situated relative to the part and confirmation must be obtained by sectioning the final part and looking at micrographs.

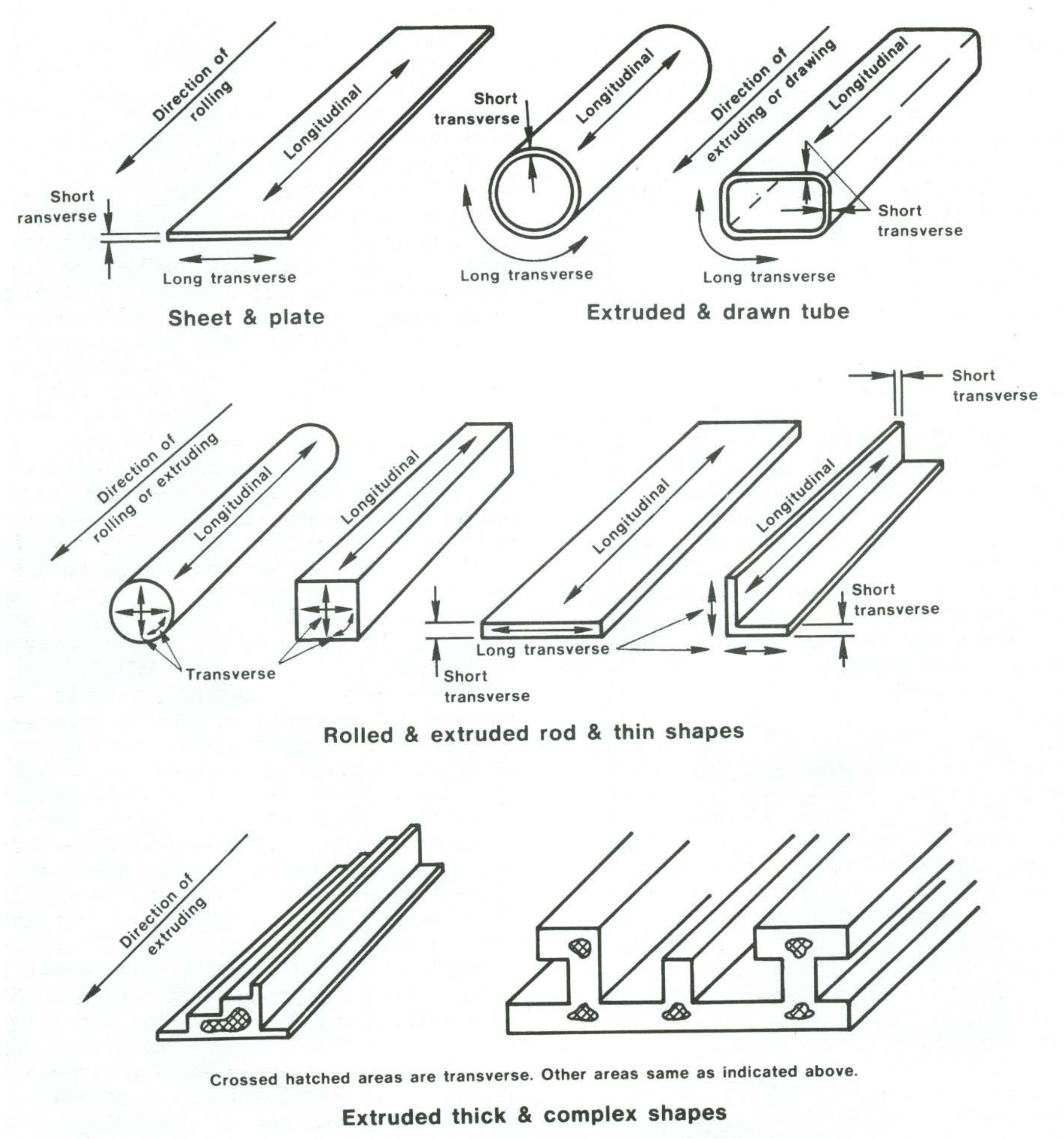


Figure 3.4.7-4 Grain Orientations in Standard Wrought Forms (Reference 3-34)

When machining a part from a thick section, it might be not quite as simple as selecting the grain orientation as shown in Figure 3.4.7-4. Careful thought must be given to any machining and forming that will be a part of the manufacturing process. Figure 3.4.7-5 illustrates what can happen if a part comes from a thick forging or extrusion. In this case the part was machined from a thick extruded shape, shown in the inset. When the metal was machined off, it exposed short transverse grain ends at the surface of the part. Additionally, there were tensile residual stresses resulting from the extrusion and cold forming operations at the surface of the part. The hole was drilled after cracking for microscopic examination and was not a contributor.

Reference 3-29 states "Metal removed from non-stress relieved structural parts after final heat treatment shall not exceed 0.150 inch per side, unless the following conditions are met. Final temper of condition has been demonstrated to have a stress-corrosion resistance of 25 ksi or higher in the short transverse grain direction as determined by a 20-day alternate immersion test provided in ASTM G47 or equivalent."

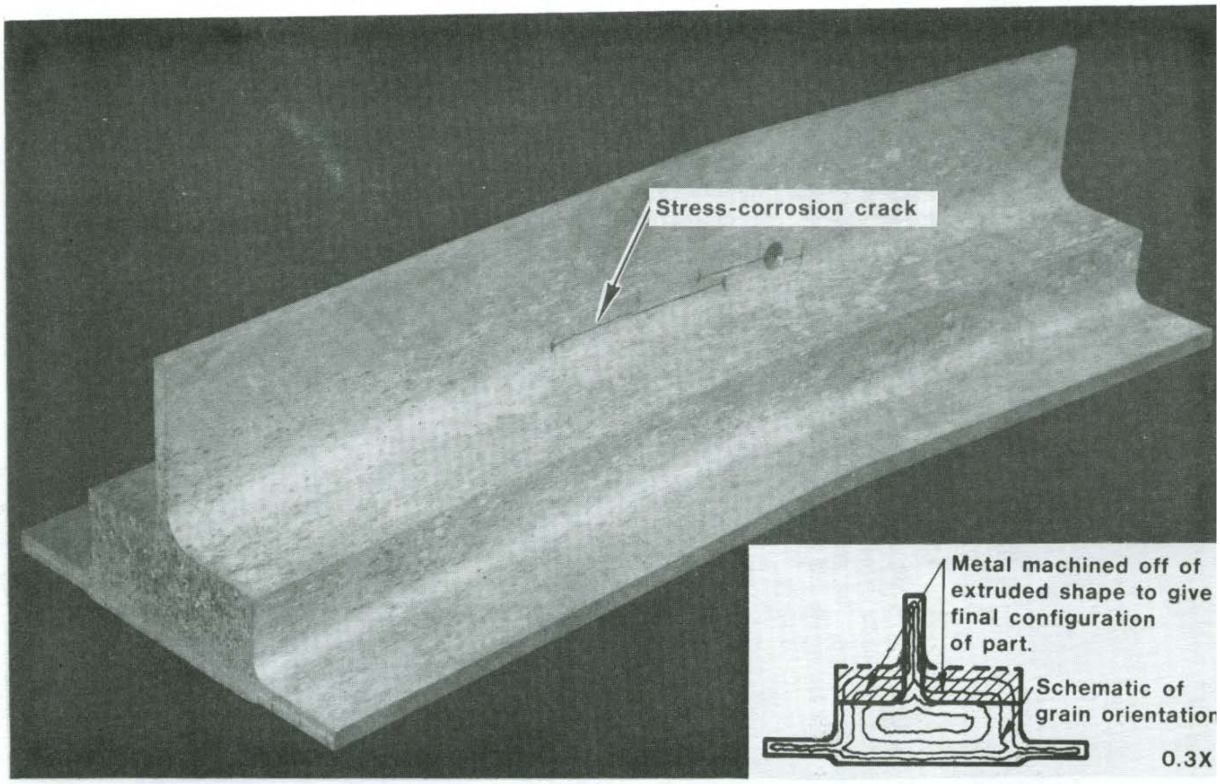


Figure 3.4.7-5 Example of Stress Corrosion Cracking in Cold Formed 7075-T6 Wing Spar Chord Machined from a Thick-Section Extrusion (Reference 3-34)

3.4.7.4 Residual Internal Stresses

Residual stresses in a part are those stresses which are present without any applied external force. These stresses may result from forging, extrusion, quenching following heat treatment or deformation of the metal during fabrication. This would include gap-pull up in lieu of shimming, the installation of high interference fasteners or bushings or any inadvertent permanent deformation resulting from assembly processing.

When aluminum alloys are solution heat treated and quenched the surface residual stresses are compressive. However, if a part is then machined from that product, the residual tensile stresses can be exposed to the new surface through machining pockets or drilling into the material. If those tensile stresses are in the short transverse direction and it is a susceptible alloy, product form and temper, then the potential for SCC is high.

This problem becomes even more pronounced for forgings because of the wide variety of cross-sections, die designs, and levels of machining making it difficult to control internal quench stresses in forgings. Methods range from re-striking the finished product with the die to stretch relieve to modifying the quench sequence and depending on the configuration, these have varying results. The optimization/ minimization of forging residual stresses for new forging designs through finite element modeling of the forging process and die is a service that some material producer/forging houses now offer for critical parts. Follow-on measurement of those residual stresses indicate there can be a wide variation of results for different parts made using the same die, same process and same quench.

Bending, joggling and roll forming result in permanent plastic deformation of the part and can induce significant tensile residual stresses in the part. These stresses can be as high as 75% of the yield strength of the material on the surface and internally can be at or above the yield strength. If these tensile residual stresses are in the longitudinal or long transverse directions they may not result in an SCC problem if no holes or pockets are later introduced; however, if the radius is small in thick material, holes are present, the part is later machined or if short transverse direction is involved, these tensile residual stresses could result in SCC. Significant forming is better done in the annealed or freshly quenched condition. As a note, hot or cold dimpling, as appropriate for the alloy, does not cause SCC concerns.

Straightening of parts, a form of bending, can also result in SCC issues if done in either plane which involves the short transverse grain direction.

Assembly stresses are another possible area of concern. Unexpected large gaps between mating surfaces which are not shimmed but instead are “pulled up” can result in significant residual stresses in the part depending on the local geometry, size of the gap and the distance over which the gap must be closed. Shimming all gaps greater than 0.005 in is the best alternative.

Interference fit bushings, pins and fasteners create hoop tensile stresses which have been reported to cause SCC. Interference fit fasteners are often used to improve the fatigue life of a joint but if installed such that short transverse grain ends are exposed during the drilling of the hole, then SCC may result. This has occurred, for instance, in integrally stiffened wing planks made from extrusions where interference fit fasteners are installed in regions of short transverse grain exposure through the blade stiffener for the attachment of rib clips. Reference 3-36 reports that cracking occurred only in the vertical blade stiffener-to-rib clip attachments, not in the horizontal skin splices, drain holes, or rib cap attachments. The latter fasteners, while interference fit, were installed in the horizontal surfaces of the extrusion where the residual tensile stresses were not in the short transverse direction.

When interference fit bushings are installed, it results in a radial compression stress and a tangential tension stress at the edge of the hole. Controlling the amount of interference between bushings and the material in which they are installed limits tangential tension residual stresses. The magnitude of the stress can be calculated per Section 5.2.5. Typical recommended bushing interferences in use at Lockheed Martin are +0.0005 to +0.0015 while maximum interference for fasteners is typically 0.0030 inch.

Testing was performed at Lockheed Martin, reported in Reference 3-35, in 2024-T3, 7075-T6, 7050-T76 and 7075-T76 extruded bar machined into a corner fitting as shown in Figure 3.4.7-6 to explore the occurrence of SCC with various interferences. The different materials were chosen because they are commonly used on Lockheed Martin Aircraft and they have different SCC ratings in different grain orientations. These are tabulated in Table 3.4.7-3 for reference. Different types of fasteners with different degrees of interference were installed and the results tabulated. The parts were sulfuric acid anodized before hole drill and experiments were performed for both dry and wet pin installation. The wet pin installations resulted in fewer reports of incipient SCC. It was noted that the examination of grain structure indicate short transverse – longitudinal plane showed the most prominent short transverse structure while the short transverse-long transverse was more equiaxed.

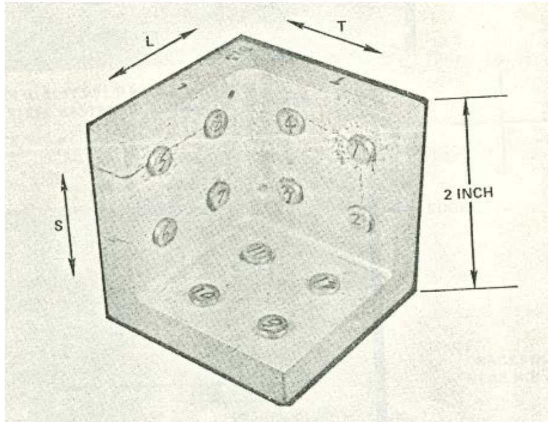


Figure 3.4.7-6 Interference Fit Corrosion Specimen After 60 Days Alternate Immersion Testing (Reference 3-35)

Table 3.4.7-3 Summary of SCC Rating, Yield Strength and Maximum Sustained Tensile Surface Stress by Grain Orientation (Reference 3-35)

Aluminum Alloy and Temper (Extruded Bar)	Grain Orientation	SCC Rating	F_{ty} (ksi) (As reported, test typical)	Reported Maximum Sustained Tensile Surface Stress (ksi)
7075-T76	L	A	70.6	>60
	LT	A	--	>55
	ST	C	64.5	35
7050-T76	L	A	77	>60
	LT	A	75	>50
	ST	C	73.2	25
7075-T6	L	A	82.5	>60
	LT	B	--	35
	ST	D	70.4	12
2024-T3	L	A	58.1	<40
	LT	B	--	18
	ST	D	47.9	7

The results of the testing is tabulated in Table 3.4.7-4. Both 7075-T6510 and 2024-T3511 materials performed poorly with fasteners installed in the short transverse-longitudinal plane. These two materials also showed a significant amount of stress corrosion cracking in the short transverse-long transverse plane. Also performing poorly was the 7050-T76510 in the short transverse direction; however it showed improvement over the 7075-T6510 and 2024-T3511 materials in the short transverse-long transverse plane. Finally, the 7075-T76510 material had a large reduction in the SCC development up to an average interference of 0.0055, although there was some incipient evidence of SCC at average interferences of 0.0035 in and higher. None of the materials showed any evidence of SCC in the long transverse – longitudinal plane.

Table 3.4.7-4 Summary of Test Results for Stress Corrosion Cracking with Varying Degrees of Interference (Reference 3-35)

	7050-T76510			7075-T76510			7075-T6510			2024-T3511		
Grain Orientation	Short Transverse-Longitudinal	Short Transverse-Long Transverse	Long Transverse-Longitudinal	Short Transverse-Longitudinal	Short Transverse-Long Transverse	Long Transverse-Longitudinal	Short Transverse-Longitudinal	Short Transverse-Long Transverse	Long Transverse-Longitudinal	Short Transverse-Longitudinal	Short Transverse-Long Transverse	Long Transverse-Longitudinal
SCC Rating	C	A	A	C	A	A	D	B	A	D	B	A
Avg Interference (in)												
0.0005	Incipient SCC	None	None	None	None	None	Incipient SCC	None	None			
0.00175	Incipient SCC	None	None	Incipient SCC	None	None	None	None	None	SCC	Incipient SCC	None
0.00325	SCC	None	None	None	None	None	SCC	None	None	SCC	Incipient SCC	None
0.00325	SCC	None	None	None	None	None	Incipient SCC	Incipient SCC	None			
0.0035	SCC	None	None	Incipient SCC	None	None	SCC	SCC	None	SCC	SCC	None
0.0045	SCC	None	None	Incipient SCC	None	None	SCC	Incipient SCC	None			
0.0045	SCC	None	None	Incipient SCC	None	None	SCC	Incipient SCC	None			
0.0045	SCC	None	None	Incipient SCC	None	None	SCC	SCC	None	SCC	Incipient SCC	None
0.004	SCC	None	None	Incipient SCC	None	None	SCC	None	None			
0.005	SCC	None	None	Incipient SCC	Incipient SCC	None	SCC	SCC	None			
0.0055	SCC	Incipient SCC	None	SCC	None	None	SCC	SCC	None	SCC	SCC	None
0.0065	SCC	None	None		None	None	SCC	SCC	None			
0.007	SCC	Incipient SCC	None	SCC	None	None	SCC	Incipient SCC	None	SCC	SCC	None
0.0085							SCC					
0.0095	SCC	None	None	SCC	None	None	SCC	Incipient SCC	None	SCC	SCC	None
0.0095	SCC	Incipient SCC	None	Incipient SCC	None	None	SCC	Incipient SCC	None	SCC	SCC	None
0.0095				SCC								
0.013	SCC	SCC	None	Incipient SCC	Incipient SCC	None	SCC	SCC	None			
Open Hole	Incipient SCC	None	None	None	None	None	None	None	None	Incipient SCC	None	None

Another key item to note is that for the interference levels typically used for interference fit bushings at Lockheed Martin none of the materials showed stress corrosion cracking, although there was some beginnings of SCC indications which were mitigated in the specimens where sealant was used. It should also be noted that the results from this report, coupled with the information from Reference 3-36 would indicate that there could be problems in some materials in the short transverse direction for interference fit fasteners. Figure 3.4.7-7 provides insight into acceptable interferences as a function of the SCC threshold and the Reference 3-4 rating system. With wet installed interference fit bushings, interferences to the left and above the “SCC hazard” curve may be used as appropriate. Expect SCC problems below and to the right of the “SCC hazard” curve and do not use interference fits in this region.

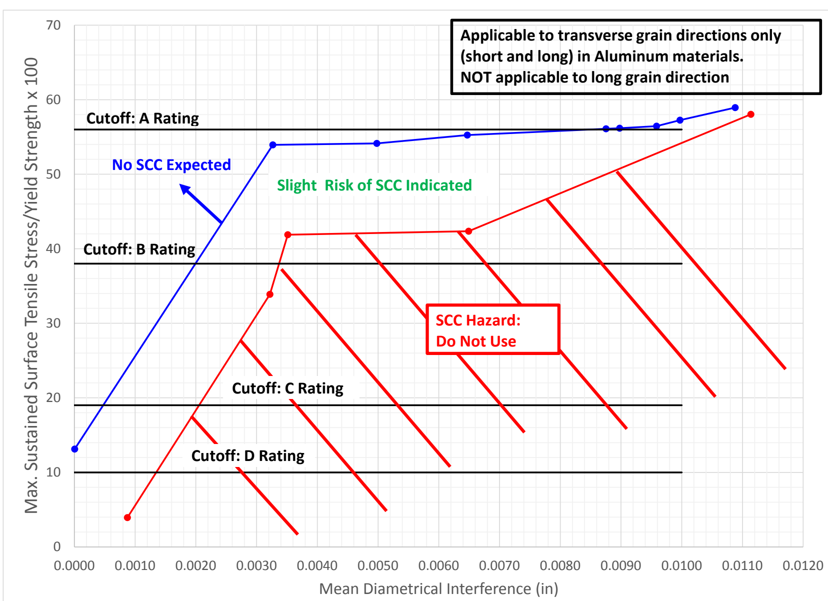


Figure 3.4.7-7 Maximum Sustained Tensile Surface Stress as a Percent of Tensile Yield Strength versus Mean Diametrical Interference

3.4.7.5 Surface Working and Protective Coatings

Shot peening and laser peening followed by applying a surface protective coating is a highly effective approach to inhibiting stress corrosion cracking. When peening is done properly it plastically deforms the surface and distorts the grain structure developing surface compressive stresses. This method is effective only if all exposed surfaces with adverse end grain structure and tensile stresses are saturation-peened and the resulting compressive layer is not penetrated by either corrosion and/or mechanical damage. Drilling fastener holes through the layer can invalidate the effect of the peening. It cannot be over-emphasized that the peening coverage needs to be thorough in order to be effective.

While surface coatings are highly effective for combatting general corrosion and there is an ancillary beneficial effect for SCC, coatings are not generally considered as a reliable safeguard against SCC. This includes anodize and paint unless used in conjunction with peening. Figure 3.4.7-8 illustrates the relative protection against SCC from various protective coating as a function of time. Better performance is to the right and top of the chart. As can be seen shot peening plus finishes provides the best protection.

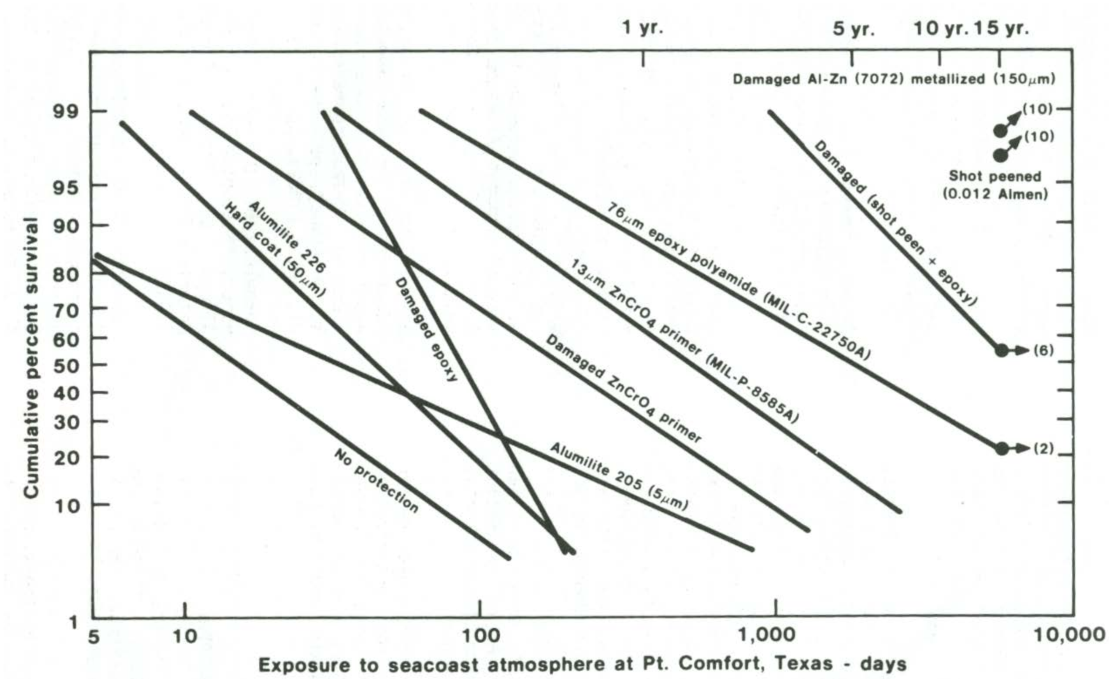


Figure 3.4.7-8 Relative Protection Against Stress Corrosion Cracking Afforded By Different Protection Systems (Reference 3-34)

3.4.7.6 Best Practices for Preventing Stress Corrosion Cracking

Methods of prevention and control of SCC include the following practices:

Materials	**Design Details**	**Processing and Finishing**
Use materials which exhibit good stress corrosion resistance	Minimize sustained tensile stresses in the short transverse planes	Use stress relief tempers or part stress relief to minimize residual stresses
Use Inconel 718, MP35 or MP159 fasteners as these fastener materials are cold worked to obtain the desired	Where stress concentrations exist, at notches, changes of section, holes, *etc.*, reduce residual surface tension stresses with large radii, gradual	Use surface cold working such as burnishing, rolling or hole finishing. Saturation shot peen

stress level and are not susceptible to stress corrosion cracking	changes, or elimination of bad details	all surfaces of susceptible parts after final machine
Do not use 7075-T6 plate greater than 0.110 in. thick (as-rolled) or forgings or shapes, particularly when loaded in the short transverse direction	Avoid using interference-fit fasteners or high interference bushings in the short transverse grain direction of susceptible materials	Use secondary environmental barriers in conjunction with good mechanical practices (shot peen, cold work…)
Do not use aluminum 2020, 7079 or 7178 for new design	Control tolerances to reduce assembly fit-up stresses. Use shims in lieu of gap pull-up	Install fasteners and bushings wet with sealant
Do not use 2024-T3 or -T4 for new design. For sheet materials in existing designs, use CLAD Sheet where possible.	Specify torque requirements of fasteners and use clamp-up bushings or shoulder bolts to minimize clamp-up stresses in a part (*i.e.*, female lugs or clevis)	Install low interference-fit bushings (~0.0005 to 0.0015) with sealant

If necessary, conduct tests as required to determine that stress corrosion will be controlled without reliance upon secondary environmental barriers which may fail in service. The use of secondary environmental barriers should always be used in conjunction with good mechanical practices.

Once a weapons system is in service, fleet management databases where history of cracking information is recorded can be used to perform periodic evaluation of crack history to identify potential SCC locations. For new programs where limited history exists using comparable aircraft with similar design and part materials may be a good source for material evaluation.

3.4.8 Galvanic Corrosion

Galvanic corrosion can occur when two metals or alloys in different groups in the galvanic series are in contact with or electrically coupled within the same electrolyte. Moisture in the air is a common electrolyte. This type of corrosion is usually accompanied by a buildup of corrosion products in the contact area. Every metal has a characteristic electrode potential. Corrosion progresses more rapidly and severely as the relative electrode potentials of various metals are separated farther in the galvanic series. The metal higher on the list will act as the anode and will corrode sacrificially. The metal lower on the list is the cathode and will remain relatively free of corrosion.

The galvanic series, Table 3.4.8-1, provides a useful guide for minimizing or avoiding galvanic-induced corrosion by indicating compatible metals and alloys, base on their electrical potential. Such a grouping, however, is not absolute. The extent of accelerated corrosion resulting from galvanic coupling will vary as a result of changes in the following:

- The potential difference between the metals.
- The nature of the environment.
- The polarization behavior of the metals.
- The geometric relationship of the component metals, *i.e.*, cathode-to-anode surface ratios.

Table 3.4.8-1 lists the metals and alloys according to their level of electrical potential. The metal on the surface of a part determines the group classification to the part. Therefore, part dissimilarity cannot be predetermined until after the required part finish has been established. For example, a steel part with a cadmium plated finish is considered a Group II material and can be used with any other Group II material, whereas bare steel integrated with other Group II materials can cause severe corrosion problems.

Note that nickel can be either active or passive. In the active state, nickel's electrical potential is closer to steel, thus indicating compatibility when listed in the galvanic series. Nickel, however, is not always compatible as plating on steel or aluminum because it usually exists in a passive state and therefore is much more cathodic when coupled with steel or aluminum. If the nickel plate is subsequently cracked or damaged, allowing an electrolyte to come into contact with the parent material, severe galvanic corrosion will ensue. When nickel plating is used for repair of steel it is always necessary to apply cadmium plating over the nickel to mitigate this potential anomaly.

Anodizing aluminum surfaces is considered superior to chemically film treated surfaces as a means of corrosion protection. However, anodizing is used primarily for inhibiting surface corrosion and not for galvanic corrosion protection. It also incidentally serves as a primer and paint base. Some forms of anodized aluminum can also have a reduced fatigue life due to the hard nature of the coating.

Application of plating can be used for making parts galvanically compatible with their mating assemblies, as well as providing protection of the underlying material.

- Cadmium plate on low-alloy steel is used to protect the base metal as a sacrificial surface and is thereby effective for a limited period of time. This period can vary depending upon the service usage and environment from a few months to a couple of years. Cadmium is a carcinogen and its use is restricted. All new applications must receive appropriate approvals as outlined in AeroCode AC-580 prior to its use in design. Cadmium plated fasteners should never be used in titanium or graphite composite materials.
- Chromium plating applied directly to steel (*i.e.,* landing gear pistons) is used primarily as a “resistance” coating. It protects the base metal by excluding moisture. However, cracks and other imperfections in the plating will allow the underlying metal (steel), which is anodic to the chromium, to corrode rapidly. Many forms of chromium and its compounds are hazardous materials and their use is restricted; however, chromium plating is excluded from this restriction.

Precipitation hardening (PH) stainless steel bushings and pins installed in aluminum wet with sealant that have been in service on several USAF, USN and FAA certified aircraft for thirty years have been found corrosion-free. The deterioration of MIL-S-8802 sealant over this time frame has evidently been negligible.

Methods of prevention and control of galvanic corrosion include the following practices:

- Use metal combinations close together in the galvanic series, preferably in the same group. Do not use magnesium.
- Use large anodic metal areas in combination with small cathodic metal areas if metals are in different groups to minimize the cathode-to-anode ratio.
- Review proposed material combinations and plating for compatibility within groups of Table 3.4.8-1.
- Avoid the use of dissimilar metal combinations in corrosive environments such as galley and lavatory areas and open bays subject to water exposure such as landing gear bays.
- Reduce the electrical potential by painting all surfaces of the part prior to assembly.
- Insulate dissimilar metals either by protective coatings or plating or inserting an inert material such as waterproof sealant or a fiberglass barrier ply between them.
- Eliminate access of water to the metals by the use of sealants, protective coatings, etc. Do not use chilled interference fits because moisture condensate can become entrapped within the hole.
- Proper selection of fastener material according to galvanic compatibility must be considered with certain types of graphite and other composite material substructure.
    - No cadmium plated fasteners in titanium or graphite composites.

Table 3.4.8-1 Galvanic Resistance of Common Materials in Order of Electric Potential

Active (Anodic or Least Noble)		
Material or Alloy	Electromotive Group	Specific Alloy, if applicable
Magnesium and Magnesium Alloys	I	AZ-31B; HK-31A
Zinc	II	
Beryllium	II	
Aluminum Alloy	II	Al 7072 clad on 7075; Al 2014-T3; Al 1160-H14; Al 7079-T6
Cadmium	II	
Mild Steel	II	
Uranium	II	
Aluminum Alloy	II	Al 218 (die cast); Al 5052-0; Al 5052-H12; Al 5456-0, H353; Al 5052-H32; Al 1100-0; Al 3003-H25; Al 6061-T6; Al A360 (die cast); Al 7075-T6; Al 6061-0
Indium	III	
Low Alloy Steel	III	
Aluminum Alloy[11]	III	Al 2014-0; Al 2024-T4; Al 5052-H16
Tin (plated)	III	
Stainless Steel	III	430 (active)
Lead	III	
Cast Iron	III	
Stainless Steel	III	410 (active)
Copper	III	plated, cast or wrought
Nickel	III	plated
Chromium	III	plated
Tantalum	III	
Stainless Steel	IV	AM350 (active), 310 (active), 301 (active), 304 (active), 430 (passive), 410 (passive), PH15-5Mo (Active), 17-7PH (active), A-286
Tungsten	IV	
Niobium	IV	
Brass, Yellow, 268	IV	
Uranium	IV	8% Mo.
Brass	IV	Naval, Plated
Nickel-Silver	IV	18% Ag
Stainless steel	IV	316L (active)
Bronze 220	IV	
Copper 110	IV	
Red Brass	IV	
Stainless Steel	IV	347 (active)
Molybdenum	IV	Commercially Pure
Copper Nickel	IV	715
Bronze Phosphor	IV	534 (B-1)
Stainless Steel	IV	201 (active), 321 (active), 316 (active) , 309 (passive), 17-7PH (passive), PH15-5Mo (passive) 304 (passive), 301 (passive), 321 (passive), 201 (passive), 286 (passive), 316L (passive), AM355 (active), 202 (active), Carpenter 20

[11] In actual practice, test, and aircraft structure aluminum and titanium are much more compatible than this table would imply due to active titanium being reported. However, since titanium rapidly oxidizes, passive titanium has an EMF that puts it in close proximity with aluminum. Appropriate protective coatings should be used.

		(passive), AM350 (passive), A286 (passive), Monel, MP35, MP159
Titanium Alloy[11]	IV	5A1-2.5 Sn; 13V-11Cr-3AL (annealed); 6AL-4V (STA); 6AL-4V (annealed); 8Mn; 13V-11Cr-3AL (STA); 75A
Stainless Steel	IV	AM35 (passive)
Silver	V	
Gold	V	
Graphite	V	
Least Active (Cathode or Noble)		

3.4.9 Hydrogen Embrittlement

Hydrogen embrittlement is created when atomic hydrogen diffuses into steel resulting in a loss of ductility, strength or cracking as well as catastrophic brittle failure below either yield strength or nominal design strength for the alloy. The hydrogen can be introduced by the service environment or during fabrication (*i.e.*, during roll forming, machining and drilling or during welding or brazing) or processing (*i.e.*, during cleaning, pickling, phosphating, or electroplating). Heat treatment procedures have been established to reduce the susceptibility of the metal to this phenomenon. In addition, paint and platings can help to diminish the threat of hydrogen embrittlement.

High strength steel fasteners in the range above 180 ksi and below 220 ksi are particularly susceptible and it is for this reason that, in general, aircraft fasteners in this range are not used. Of course, if manufactured incorrectly, any high strength steel fastener can be subject to hydrogen embrittlement.

Titanium alloys can also undergo hydrogen embrittlement in higher temperature environments (> 176 °F) and when the protective oxide coating has been breached. There must also be some mechanism for generating hydrogen such as a galvanic couple, cathodic protection by impressed current or dynamic abrasion of the surface with sufficient intensity to depress the metal potential below that required for spontaneous evolution of hydrogen.

Additional information can be obtained from the cognizant Materials and Processes Engineer.

3.5 Forgings

Forged parts are manufactured by impacting or pressing the material, generally at an elevated temperature, into a predetermined shape. This causes the material to exceed the yield point and aligns the grain structure along the flow lines of the material. Forged parts usually have much better material properties than cast or wrought product. After the forming process, the parts are heat treated and quenched which can result in significant residual stress in the part. Metallurgists and material manufacturers have focused much effort in processing techniques that limit or relieve these residual stresses. The residual stresses can cause distortion of the part during machining such as warping of flanges or oil-canning of webs. In some alloys the residual stresses can lead to stress corrosion cracking. Some of the techniques used to reduce the residual stresses include striking the part with the die a second time and then aging or compression stretching[12] the part. Also special quench sequences have resulted in a reduction of residual stresses.

In aerospace, the materials most commonly used as forgings include aluminum, titanium and steel. Alloy steel is the most easily forged of the three materials and can be forged hot, warm, or cold. Stainless steels, however, are very difficult to forge because of their strength at temperature and the susceptibility to microstructure damage at elevated temperature. Aluminum can require higher forging pressures than steel but it can be forged at lower temperatures. The 7XXX series aluminums are the least forgeable of the aluminum alloys. Titanium is more difficult to forge than both carbon steel and aluminum. Both aluminum and titanium require both heating the dies and preheating the billet as the temperature must be controlled very carefully to achieve optimum material properties. Titanium is generally

[12] This process consists of performing a cold temperature mechanical stretch to a part followed by applying a cold temperature compression stress relief cycle. This results in improved toughness and minimizes distortion after machining.

coated with a ceramic prior to the forging process to retard oxidation. Titanium is also very abrasive during the forging process which causes die wear. After forging, if the titanium is a net forging, it must be chemically-milled to remove the alpha case[13]. These all add up to titanium forgings being significantly higher cost than aluminum forgings. For alloy steel forgings, if as-forged surfaces are to be use on the finished part, removal of the de-carburized layer[14] will be required. This may be accomplished by mechanical means or chemical milling.

3.5.1 Types of Forgings

There are many types of forging processes. Some of the more common ones used for aerospace applications are described in this section.

Hand forging is the least expensive method of forging because of the relatively simple dies. The final shape is usually a billet or a part having only the most general shape of the finished part. This has the shortest time between order and delivery of the forging; however, extensive machining is often required. Care must be taken to ensure the correct material properties are used. Strength will be a function of heat treat thickness. If the final heat treat is at the billet level, the thick part allowables must be used. If the part is machined prior to final heat treat, thin part allowables may be used. A hand-forged billet could have a much higher area of short transverse grain flow.

A blocker die forging is used in the early phase of the conventional die process. The die has the shape of the finished part but with 0.25 to 0.5 in of excess material on the periphery. Complete machining on all surfaces is generally required. A finished forged part made by this process is more expensive than a hand forging and will still require all-over machining; however, the amount of metal removed will not be as great as for a hand forging. There are also smaller cross grain areas. A blocker die may also be used as a first step in the conventional die forging process to rough shape a complex part.

Conventional die forging is the most common type of forging used in design. This is a closed die process which results in controllable, repeatable grain flow with good dimensional tolerance. The final part is fabricated in progressive forming operations. Some “as forged” surfaces require no machining. This process has higher die costs and overall machining may not be required.

Precision die forging is a close-tolerance forming which results in a part that requires little to no machining. This is the most expensive die to manufacture, however machining costs are minimal. This would generally be used on a design which had a large number of parts to produce.

3.5.2 Forging Grain Flow

The mechanical properties of forgings are at their maximum values in the direction parallel to the grain flow (L-direction), which is one of the primary advantages of using forgings since the material grain flow can be optimized relative to the orientation of the finished part. The big disadvantage lies in the fact that the properties transverse to the grain flow are reduced and care should be taken when applying a concentrated load in the short transverse direction, since cross-grain elongations can be on the order of 0.01 in/in resulting in a part which behaves in a very brittle fashion

The location of the parting plane, or the point where the two dies come together, can be very important in the design of a forging to maximize the benefit of improved properties through improved grain flow. If the parting plane is poorly placed the material will not be able to flow and there will be an increase in defects. Typical examples of the grain flow variation are shown in Figure 3.5.3-1

[13] Alpha case is a brittle layer on the external surface of titanium which is rich in oxygen after exposure to elevated temperature.
[14] Decarburization is the loss of carbides at and near the surface of the part during processing, which weakens the material and reduces its fatigue strength. The thickness of this layer is a function of the processing.

In order to ensure that the allowables used in design are obtained in the finished part, the analyst and designer must have a good understanding of the forging process and material characteristics. Consult with Materials and Processes Engineering to obtain detailed assistance. Specific control information must be added to the forging drawings to define the following:

- Specify the predominant grain direction, oriented with the maximum tension and compression stresses.
- Control the local contour grain flow areas with sufficient radii and depth to allow smooth and continuous grain flow.
- For hand forged billets, specify the maximum permissible billet size and ensure the selected allowable stresses are consistent with this size.
- The drawing should have the parting plane explicitly located.
- If the part is a critical part or it has significant loading in line with the short transverse direction, require ultrasonic inspection of the part. This may not be practical except for small forgings.
- Define the location of prolongations and first article cut-up specimens. The minimum strength requirements should also be specified.

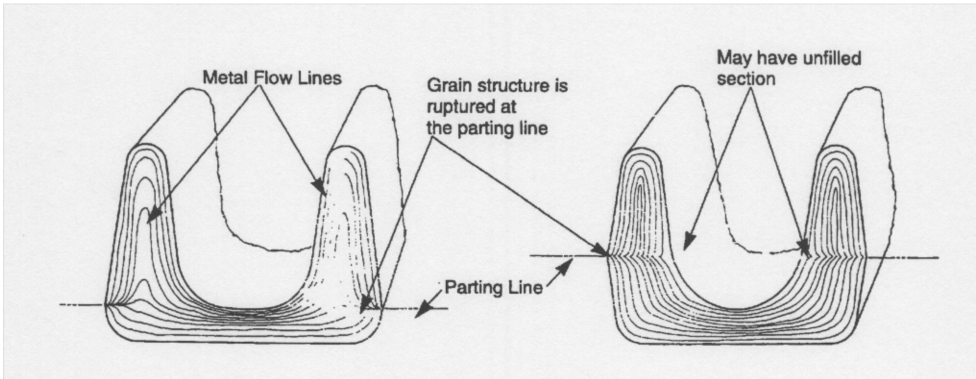
3.5.3 Mechanical Properties

For all critical, single-load-path parts, material properties should be developed for the forged part by cutting up and testing numerous parts. For other parts, it may be sufficient to use MMPDS allowables, which were likely obtained from hand forged billets. The number of parts required is dependent on the Basis of the allowable required. Reference 3-5, Chapter 9, provides guidelines for the number of specimens for the development of Basis allowables.

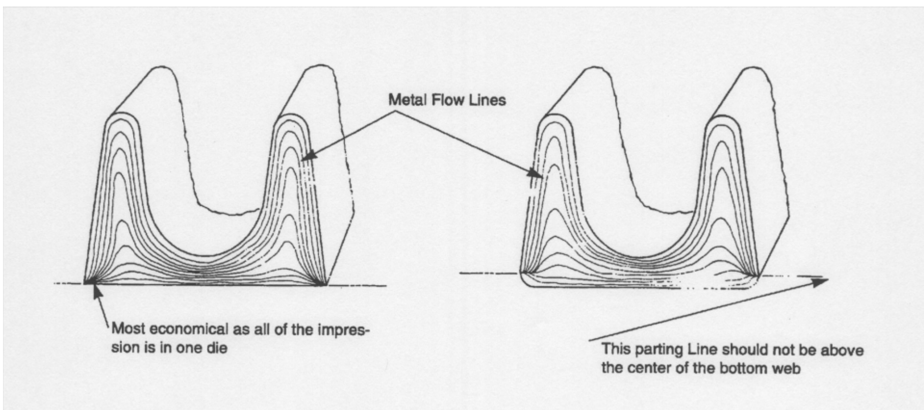
Once the allowables are established, and the part is designed and built, the strength of the finished part must be verified by testing. An article from the first lot of forgings shall undergo mechanical property testing. Specimens are machined from the forging after heat treatment and tested for conformance to the required mechanical properties. Cutting test coupons from these parts will destroy the part. This forging selected should be the least acceptable forging of the lot, which passes all inspection requirements. All test results must meet or exceed the specification minimum properties. The configuration and location of test coupons shall be marked on the forging drawing. These coupons should be from the maximum, average and minimum thickness locations and across all grain directions. Testing should include tension, compression and shear ultimate strength, tension and compression yield strength, modulus, and bearing. Additionally, on all critical parts, there will be specimens for durability and damage tolerance. The analyst should coordinate with the Durability and Damage Tolerance Group for the location of these specimens.

A sampling procedure should be instituted for future lots of parts to ensure that the parts continue to meet requirements. Because forgings can be large expensive parts, this is often done through the use of prolongations which are removed from excess material on the forging. They are integral with the forging during all processing steps and are removed only after final heat treat and then are tested. Additionally, because space is limited, these test specimens are generally limited to tension ultimate and yield. In some cases, depending on the size and/or criticality of the part, separately forged coupons may be acceptable.

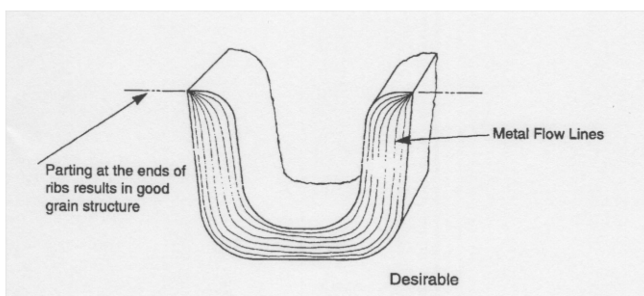
If the material chemistry is modified or the forging or heat treatment process or the forging die design is significantly changed, another cut-up article shall be required to ensure the part still meets the strength and life requirements. This should be specified on the drawing.



Undesirable – Parting Lines result in Complex Grain Flow which causes Forging Defects



Desirable – Economical and Good Grain flow



Most Desirable Grain flow

Figure 3.5.3-1 Examples of Forging Grain Flow

Courtesy of The Aluminum Association, Reference 3-31.

3.5.4 Required Inspections for Forgings

There are several standard inspection processes to help determine that the completed forging is of good quality. These include visual, dimensional, ultrasonic and dye-penetrant. The section below will discuss these methods and the types of defects they are used for.

Close Visual Inspection A close visual inspection will reveal areas which may have surface blisters, cold shuts, laps, cracks or corrosion.

Dimensional Checks The part should undergo dimensional checks using gages or a coordinate measuring machine (CMM) to ensure that it meets drawing requirements and that there are no under-filled areas of the forging die and there is not significant warpage or distortion.

Ultrasonic Testing is used to determine the metallurgical soundness of the forging. Techniques include both longitudinal and shear wave testing and the types of defects found include near-surface blisters, internal slag, porosity, and excessive grain size. Large grain sizes can cause the ultrasound to experience variations in penetration and defect resolution. Ultrasonic testing may be limited to forging stock because of limitations on access caused by part geometry complexity.

Dye-penetrant inspection is a process where a fluorescent dye is used to coat the surface of a part. The dye wicks into any surface imperfections and when viewed under an ultraviolet light makes the imperfections visible. It is used in conjunction with visual inspection to detect surface defects such as cold shuts, laps, cracks or corrosion.

3.5.5 Forging Defects

This section discusses some of the more common defects found in forgings, as an overview for the analyst who might be confronted with these defects as part of a material nonconformance. Consult with the Materials and Processes organization for greater detail as well as information regarding other defects not included below.

Aluminum forgings can see **blistering** both on the surface and below the surface. Often these blisters only appear after solution heat treatment. On the surface they appear as a pattern of small bumps. These may be removed by polishing if a net forging, or they may be machined off, if the forging undergoes an overall machining operation. The blisters are generally one of three types:

- Scrub blisters caused by the movement of the aluminum material over the die surface and the collection of lubricant. These will appear dark under the blister, due to the lubricant, and follow repeating patterns
- Hydrogen blisters are caused by excessive hydrogen. They are very random in appearance
- Burned metal blisters where the metal overheats. They also tend to be in a pattern and the material below is gray in color.

The last two types are cause for rejection and the manufacturer should not routinely polish them out.

Abnormal grain growth is particularly a problem of aluminum and titanium forgings. In aluminum forgings this is caused by improper forging reduction, which doesn't show up until after solution heat treatment and causes a reduction in strength. For the titanium forgings, it is caused by improper control of temperature during the process.

Cold shuts are areas where two flows of metal do not properly fuse. It can be caused as metal folds over itself during the forging process. A cold shut commonly occurs where the vertical and horizontal surfaces meet.

Cracks can be caused by uneven cooling and shrinkage of the metal.

Flash is the flow of the molten material outside of the die if the die does not close properly. Flash is generally removed by sawing or through the use of trim dies. If the forging is to be completely machined, flash is not generally an issue. If the forging is net, then the surface finish and amount of protrusion of the flash is of a concern to the analyst as it can be a site of crack initiation or increased stress due to the stress concentration effect. In critical areas, the flash should be entirely removed and the required surface finish specified on drawing. Note that if a drawing calls out "shot peen all surfaces" the flash surface is not included in "all surfaces" unless explicitly called out.

Internal slag is an area of the forging where the metallic waste product, or slag, pools within the forging creating an area of lower material strength. Unless the area of internal slag is to be removed during final machining, a part containing internal slag should be scrapped.

Laps appear as a seam on the surface. These are very similar to a cold shut in that there are two layers of material which have not fused.

3.6 Castings

Casting is the process where a molten metal is poured into a mold and allowed to solidify. The solidification process can lead to defects on both a microscopic and macroscopic scale which affect the strength and durability of the part. The most common cast metals used in aerospace applications are aluminum, magnesium and titanium, although others may be used. The quality of the casting, in general, is directly proportional to the cost.

Mechanical properties vary throughout a casting, due to the complexities of flow during the pouring of the metal. Obviously, this is very shape-dependent as well as cooling-rate-dependent and consistency is hard to obtain. For this reason, foundrymen use a variety of techniques to manage the end result. Devices like chill bars and positioning of entry/exit points or parting lines can all affect the properties. The analyst must be aware that this means many uncontrolled areas of the casting will have lower properties, and must assure that the important areas are properly managed. This section provides guidance for these issues.

In recent years casting manufacturers have worked to improve the quality of castings through various processes. One which has been used in aerospace applications is the hot isostatic press (HIP) process. Both aluminum and titanium castings can undergo the HIP process; however, it is expensive and it does have limitations in what improvement can be expected. The HIP process involves applying a high pressure gas to the surface of the casting under elevated temperature. It is particularly effective at 'healing' internal porosity through the plastic deformation of the pores. The process is controlled very tightly to ensure that the time at specific temperature and pressure is optimal for the permanent removal of the porosity. Internal porosity responds well to the HIP process, however surface connected porosity does not. It is important that the surface of the casting be dense prior to the HIP process and it is recommended that any surface porosity be repaired through welding prior to undergoing the HIP process. It has also been shown on actual aircraft parts that defects within very thick parts do not respond as well to the HIP process and there may be remaining defects which are not healed.

In general, the ductility of cast material can be lower than that of wrought products, even though the static strength may not be reduced. Some cast material has extremely small elongations, such as 1 to 2%, making it a very brittle material subject to catastrophic failure with little deformation. In addition, cast material has more defects and grain irregularities than wrought material. Because of the unique characteristics of castings, adherence to some special design considerations can result in an enhanced design. This section will address some of these guidelines.

- Avoid castings in areas where significant flexure is likely to occur.
- Plastic bending analysis can be very risky due to the low elongation; the analyst is cautioned to pay special attention to this consideration if plastic bending analysis is used.
- The non–cast surface roughness (*i.e.,* areas at gates or risers) shall not exceed the surface roughness of the as–cast surface.
- Castings should be designed so that there is no rapid change in cross sectional area in any direction, *i.e.,* no thick/heavy areas adjacent to thin areas and constant cross-section areas are most desirable.
- Because of the low elongation, castings should not be threaded with male or female threads. If castings are threaded, torque values shall be established specifically for cast parts. Aluminum castings shall not be threaded.
- Fasteners installed in castings should be installed with sealant in clearance holes. If a tighter tolerance hole is required, such as a transition fit, then a minimum elongation of 5% must be specified and the area must be a Grade C or better (See Table 3.6.1-1). For fatigue analysis, a multiplication factor applied to the stress concentration factor may be appropriate for holes in castings. More information can be found in Reference 3-6.
- In order to achieve a higher elongation, it may be necessary to reduce the design property stresses. The casting heat treatment can increase the elongation while reducing the ultimate and yield stress of the material. While it is generally best to stick to established tempers and heat treat practices, in rare cases special handling may be desirable. This would need to be negotiated with the casting house and the modified strength would need to be specified on the drawing.

The following is a checklist to ensure the casting design meets all structural integrity requirements and drawings have all of the appropriate notes and callouts.

- Classify the structure per the program Aircraft Structural Integrity Program (ASIP) master plan and the casting classification table, Table 3.6.2-1.
- Classify the casting for inspection per Section 3.6.1, 2.6.2 and 3.6.7 and Table 3.6.4-2, if applicable.
- Grade the casting per Table 3.6.1-1 and Table 3.6.2-1 .
- Designate the casting Class and Grades on the drawings and any applicable zoning
- Determine the number of castings required for the static tests per guidance in Section 3.6.5 and add a drawing note, if required.
- Call out special heat treatment requirements as appropriate.
- Call out the material properties on the drawing. See Section 3.6.8 for typical notes
- Review the casting specification inspection requirements and call out the special inspection notes, if required, on the drawings.
- Zone and grade the areas of the casting that require X–ray inspection, if any, on the casting drawings. See Section 3.6.8 for typical notes.
- Call out the repair welding by a drawing note and any stay out areas for the repair procedure per sample in Table 3.6.8-1.
- Call out the fastener installation fit
- If the casting has internal or external threads, a drawing note must be added to specify the torque values[15]
- Call out the roughness requirements for the non–cast surfaces (*i.e.*, gates, risers, etc) and add appropriate note to drawing per Table 3.6.8-1.
- If a first article or lot acceptance article cutup and test is required, include the location of the specimens on the drawing.
- Locate possible flash areas away from DESIGNATED areas.

Each of the above items is discussed in more detail in the following sections.

3.6.1 Casting Grade

The term "GRADE" is used to differentiate between the degrees of foundry control during production of a casting. Rejectable defect sizes and levels are a function of the grade of a casting in the casting specification. The level of inspection performed is also a function of the specification grade of the casting. The Structural Class of the casting, per Section 3.6.2, is used to determine its specification grade. In general, a casting is zoned on the drawing to reflect the critical and non-critical areas. These areas are called "DESIGNATED" and "NON-DESIGNATED" and these will be discussed in more detail in a later section. Designated areas are usually a higher grade, requiring more controls and a higher inspection level. The zoning of drawings is discussed in Section 3.6.3. The grades are defined in Table 3.6.1-1:

Table 3.6.1-1 Casting Grade Definition[16]

Casting Grade	Typical Structural Class	Elongation	Discussion
A "Highest Quality"	Class 1 : (DESIGNATED AREAS)	minimum 6%	- Requires exceptional foundry controls during production for minimum allowable discontinuities. - Negotiate with casting house to obtain elongation required. - Transition fit fasteners may be used due to higher elongation

[15] Aluminum castings shall not have threads.
[16] Reference 3-32

			- No more than 10-15% of the casting area – generally in areas of mounting lugs or other critical stress regions - used in high stress areas
B “Premium Quality”	Class 1 or Class 2 : (DESIGNATED AREAS)	minimum 6%	- Requires close foundry controls during production - Negotiate with casting house to obtain elongation required. - Transition fit fasteners may be used due to higher elongation - If Class 1 – all areas not designated Grade A - If Class 2 - No more than 15% of the casting area – generally in areas of mounting lugs or other critical stress regions - used in high stress areas
C “High Quality”	Class 2 or Class 3 : (DESIGNATED AREAS)	minimum 5%	- Obtainable throughout entire casting - Transition fit fasteners may be used due to higher elongation - May be used for lugs[17] or bosses[18] - Should comprise the major part of the casting to obtain the greatest possible weight and cost savings commensurate with the size and complexity of the part. - Used in medium stress areas - Limit thickness to less than 0.625 in.
D “Normal Quality”	Class 3 and 4	minimum 3%	- Obtainable throughout the entire casting - All sections thicker than 0.625 inch would normally be designated a Grade D area. - Sections 0.625 to 1.5 inches thick can obtain minimum properties. - Sections heavier than 1.5 inches and areas inaccessible to single–wall radiographic inspection must be low stress areas. - Used in low stress, non critical areas

Both the grade of the casting, and zoning of the casting if appropriate, and the structural classification of the casting should appear on the face of the drawing.

3.6.2 Casting Class

The class of the casting designates how critical its function is to the aircraft and mission and is used by the casting specification to determine the required inspections. The following table describes the classes of castings and the definition of the types of parts for which the class designation is appropriate per Reference 3-32.

Table 3.6.2-1 Casting Class Definition

Class	Approval for Use	Usage Description
Class 1	Requires IPT / Chief Engineer / Customer Approval	A casting, the single failure of which would endanger the lives of operating personnel or cause the loss of missile,

[17] Protuberances from main body of the casting.
[18] raised surfaces at points of attachments for concentrated loads

Class	Approval for Use	Usage Description
		aircraft or other vehicle. Note this is very rare on newer aerospace vehicles.
Class 2	Requires IPT Approval	A casting the single failure of which would result in significant operational penalty. This includes the loss of major components, unintentional release or inability to release armament stores or failure of weapon installation components
Class 3	Requires Stress Lead Approval	Castings not included in Class 1 or 2 having a margin of safety ≤ 2.0
Class 4		Castings not included in Class 1 or 2 having a margin of safety > 2.0

3.6.3 Zoning of Castings

Because making a casting which is free of all defects is not practical, it is necessary that the foundry technique be so established that the worst of these defects are situated in least critical areas of the casting. The “DESIGNATED AREAS” of all castings shall be clearly defined to avoid these defects. The casting “Grade” defines the maximum acceptable limit for each type of defect in each area of the casting as designated on the drawing.

A minimum of two grades should be specified on the drawings of the rough casting to distinguish the “DESIGNATED” from “NON–DESIGNATED” areas. The “DESIGNATED AREA” should consist of no more than 10-15% of the casting. Indiscriminate upgrading will result in unnecessary rejections during quality inspection with increased cost. Table 3.6.1-1 and Table 3.6.2-1 should be used to aid the analyst in determining the proper Grade and Class and, thus, the appropriate zoning. The zoning of the casting should be clearly shown on the drawing. See Section 3.6.7 for a discussion of the inspection requirements.

Foundries will avoid DESIGNATED areas when locating parting planes for the mold, sprues, risers and vents. Flash is a defect that arises at the parting plane. It is a very thin surface that is exuded from the parting line between the dies. Even when removed it leaves a rough surface that could be the source of fatigue cracks. Sprues are the primary metal supply while risers are part of the gating system supplying metal to compensate for the shrinkage of the casting. When the part is complete, the excess material from sprues or risers is sawed or flame cut off leaving a rough surface and, potentially, a different grain structure. Both of these could affect the fatigue performance of the part. If necessary the surface can be smoothed, but this should be specified in a note on the drawing. A sample note is provided in Table 3.6.8-1.

3.6.4 Use of Casting Safety Factors

Often a casting factor is used in the calculation of margins of safety for castings. These casting factors are generally specified by program and can be waived if the casting design is tested to failure or the allowables for a given part are developed from specimens cut from that part. Customer / certification agencies approval is always required for the elimination of safety factors.

The design properties for castings were originally obtained from tests of separately cast bars. Comparison testing later disclosed that, as the result of the many variables in the range of acceptable chemistry, the casting process and heat treatment response, coupons cut from the actual castings exhibited mechanical properties lower than those obtained from separately cast bars. Coupons cut from risers and prolongations were somewhere in between. This difference in material properties is recognized in some specifications by requiring “the average ultimate tensile strength and average elongation of test specimens (4 to 10) cut from castings shall be not less than 75% and 25%, respectively, of the values specified for separately cast test bars.” This 75% is the origin of the 1.33 casting factor that is generally used.

There are two types of design properties: the properties from cast bars and the properties from coupons cut from heat treated castings. The design properties from cast bars are divided by a "Casting Factor" to take this difference into account. The casting factor may be eliminated by requiring that all the test specimens cut from heat treated castings meet or exceed the values called out on the drawings. If cutting coupons from the casting is impossible, static testing may be substituted for cutting coupons from finished castings. It is generally a good idea to specify the design properties on the drawing so that there is no confusion as to the strength of the part.

The margin of safety is written as

$$M.S._u = \frac{P_u}{C_u P} - 1$$

$$M.S._Y = \frac{P_y}{C_L P_L} - 1$$

where
C_u is the ultimate casting safety factor from Table 3.6.4-1 or as specified by the program
C_L is the limit casting safety factor from Table 3.6.4-1 or as specified by the program
P is the ultimate applied load (lb)
P_L is the limit applied load, generally P/1.5 (lb)
P_u is the ultimate allowable load (lb)
P_y is the allowable yield load (lbs)

Table 3.6.4-1 provides a summary of casting factors specified by various procuring agencies and specifications. In the absence of specific program guidance, an appropriate factor shall be selected from Table 3.6.4-1.

Table 3.6.4-1 Suggested Casting Factors

	Design Properties from Cast Bars			Design Properties from Coupons Cut from the Part (heat treated casting)	
				Air Force (Mil-A-21180, Joint Services Specification Guide)	
Factor	FAA – FAR 25	Mil-A-8860 (ASG)	SD-24, Mil-A-008860, ASFC Design Handbook, Joint Services Specification Guide	Navy and FAA (FAR 25)	AFSC Design Handbook (can be waived by procuring agency)
C_u	1.25	1.25	1.33	1.00	1.33
C_y	1.15	1.25	1.33	1.00	1.33

In addition to the use of casting factors of Table 3.6.4-1, many of the referenced specifications also required static testing of castings, particularly when the casting factor is 1.0. The analyst should be aware of what specification is governing the use of castings on their specific program to ensure that all the requirements are met.

Commercial aircraft, which are governed by FAR 25, also allow for an increased casting factor for Class 3 and 4 castings in lieu of performing various types of inspections. Table 3.6.4-2 provides a summary of these factors. Multiply the casting factor of Table 3.6.4-1 by the factor of Table 3.6.4-2; if joint analysis is performed an additional fitting factors shall not be included. The casting factor would need to be approved by the program Designated Engineering Representative (DER) and the FAA.

Table 3.6.4-2 Casting Factor Multiplication Factors For FAR 25 Aircraft For Reduced Inspection for Class 3 and 4 Castings

Casting Multiplication Factor, C	Visual	Magnetic, penetrant or other NDT	XRAY
$1.0 \le C \le 1.2$	100%	100%	100%
$1.2 < C < 1.6$	100%	100%	NO
$C \ge 1.6$	100%	NO	NO

Thus, to calculate a margin of safety for reduced inspection, the analyst would select the degree of inspection desired and the appropriate factor from Table 3.6.4-2. The margin would be calculated as follows:

$$M.S._u = \frac{P_u}{CC_u P} - 1$$

$$M.S._y = \frac{P_y}{CC_L P_L} - 1$$

where
C_u is the ultimate casting safety factor from Table 3.6.4-1 or as specified by the program
C_L is the limit casting safety factor from Table 3.6.4-1 or as specified by the program
C is the factor from Table 3.6.4-2 for the level of reduced inspection required
P is the ultimate applied load (lbs)
P_L is the limit applied load, generally P/1.5 (lbs)
P_u is the ultimate allowable load (lbs)
P_y is the allowable yield load (lbs)

3.6.5 Static Testing of Castings

All Class 1 and 2 castings, whose true margin of safety is calculated using only the casting factors of Table 3.6.4-1, must be static tested. FAA FAR 25 requires a total of three castings and the AFSC Design Handbook requires one casting from each lot shall be static tested to failure to demonstrate:

- The strength requirements at a load of $C_u(P)$,
- The deformation requirements at a load of $C_y(P_y)$
- Verification of the failure mode predicted by analysis.

It is also recommended that large, complex or unconventional castings whose strength cannot be adequately substantiated by stress analysis alone, be tested. One casting will be tested to failure unless there is more than one critical condition. In that case, one casting should be tested to failure for each of the critical conditions.

Additionally, in the interest of saving weight, the idea of waiving the casting factor by performing satisfactory testing is often suggested. Prior to making the decision to waive the casting factor for any casting design, the analyst should carefully consider how the part can be adequately tested to ultimate strength. Both cost and complexity should be considered:

- Can this part be reasonably tested in a test fixture or must the test be conducted as part of the full scale static test?
- Can all of the load components be properly introduced, including pressure and point loading?
- How many specimens must be tested?
- Where can the testing occur in the program schedule? How does this impact the production part if the design must be changed?

- Is there substantial weight benefit which justifies the cost and complexity of the testing?

Additionally, often customer or certification agency approval is required before waiving the casting factor even if testing is planned.

Once a decision to test has been made, the requirement should be designated on the drawing including the expected failure load for a successful test. In the static test, the casting shall be required to withstand a load of $C_u(P)$ without failure and C_y (P_y) at limit load without objectionable or detrimental permanent set. The test castings should be selected, tested and the data reduced, as follows.

If more than one condition is critical, two castings shall be tested for each condition. The casting(s) to be tested should be selected in the following manner:

- The static test casting shall be the least acceptable casting (established by radiographic standards) of the first lot of castings which pass all inspection requirements.
- The first casting (first article part), which is used as a fit, functional, and dimensional check, shall not be one of the static test castings.

For FAA licensed aircraft, if the first test substantiates a true margin of safety equal to or greater than 0.20, the static testing of the remaining castings is not required, provided that the final stress analysis demonstrates that the part has positive margins. If the test specimens reach a load of 150% of $C_u(P)$, structural damage or fatigue cracks should be introduced to the test specimens and the specimen tested to failure.

The testing and discussion of results should be documented in a stress report prepared by the cognizant stress engineer which contains all the pertinent information for each casting which has been static and fatigue tested. Detail design of the loading fixture as well as history of the test and tensile specimen test results shall be included. Tensile test specimens shall be cut from the failed casting as specified on the drawing and the “average material properties” of the tested part determined. The part should then be reanalyzed using the “average material properties” and the actual failure mode to verify the method of analysis. If the test load divided by the predicted load is less than one, redesign is required. The tensile test results may be incorporated with the inspection requirement tensile test data to produce design mechanical properties (B-basis values) for this casting to be used in the final stress analysis of this part. The report number for this report should be documented on both the casting drawing and the finished part drawing for future reference. A sample format for this note is given in Table 3.6.8-1.

3.6.6 Mechanical Properties

Material properties tend to be highest in the designated areas of the casting, due to the care taken by the foundry in those areas. To take advantage of this or if the casting is designated Class 1 or 2, “B” properties must be obtained for the “DESIGNATED” and “NON–DESIGNATED” areas of the specific casting. If this is not possible, generic allowables from the MMPDS can be used but, from an analytical standpoint, the benefit of the use of better property allowables in designated areas is lost and a casting factor shall be used. Sample testing of the finished, heat treated casting must ensure that the casting is meeting the minimum requirements of the specification to be able to use the MMPDS material properties.

If the finished casting is not tested to failure, tensile specimens shall be machined from the casting after heat treatment and tested for conformance to the required mechanical properties. These specimens, which are designed into periphery material on the part, are called prolongations and are used where the shape and material are made simultaneously to obtain certification properties of parts. The use of prolongations is to avoid having to destroy a part to obtain test coupons. The casting used for prolongation testing is selected in the same manner as a casting undergoing static testing would be selected, *i.e.*, it should be the least acceptable casting of each lot, which passes all inspection requirements. At least one specimen per lot is tested. All test results must meet or exceed the specification minimum properties. A sampling procedure should be instituted to ensure the additional data falls within the established requirements.

The configuration and location of tensile coupons shall be marked on the rough casting drawing. Casting cut-up article or prolongation specimens should represent maximum, typical and minimum thickness locations, for both the "DESIGNATED" and "NON–DESIGNATED" areas of the casting. All test coupons should have a gage length of 2 inches, 4D or 4.5√A, whichever is appropriate for the casting geometry. Prolongations should not be thinner than the minimum thickness of the quenched part.

3.6.7 Inspection of Castings

Table 3.6.7-1 describes the types of inspections available for castings. The casting specifications call out the types of inspections to be performed and the applicable class. Typically the lower the grade, the fewer the inspection requirements levied, and thus the larger the allowable defect size and the larger the number of acceptable defects. The types of inspections available are visual, magnetic particle for ferro-magnetic alloys and dye-penetrant inspection for other alloys, and radiographic or XRAY inspection. The magnetic particle or dye-penetrant inspection is used to reveal defects on or near the surface and is to be performed twice: in the as-cast condition and after all machining and heat treating operations.

Ultrasonic inspection, often used in other product forms to detect flaws, can be difficult to use with cast products. The surface roughness of castings and their dimensional variations scatter the sound pulse and make detection of discontinuities difficult. In addition, the grain size variations can cause further scattering of the sound waves.

Reduced inspection reduces the cost of the casting; however, it is incumbent upon the analyst to ensure the inspection level is consistent with the criticality of the part. The following table outlines the recommended inspections for the different classes of casting as listed in AMS2175, Reference 3-32. However, these are recommendations and drawing requirements or specific casting specifications may supersede these requirements. For large parts, selected XRAY may be performed only in critical areas, no matter what the class or the requirement. Dye penetrant inspection may be waived on a non-critical casting. The analyst should work with the materials specialist and designer to ensure the appropriate inspection is selected and called out on the drawing if different from the casting specification.

Table 3.6.7-1 Inspection Requirements for Castings

Type of Inspection	Class 1	Class 2	Class 3	Class 4	Requirements[19]
Visual Inspection	100% 100%	100% 100%	100% 100%	100% 100%	Part Lot
Magnetic Inspection or Penetrant Inspection	100% 100%	100% 100%	100% 100%	100% Sample	Part Lot
X-RAY	100% 100%	100% Sample	100% Sample	Not req'd	Part Lot

3.6.8 Typical Drawing Notes

The stress engineer shall indicate the Class and Grades of the casting. The design group shall put the final markings on the drawing in a manner and format consistent with the design manual. The rough casting drawings shall contain general notes which state the Class and Grades of the casting.

<u>Sample Notes for Class 1 Structures – Grade A (DESIGNATED)/Grade B (NON-DESIGNATED)</u>

Only certain areas of the casting are considered to be critical. These "DESIGNATED' areas, normally <10-15% of

[19] Part indicates how much of the part is examined for the given inspection type. Lot indicates how many parts within a lot of material are inspected.

the total surface area of the casting, shall be circled and a flag note placed in the region. The flag note shall be tied in with the following general notes on the rough casting drawing and the finished part drawing.

5. (flag note)	Grade A area – Minimum F_{tu} = XX.X ksi; minimum F_{ty} = YY.Y ksi. Class 1 casting per Mil-X-XXXX – minimum 6% elongation in 4D required.
4. (flag note)	Grade B casting – Minimum F_{tu} = XX.X ksi; minimum F_{ty} = YY.Y ksi. Class 1 casting per Mil-X-XXXX – minimum 5% elongation in 4D required.
3.	Class 1 Structure
2.	Tensile specimens shall be cut from the casting after heat treatment as indicated on the drawing and all coupons shall exceed the minimum values specified in notes 4 and 5.
1.	List the casting and material specifications

<u>Sample Notes for Class 2 Structures – Grade B (DESIGNATED)/Grade C (NON-DESIGNATED)</u>

Only certain areas of the casting are considered to be critical. These "DESIGNATED' areas, normally <10-15% of the total surface area of the casting, shall be circled and a flag note placed in the region. The flag note shall be tied in with the following general notes on the rough casting drawing and the finished part drawing.

5. (flag note)	Grade B area – Minimum F_{tu} = XX.X ksi; minimum F_{ty} = YY.Y ksi. Class 2 casting per Mil-X-XXXX – minimum 6% elongation in 4D required.
4. (flag note)	Grade C casting – Minimum F_{tu} = XX.X ksi; minimum F_{ty} = YY.Y ksi. Class 2 casting per Mil-X-XXXX – minimum 5% elongation in 4D required.
3.	Class 2 Structure
2.	Tensile specimens shall be cut from the casting after heat treatment as indicated on the drawing and all coupons shall exceed the minimum values specified in notes 4 and 5.
1.	List the casting and material specifications

<u>Sample Notes for Class 3 Structures – Grade C (DESIGNATED)/Grade D (NON-DESIGNATED)</u>

Only certain areas of the casting are considered to be critical. These "DESIGNATED" areas, normally <15% of the total casting area, shall be circled and a flag note placed in the region. This flag note shall be tied in with the following general notes on the rough casting drawing and the finished part drawing:

5. (flag note)	Grade C area – Minimum F_{tu} = XX.X ksi; minimum F_{ty} = YY.Y ksi. Class 3 casting per Mil-X-XXXX – minimum 5% elongation in 4D required.
4. (flag note)	Grade D casting – Minimum F_{tu} = XX.X ksi; minimum F_{ty} = YY.Y ksi. Class 3 casting per Mil-X-XXXX – minimum 3% elongation in 4D required.
3.	Class 3 Structure
2.	Tensile specimens shall be cut from the casting after heat treatment as indicated on the drawing and all coupons shall exceed the minimum values specified in notes 4 and 5.
1.	List the casting and material specifications

<u>Sample Notes for Class 4 Structures – Grade D</u>

No areas of the casting are considered to be critical; therefore, the following general notes shall appear on the rough casting drawing and the finished part drawing:

4.	Grade D casting – Minimum F_{tu} = XX.X ksi; minimum F_{ty} = YY.Y ksi. Class 4 casting per Mil-X-XXXX – minimum 3% elongation in 4D required.
3.	Class 4 Structure
2.	Tensile specimens shall be cut from the casting after heat treatment as indicated on the drawing and all coupons shall exceed the minimum values specified in notes 4.
1.	List the casting and material specifications

Other notes may also apply. The table below explains the purpose of the note and provides a sample.

Table 3.6.8-1 Miscellaneous Casting Drawing Notes

Drawing Note Purpose	Sample Note
Document existence of static and/or fatigue test, setup, results and post test analysis report	Physical Test per Lockheed Martin Report XXX.
The rough casting drawing shall specify what repair welding is allowed, if any, in what areas of the casting prior to solution treatment and aging; and including a drawing note as in the following example	Repair welding in the Grade C and D areas per Lockheed Martin Process specification _____ is permissible.
Non-cast surfaces shall not occur in "Designated" areas of the casting. Surface roughness from removal of gates, risers, tie–bars, chills, fillets, or any other machine finishing shall not exceed the finish of the as–cast surface. Add the following note to the finished drawing:	Surface roughness for non-cast surfaces shall not exceed XXX Ra.

3.7 Mechanical Fasteners

Structural fasteners may be defined as the elements which attach one part to another for the purpose of making the two parts act together as one for stiffness and for the transfer of loads. Because the fastener strength is a function of fit, fastener and nut or formed tail, the stress engineer must make sure the application matches the conditions for which the fastener was tested. To ensure the fastener shear and tension allowables are applicable, the fastener must be installed with the specified fit and assembled with the correct nut or collar. If the fastener includes a formed tail then the tail must be bucked or formed to the specification size.

Fastener allowables are provided in the IDAT Fastener Database. These allowables have been developed based on LM Aero approved methods which have been correlated to fastener testing and include values for fastener shear, tension and bending. This database should be the primary source of fastener allowables data for joint design. For fasteners not found in the fastener database or to add new fasteners to the database, contact 6E5 Structures Core. The discussion below provides some details on how these allowables are defined.

Fastener shear strength is generally a function of the minimum shank diameter of the fastener and the fastener material shear strength; however, there are occasionally fastener features such as grooves or slots which can limit the shear capability and result in reduced allowables. The fastener shear values in the IDAT Fastener database reflect any required reductions.

Tension allowables published in the IDAT fastener database are based on a combination of test data and calculations. Occasionally the results of these tests indicate the allowable calculated as described below may be unconservative due to a feature on the fastener, nut or tail, or head. In the event that in-house testing of a fastener indicate that the calculated value is unconservative, the allowable presented in the IDAT Fastener Database is adjusted appropriately based on the empirical data. Allowables for fasteners with similar features may also be adjusted.

- Tension allowables found on fastener data sheets published by the Aerospace Industries Association, vendor or program fastener specification sheets and in many military specifications are based on the maximum pitch diameter. The pitch diameter is the average of the major and minor diameters where the major diameter is the diameter of an imaginary cylinder which bounds the crests of the threads. These allowables are acceptable for use in shear dominated joints, redundant structure and non-critical tension applications. Based on a study performed in support of Mil-Hdbk-5, they are the approximate equivalent of a B-Basis allowable.
- Tension allowables for fasteners in Reference 3-4 are based on the maximum minor diameter of the fastener. The minor diameter is the diameter of the cylinder of the fastener if all the threads were removed. It is also called the root or thread diameter. These are used for critical tension applications and, again based on the study in support

of Mil-Hdbk-5, are the approximate equivalent of A-Basis allowables. A table of these diameters for Mil-S-8879 threads can be found in Section 5.5.1.

Fastener bending moment allowables are calculated based on several considerations. FZM 9379, Reference 3-33, derives a method to calculate moment allowables for most of the fasteners used by Lockheed Martin to be used with the bolt bending analysis methods described in Section 5.2. These allowables have been correlated to lap shear tests and provide a reasonable result. The fastener bending allowables which are a part of the fastener database within the IDAT program have been calculated in a manner consistent with FZM 9379.

All published fastener allowables apply only to joints that are not degraded by corrosion and which have been properly torqued. Appropriate corrosion protection shall be specified on the drawing to ensure the joint strength remains unimpaired during the life of the vehicle in the environment in which the vehicle will operate.

3.8 Structural Adhesives

Refer to Program-specific and customer-generated guidance; and LMAS Stress Memo 133, Reference 3-1.