Chapter 2. Failure Assessment of Brazed Structures

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Abstract: Despite the great advances in analytical methods available to structural engineers, designers of brazed structures have great difficulties in addressing fundamental questions related to the load-carrying capabilities of brazed assemblies. In this chapter we will review why such common engineering tools as Finite Element Analysis (FEA) as well as many well-established theories (Tresca, von Mises, Highest Principal Stress, etc) don't work well for the brazed joints. This chapter will show how the classic

approach of using interaction equations and the less known Coulomb-Mohr failure criterion can be employed to estimate Margins of Safety (MS) in brazed joints

Key words: brazed joints; margins of safety; failure assessment diagram; interaction equations; Coulomb-Mohr failure criterion.

2.1 Introduction

It is hard to overestimate an importance of brazing in modern manufacturing processes. Sophisticated designs of structures and mechanisms used in airspace, aircraft, automotive, power and medical industries quite often expect various brazed joints to perform under complicated multi-axial loading conditions.

Despite great advances in brazing technology and applications, reliability of brazed joints remains to be one of the least developed fields of structural analysis. Mechanical, welded or adhesively bonded joints in metallic and composite structures are routinely assessed for their load-carrying capabilities in accordance with widely accepted engineering analysis techniques and failure criteria (Blodgett, 1963; Bruhn, 1973; Astronautic Structures manual, 1973; Hart-Smith, 1973; Shingley et al, 1989; Tong et al, 1999). An effort to find any information on engineering practice of estimating or predicting load carrying capability of brazed, however, produces almost no results.

Consequently, there is a need for a simple engineering methodology that would enable designers and structural analysts to evaluate strength margins of the brazed joints exposed to combined shear and normal stresses.

This chapter reviews the challenges of using common failure criteria in predicting failure of the brazed joints and offers an alternative approach based on developing failure assessment diagrams (FAD). First step in constructing FADs is to identify or develop brazed joint failure criteria. It would be highly desirable for such criteria to satisfy the following conditions:

- criteria should be applicable to any brazed joint geometry
- it should be fairly conservative to account for the many uncertainties associated with the brazing process, properties and analysis of the joints.
- it should be sufficiently simple and easy to use so designers and structural engineers find it helpful for practical applications.
- it should be based on clearly defined properties of the brazed joints that can be determined in a fairly straightforward manner.

For now, this Chapter is limited only to static loading of the brazed assemblies. As our knowledge expands, future revisions and/or updates of this chapter may address the brazed joints subjected to dynamic loading.

2.2 Applicability of Common Failure Criteria to Analysis of Brazed Joints

2.2.1 Maximum Normal Stress

This criterion predicts failure when the largest normal principal stress reaches the uniaxial tensile strength of the material (Dieter, 1976; Dowling, 1993). This criterion is commonly used in predicting failure of brittle materials. It is perhaps the simplest failure criterion around and can be expressed as:

[1.1]

$\sigma_1 = \sigma_o$,

where σ_1 is maximum normal or, according to a convention, 1st principal stress and σ_o is the yield tensile strength obtained from tensile test of the standard tensile test specimen (ASTM, 2009). It has to be pointed out that in most structural applications yielding is considered to be a form of failure. σ_o is calculated as $P/_A$, where, P is the yield load observed during the tensile test and A is the initial cross sectional area of the test specimen. Engineering community defines yield load as a load causing 0.2% strain in uniaxial tension test. As one can see, σ_o is an average stress – an important point in our upcoming discussion. σ_o is commonly used in structural design as a mechanical property of the material (MMPDS-02, 2005) or tensile yield strength allowable. Value of σ_1 is calculated, typically, using finite element analysis (FEA) performed on the entire structure or its component.

An attempt to use this criterion for failure assessment of the brazed joints leads to several complications. First of all, the "uniaxial tensile strength of the material" is not defined when it comes to the brazed joints. For homogeneous metallic material, uniaxial tensile strength is a mechanical property of that material, determined, as mentioned above, from the standard tensile test, such as, for example, described in (ASTM, 2009). Uniaxial tensile test of the butt brazed tensile specimen determines the tensile strength of the joint, not the strength of a specific material – brazing filler metal or adjacent base metal. Obviously, properties of the filler metal and the base metal do contribute to the overall strength of the brazed joint. It is a well established fact that the tensile strength of the butt brazed joints exceeds, by far, the tensile strength of the filler metal tested in

bulk form (Brazing Handbook, 2007; Rosen *et al*, 1993). Second problem with this criterion is when it is applied to ductile and lap shear brazed joints. Such joints undergo relatively large plastic deformation prior to failure, which is quite different from the brittle behavior. Consequently, if selected, maximum normal stress criterion may be applicable only to a case of uniaxially loaded butt brazed joints where filler metal constraint results a highly triaxial stress state causing the braze joint to behave in quasi-brittle manner.

2.2.2 Maximum Shear and Octahedral Stress

These two criteria are very similar. Maximum shear stress or Tresca criterion predicts failure, manifested by yielding, when maximum shear stress τ_{max}on any plane reaches certain critical value τ_o, as expressed in equation below:

$$\tau_{max} = \tau_o \,, \qquad [2.2]$$

where, again, τ_o is the shear yield strength of the material, i.e. a material mechanical property. Determination of τ_o is not as straight forward as tensile allowable. In fact, only a thin wall tube subjected to a pure torsion renders a direct measurement of τ_o. But such type of tests and their results are not readily available. A more common approach is to perform a uniaxial tension test and calculate τ_o from σ_o using the relationship between maximum shear and principal normal stresses. Equation [2.2] can be written as:

$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2} = \tau_o \,, \qquad [2.3]$$

where σ_1 and σ_3 and first (maximum) and third (minimum) normal principal stresses. In uniaxial tension $\sigma_3 = 0$ and $\sigma_1 = \sigma_o$. Consequently,

$$\tau_{max} = \frac{\sigma_o}{2} = \tau_o \ \ or \ \ \tau_o = \frac{\sigma_o}{2}, \quad [2.4]$$

As we can see, according to the maximum shear stress theory, maximum value of τ_o is 0.5 of σ_o.

Maximum octahedral (von Mises) or maximum distortion energy criterion predicts failure when shear stress τ_h in octahedral plane reaches critical value τ_{ho} (Dowling, 1993), or:

$$\tau_h = \tau_{ho}, \quad [2.5]$$

where τ_{ho} is also a material property that now represents a critical value of shear stress on octahedral plane that causes yielding. The shear stress on octahedral plane can be expressed in terms of principal stresses as (Dowling, 1993):

$$\tau_h = \frac{1}{3}\sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2} \quad [2.6]$$

Again, applying von Mises criterion to uniaxial tension test, $\sigma_1 = \sigma_o$ and $\sigma_2 = \sigma_3 = 0$, we obtain:

$$\tau_h = \frac{1}{3}\sqrt{(\sigma_o)^2 + (\sigma_o)^2} = \tau_{ho} \quad [2.7]$$

From equation [2.7] the value of τ_{ho} can be also obtained from the uniaxial tension test as:

$$\tau_{ho} = \frac{\sqrt{2}}{3}\sigma_o \quad [2.8]$$

Consequently, in accordance with von Mises criterion, $\tau_{ho} = 0.47 \cdot \sigma_o$ compared to 0.5 in Tresca theory.

There are several problems with using these criteria for predicting failure in brazed joints.

Both Tresca and von Mises criteria are essentially yielding criteria that are typically used to predict an onset of yielding in homogeneous or isotropic ductile metals [Dieter, 1976; Dowling, 1993). Brazed joints, however, are quite far from isotropic. Physical and mechanical properties within the brazed joins undergo significant changes over very short distances as we transverse the brazed joint form one adjacent side of the base metal into another. Situation becomes even more complicated when drastically dissimilar materials form a brazed joint. Furthermore, a concept of brazed joint yielding is not well defined. Tensile tests of the butt brazed specimens as well as the lap shear pull tests show practically no difference in stress – strain behavior between the brazed and solid specimens up to the point of failure of the brazed joints (Flom, 2011; Spingarn *et al*, 1983; Flom *et al*, 2004), as shown in Fig.2.1-2.3.

Recall that successful failure criteria should be applicable to any brazed joint geometry. When a butt brazed joint is tested in uniaxial tension, a mechanical constraint provided by the base metal develops a triaxial tensile stress state within the braze layer. Even in such ductile filler metal as pure silver a level of constraint is so high that hydrostatic stress is very close to the axial one, which means that the values of principal stresses are very similar (Rosen *et al*, 1993). In pure hydrostatic stress state (all principal stress are equal), shear and von Mises stresses are zero and failure occurs without plastic

deformation. Similarly, in butt brazed joint under uniaxial tension, shear or von Mises stresses are quite low. Consequently, these stresses would not be good criteria in brazed joints with high mechanical constraint and would result in under-prediction of failure.

Let's consider lap shear brazed joints in which both base and filler metals are ductile. It would appear that shear or distortion energy criteria would be much better suited for this type of joints, which are typically undergoing large plastic deformation prior to failure. However, due to non-uniform distribution of shear stresses within the lap shear joints, the values of the shear and von Mises stresses could be quite high, particular at the joint ends (Flom *et al*, 2004), as shown in Fig.2.4. Experimental results indicate that such values could exceed the strength of the filler metal by 2 or 3 times. If one attempts to correlate the highest von Mises stress values with the event of failure in lap shear joints, such values are going to be much greater than those observed in butt-brazed specimens, as shown in Fig.2.5. Consequently, von Mises stress is not a very good choice for failure criterion due to its great variation with brazed joint geometry. In addition, a major difficulty in estimating von Mises stress in the brazed joint is a reliance on our knowledge of the elastic modulus and the yield strength properties of the braze layer within the brazed joint. Without such knowledge, the use of Finite Element Analysis (FEA) in calculating von Mises stress within the filer metal layer is very limited, if not impossible.

2.2.3 Interaction Equations

Interaction equations were introduced to predict failures in structures subjected to combined loading conditions (Shanley *et al*, 1937). These equations incorporate both maximum shear and normal stresses and are expressed in terms of the stress ratios. In their simplest generic form interaction equations can be written as (Peery *et al*, 1982) :

$$R_\sigma^m + R_\tau^n = 1 \,, \qquad [2.8]$$

where R_σ and R_τ are normal and shear stress ratios, respectively, and the exponents $m,$ n are determined experimentally. Typically, experimental results are plotted as shown in Fig.2.6. Stress ratios are determined by calculating maximum normal and maximum shear at some specific point in the structure and dividing them by their respective tensile and shear allowables, such as:

$$R_\sigma = \frac{\sigma_1}{\sigma_o} \quad and \quad R_\tau = \frac{\tau_{max}}{\tau_o} \qquad [2.9]$$

Over the years, interaction equations have evolved into comprehensive and quite effective relationships verified experimentally for different structural shapes and loading conditions, such as tension, compression, bending, shear, torsion (Blodgett, 1963; Engineering Stress Memo Manual, 2008). Before FEA became a standard tool in structural analysis, these interaction equations were used very successfully to predict failures in astronautic and aircraft metallic structures (Astronautic Structures Manual, 1975; Bruhn, 1973; Sarafin, 1998). Examples of some of such equations are shown in the Table 2.1 below (Astronautic Structures Manual, 1975)

Table 2.1. Some of Well-known Interaction Equations

LOADING COMBINATIONS	INTERACTION EQUATIONS	MARGINS OF SAFETY (MS)
Normal and Bending Stresses	$R_\sigma + R_b = 1$	$\frac{1}{R_\sigma + R_b} - 1$
Normal and Shear Stresses	$R_\sigma^2 + R_\tau^2 = 1$	$\frac{1}{\sqrt{R_\sigma^2 + R_\tau^2}} - 1$
Bending, Torsion and Compressions	$R_b^2 + R_\tau^2 = (1 - R_c)^2$	$\frac{1}{R_c + \sqrt{R_\sigma^2 + R_\tau^2}} - 1$
Bending and Torsion	$R_b + R_\tau = 1$	$\frac{1}{R_b + R_\tau} - 1$

Fairly comprehensive compilation of interaction equations is provided in (Engineering Stress Memo Manual, 2008). In addition to their great practical value, interaction equations have an interesting feature that may be quite useful for brazed joints discussion. There is no requirement that stresses used in interaction equations have to act on the same planes. Interaction equations are well suited for structural analysis of homogeneous metallic materials. It would be interesting to investigate their suitability for predicting failures in the brazed joints. Preliminary results indicate that interaction equations can be used for a conservative, lower bound estimate of the failure conditions in several base metal / filler metal combinations (Flom, 2011; Flom *et al*, 2011).

2.2.4 Coulomb-Mohr Failure Criterion

This criterion states that fracture takes place in a given plane when a critical combination of normal and shear stresses has occurred (Dowling, 1993). This is a very

interesting criterion and definitely worth considering when discussing the brazed joints that fail within the braze plane. Coulomb-Mohr criterion has a very simple form that assumes a linear relationship between normal and shear stresses:

$$\tau + \mu\sigma = c \qquad [2.9]$$

In this expression, μ and c are material-specific parameters. Later in this chapter we will spend more time discussing this criterion. A modified form of the Coulomb-Mohr criterion, proposed by Christensen (2004), shows better correlation with experimental results for homogeneous materials. It offers a more general form of failure condition and considers a combined effect of hydrostatic (dilatation) and distortion (von Mises) components of stress. However, its practical use in analysis of the brazed joints is rather limited, since it requires a detailed FEA analysis of the brazed joints which, in turn, relies on the knowledge of mechanical properties of the braze layer.

2.2.5 Fitness-For-Service (FFS) Approach

This approach was first introduced in welding industry and now is widely accepted in analysis of the critical welded structures containing discontinuities (Dowling *et al*, 1975; Webster *et al*, 2000; Gordon, 1993; API, 2007). The brand new or existing welded structure is evaluated on the basis whether it can safely operate under given loading and environmental conditions. Using a certain amount of mechanical testing and analytical techniques, a safe-to-operate zone is established for a particular weldment containing flaws. Failure Assessment Diagrams (FAD) are constructed to define such safe zones. In order to construct FADs, welding industry has adopted a specific failure criterion based on static strength and fracture mechanics characteristics of the weld

joint containing flaws. An example of such FAD with respect to the weld joint is shown in Fig.2.7.

FADs are plotted in terms of the fracture toughness and plastic collapse stress ratios (Gordon, 1993). The vertical axis represents ratios of $R_K = K_1/K_{mat}$ and horizontal axis represents ratios of $R_\sigma = \sigma/\sigma_{pc}$, where K_1 is the stress intensity at existing flaw due to applied load, K_{mat} is a fracture toughness of the material, σ is applied stress and σ_{pc} is a plastic collapse stress for a given welded component. An attempt to apply this fracture toughness and plastic collapse - based FAD to the brazed joints is described by Leinenbach *et al* (2007).

There are several problems of using fracture toughness - and plastic collapse stress – based criterion for predicting failures in the brazed joints. First, a concept of brazed joint fracture toughness is not well defined. It is not clear what fracture toughness of the material means in case of the brazed joint consisting of the two adjoining base metals (similar or dissimilar) and a thin layer of the filler metal, metallurgically different from the base metals. Consider the following argument. Recall, that for a crack to grow, energy available for crack extension should exceed the crack resistance which is the energy requires to create new crack surfaces. Each material has its own surface energy – it is a physical property. If crack is propagated through the filler metal, the energy to create new crack surfaces is different, than the energy required for creation of new crack surfaces in the base metal. If a crack chooses to propagate through the base metal/filler metal interface, the surface energy again will be different. And, finally if the crack meanders through the base, filler and interface regions of the brazed joint, than the

energy of newly created surfaces will be even harder to define. If the fracture toughness of the brazed joint does not have a well established definition, measurements of the brazed joint fracture toughness is even less clear, particular when it comes to a discussion of validity of the of the fracture toughness testing. Similar problems arise when attempting to define and/or measure plastic collapse stress of the brazed joints. One can see now how problematic, particular from the practical sense, it would be to try to incorporate fracture toughness and plastic collapse stress into failure criteria of the brazed joints.

2.3 Alternative Approach for Developing Brazed Joints FADs

Let's consider Coulomb-Mohr criterion and see if it can be used to predict failures in the brazed joints while satisfying as many conditions listed in the introduction as possible. To begin, we are going to treat the brazed joint as a system, rather than trying to study separate regions of the joint which are influenced by complex metallurgical reactions of the brazing process and, as a consequence, having significantly different materials properties. The latter had been more of a traditional approach taken by many investigators attempting to study mechanical properties of the brazed joints [Flom *et al*, 2004; Rosen *et al*, 1980; Tolle *et al*, 1995; Wen-Chun Jiang *et al*, 2008). As it was briefly mentioned earlier in this chapter, mechanical properties of the braze layer are not readily available or can be determined through conventional methods. An evaluation of mechanical properties of brazes is a rather challenging endeavor. A very thin cast layer of filler metal consists most often of multiple phases and is affected by the braze gap size, dilution from the base metal as well as by possible formation of intermetallic compounds located at the filler metal / base metal interfaces. Even the properties of a

braze layer consisting of a single phase pure metal may be significantly different from mechanical properties of identical wrought pure metal tested in the bulk form (Rosen, 1980), as shown, for example, in Figure 2.8. A presence of additional phases and eutectics makes the situation even worse. For example, it is a well know fact that joints brazed with Ni-based filler metals, such as AWS BNi2, could develop a variety of microstructures and properties depending on joint geometry and the brazing cycle (Brazing Handbook, 2005; Lugscheider *et al*, 1983). Consequently, trying to predict mechanical properties of the braze layer either by testing some bulk form of the filler metal or using some software specialized in calculating of the material properties of a given alloy (Wen-Chun Jiang *et al*, 2008), may produce unreliable results. Other attempts to measure properties of the braze layer were based on testing miniature test specimens containing braze (Leinenbach *et al*, 2007). This approach may also present some problems since the aspect ratios of such brazed joints are significantly higher than the typical structural joints. Typical ratios of the brazed gaps to the joint size (diameter or width) are less than 0.005. Thus, the level of constrain within the braze layer and triaxiality of the stress state is very different from the actual brazed joints, which, in turn may result in unrealistic ductility and stress-strain response of such miniature specimens.

Consequently, rather than trying to predict the material properties of the braze layer, we will focus on the properties of the brazed joint as a whole, or a system. Also, this will be more in line with the FFS approach.

Now, as we ready to apply Coulomb-Mohr criterion to the brazed joints, we can think of the constants μ and c , see Eq.[2.9], as representing the properties of the system, not

the material properties of the braze layer. Since our goal is to develop braze joint failure criterion applicable to any brazed joint geometries, it is constructive to start with the two most fundamental ones: a lap and a butt-brazed joints.

When the brazed joint is subjected to a pure shear loading conditions, normal stress acting on the braze plane is zero. The lap shear brazed joints tested under uniaxial load do not meet, strictly speaking, the conditions of pure shear. Consequently, the results are reported in terms of an average shear stress. In this case, a non-uniform distribution of shear stresses within the lap and the peel effects at the joint ends are ignored (AWS C3.2, 2008). Therefore, from a practical sense, the presence of normal stresses in standard lap shear test specimen is also ignored. If we let $\sigma = 0$, the Coulomb-Mohr expression for the lap joint can be written as:

$$\tau = c \qquad [2.10]$$

Now constant c can be interpreted as simply average shear strength of the lap joint, as written below:

$$\tau = c = \tau_o \qquad [2.11]$$

where τ_o is the shear strength or allowable of the lap shear brazed joint. It is interesting to note, that for the lap shear brazed joints which represent the most ductile geometric configuration, eq. [2.11], takes a form of the Tresca criterion discussed in section 2.2.2 of this chapter. There are various types of lap shear brazed joint used in the brazing industry to test specimens. Several of them are shown in Fig. 2.9. Some of these joints may be a little closer to pure shear then the others and the question is which lap shear

type is more suitable for measuring shear allowable. A detailed discussion on this subject is provided by Peaslee, (1976). It turns out that a single leap shear specimen is quite adequate for measuring average shear strength of the brazed joints and any attempts to develop braze specimen or test fixtures to eliminate or minimize the peel effects as well as the bending of the specimen during testing are of little or no consequence. Apparently, the behavior of the lap shear – type joints is predominantly controlled by shear which causes extensive plastic deformation and the influence of normal components of stresses is typically obscured by the experimental scatter when testing any type of the brazed specimens.

On the other hand, when butt-brazed joint is tested in tension under uniaxial loading condition, the shear stress within the brazed plane is essentially zero and can be ignored in the practical sense. Therefore, assuming $\tau = 0$ and substituting c = τ_o , Coulomb-Mohr criterion for the butt-brazed joint can be written as:

$$\mu \cdot \sigma = \tau_o \; or \; \sigma = \frac{\tau_o}{\mu} \qquad [2.12]$$

When testing standard butt-brazed test specimens to failure, we obtain their ultimate tensile strength (AWS, 2008) or tensile allowable σ_o . It is important to keep in mind that the value of σ_o is constant for a specific base metal/filler metal combination as long as it is determined from testing the standard butt-brazed test specimens. This is no different from testing material properties of any metallic materials. Consequently, butt-brazed or any other brazed joint in which the braze plane is subjected to predominantly normal stresses, is going to fail when the maximum normal stress $\sigma = \sigma_o$. For such condition, equation (12), can be expressed as:

$$\sigma = \frac{\tau_o}{\mu} = \sigma_o \;\; or \;\; \mu = \frac{\tau_o}{\sigma_o} \qquad [2.13]$$

Now we can define constant μ as a ratio of the brazed joint shear and tensile allowables. It is important to remember that τ_o and σ_o are not the properties of a specific material, but the properties of a collection of materials, forming the brazed joints or systems subjected to their two most extreme conditions: 1) butt-brazed joint under uniaxial load which results in the highest degree of constraint and 2) the lap-shear joint also subjected to uniaxial load, which, in turn, results in the most ductile behavior. Substituting μ and C in equation [2.13] and dividing by τ_o, Coulomb-Mohr criterion for the brazed joints can be written as:

$$\tau + \frac{\tau_o}{\sigma_o} \cdot \sigma = \tau_o \;\; or \;\; \frac{\tau}{\tau_o} + \frac{\sigma}{\sigma_o} = 1 \qquad [2.14]$$

As one can see, for the brazed joints dominated by shear stresses, i.e. $\sigma = 0$, equation [2.14] transforms simply into failure criterion of lap shear joint, such as $\tau = \tau_o$; Likewise, for the brazed joints dominated by normal stresses ($\tau = 0$) , such as, for example, butt-brazed joints, eq. [2.14] becomes simply the failure criterion of the butt-brazed joint subjected to uniaxial tensile load: $\sigma = \sigma_o$.

The same equation, using relationships [2.9], can be written in terms of stress ratios R_τ and R_σ:

$$R_\sigma + R_\tau = 1 \qquad [2.15]$$

As one can see, eq. [2.15] is identical to interaction equation [2.8] when exponents m and n equal to 1. Another words, equation [2.15] represents perhaps one of the most

conservative forms of interaction equations. Graphically, this expression can be plotted as a straight line shown in Fig. 2.6.

A number of the brazed joint systems subjected to multiaxial loading were tested to see if the equation [2.15] can be used to conservatively predict failure of various brazed joint geometries (Spingarn et al, 1983, Flom, 2011; Flom, 2011 *et al*, Flom *et al*, 2009). The base/filler metal combinations used in these studies are listed in Table 2

Table 2.2 Base and Filler Metal Combinations Tested in Previous Studies

Base Metal	Filler Metal	Test Temperature	Source/Year
Incoloy 800	AWS BNi-8	650°C	Spingarn et al, 1983
Albemet 162	AWS BAlSi-4	RT	Flom et al, 2009
304 Stainless Steel	AWS BAg8	RT	Flom, 2011
304 Stainless Steel	Pure silver	RT	Flom, 2011
Ti-6Al-4V	Al 1100	RT	Flom et al, 2011

For each base metal / filler metal family of brazed joints, standard lap shear and butt brazed tensile specimens were tested to determine tensile σ_o and shear τ_o strengths (allowables) of the respective brazed joints. In addition to standard braze test specimens, more complex (verification) test specimens, designed to create combined tensile and shear stresses in the brazed joints, were fabricated and tested using identical braze processes and test temperatures. For a detailed description of the verification specimens, the readers are referred to the references listed in Table 2.2. For convenience, all experimental results, expressed in terms of the stress ratios are plotted on the same graph shown in Fig. 2.10. As one can see, FAD based on equation [2.15] represents a very conservative lower bound estimate of failure condition in the brazed joints. It is a well known fact that brazing process variables can greatly affect the

strength of the brazed joints (Brazing Handbook, 2007). Our ability to account for all process variables and their influence on properties of the brazed joints is rather limited and accompanied with considerable uncertainty. Therefore, in an attempt to address such uncertainties and increase the level of conservatism, the following procedure was used for data analysis and graphing the plots shown in Fig.2.10:

- First, using global model FEA of the brazed specimens, maximum normal and maximum shear stresses were calculated in the finite elements located in the brazed plane of the brazed joints. Maximum normal and maximum shear stresses were all acted on the braze plane.
- Second, it was assumed that maximum normal and maximum shear stresses were located in the same finite element within the braze plane even though their actual locations could be different.

Two interesting observations can be made when examining experimental results plotted in Fig. 2.10. One is that all data points representing specific joint geometries are aligned along the same trend lines, as emphasized in Fig. 2.11. The second observation is that the stress ratios representing failure of the brazed joints fall on the same trend lines regardless of what combination of base and/or filler metal are used to fabricate brazed joints, or even their test temperature. These observations can be explained with the help of the Mohr circles construction using scarf joints, as an example, as shown in Fig. 2.12. However, this explanation is not sufficient to rationalize behavior of the T-type titanium specimens also showing similar trend, see Figs.2.10 and 2.11. As of the time of this writing, no rigorous explanation of the observed trend line for T-specimens have been developed. A well-pronounced data dispersion or scatter observed on the graphs,

is, most likely, related to the inherent scatter in test results associated with testing of the brazed specimens, even the standard ones (AWS, 1963). For example, the results for lap shear and butt-brazed specimens, presented in Fig. 2.10 as the data points located along each axis, also show considerable scatter. The scatter is most likely a result of the variability in internal quality of the brazed joints. Consequently, due to propagation of scatter or error, it is quite reasonable to expect even larger scatter in testing more complicated brazed specimens. The observed trend lines could provide an important tool useful during preliminary design of the brazed structures. It can help in estimating brazed joints margins of safety and predicting their failures. An example of using such tool will be given later in this chapter.

These findings lead to the following simple engineering methodology of developing and using Coulomb-Mohr – based FADs:

1. determine tensile and shear allowables by testing standard brazed test specimens (AWS, 2008) and construct FAD line;
2. using FEA determine maximum normal and max shear stresses acting on the braze plane in the actual structural brazed joint subjected to a small arbitrary load. This load should act on the joint in the same manner as the design load. These stresses will define the coordinates of the point needed to construct the trend line.
3. connect the origin with the point determined in 2) and construct a trend or as we call it braze joint line (see Fig.2.13);
4. an intercept of FAD line and the braze joint line corresponds to a zero safety margin condition or a very conservative, lower bound failure condition.

5. fabricate a small number (two or three) of identical or “realistic” specimens representing actual brazed joint geometry and test them to failure under identical loading conditions. This step will help to determine the actual values of maximum normal and maximum shear stresses causing failure. Combination of these failure stresses will define the failure point that can be plotted to validate the brazed joint line. If the actual level of stresses causing failure is of no consequence, this step can be omitted

Now we can demonstrate how beneficial the brazed joint lines can be in designing brazed assembly. Suppose such structure is to be fabricated from an expensive and difficult to work with material, such as beryllium, for example. Unless one can find a reliable source for tensile and shear allowables that have already been established, it would be necessary to test certain number of standard lap shear and butt brazed specimens. Depending how rigorous and conservative the requirements are, it would be up to the program to determine the quantity of test specimens so for instance either A-basis or B-basis (MMPDS-05, 2010) allowables could be established. The more critical the requirements are, the smaller the zone representing safe combinations of stresses (safe zone) is, as shown in Fig. 2.14. It is very important to mention that the standard brazed test specimens should be manufactured using the same brazing procedure and by the same vendor selected for brazing of the actual brazed structure. When step 1 of the procedure outlined above is completed and FAD line is constructed, the designer needs to define the brazed joint line or trend line specific to the joint geometry considered for the brazed structure. In order to do define the trend line, all one needs to

do is to perform simplified FEA analysis of the imaginary brazed joint fabricated from any well characterized, more conventional base metal/filler metal combination. For example titanium base metal brazed with 1100 Al alloy filler metal. Assuming that our observations of the brazed joints trend lines (see Figs. 2.10 and 2.11) hold true and are validated in future studies, a ratio of maximum normal and maximum shear stresses should define the point to construct the brazed joint line, as described in Steps 2 and 3. After that, margins of safety (MS) can be estimated as (see Fig. 2.14):

$$(OB/OA) - 1 \qquad [2.16]$$

This geometric procedure, when expressed mathematically, takes form of:

$$\frac{1}{R_\sigma + R_b} \qquad [2.17]$$

Equation [2.17] is identical to some of the equations listed in the last column in Table 2.1. By changing the brazed joint geometry and/or design (for example changing the angle in the scarf joint), one can actually see how such change affects MS of the brazed joint. Then, the brazed joint design can be modified to achieve the desired MS. Obviously, more base metal/filler metal combinations need to be tested before this simple engineering procedure can be accepted in the brazing industry. It is our opinion, however, that the preliminary results described in this chapter are very encouraging and may generate enough interest in the industry to warrant additional studies of other brazed joint systems.

A word of caution when developing brazed joint shear strength allowables. It is a well established fact that average shear strength of the brazed lap joints drops as the overlap length increases (Brazing Handbook, 2007; AWS, 2008). Thus, when testing lap

shear specimens having short overlap lengths (less than 2T, where T is the thickness of the base metal), one may get a rather high values of shear strength. This is a typical behavior of joints brazed with ductile filler metals. In practice, however, when the lap shear joint geometry – based structures are fabricated, the practical overlap lengths are kept at 4T or even higher in order to achieve a full load carrying capability of the brazed joints. Full load carrying capability or full strength of the brazed joint is considered to be achieved when the joint strength becomes equal to the strength of the base metal. Such condition is observed in lap shear joints when their overlap lengths are 4T or greater (Brazing Handbook, 2005). Therefore, testing specimens with short overlap lengths may lead to artificially high values of shear strength allowables. Consequently, a series of lap shear specimens covering a range of overlap lengths, typically between 1T and 5T should be tested in order to establish the lowest, and not the highest average shear strength or allowable, as described in AWS C3.2 (2008).

2.4 Conclusions

- Construction of FADs based on Coulomb-Mohr failure criterion provides simple engineering tool for conservative estimate of margins of safety in braze joints;
- More work is required to further validate and better understand the trend line behavior of the brazed joints.

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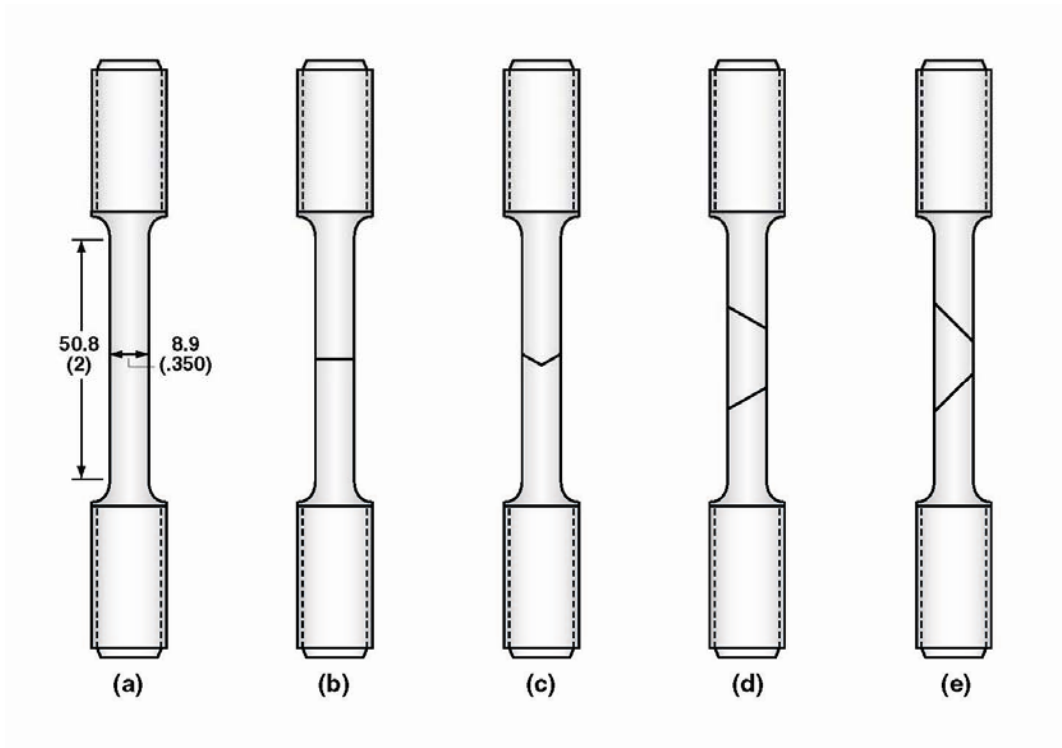

(a) - base metal blanks; (b) – butt joints;(c) – V60; (d) – D60 and (e) –*45˚(e)*

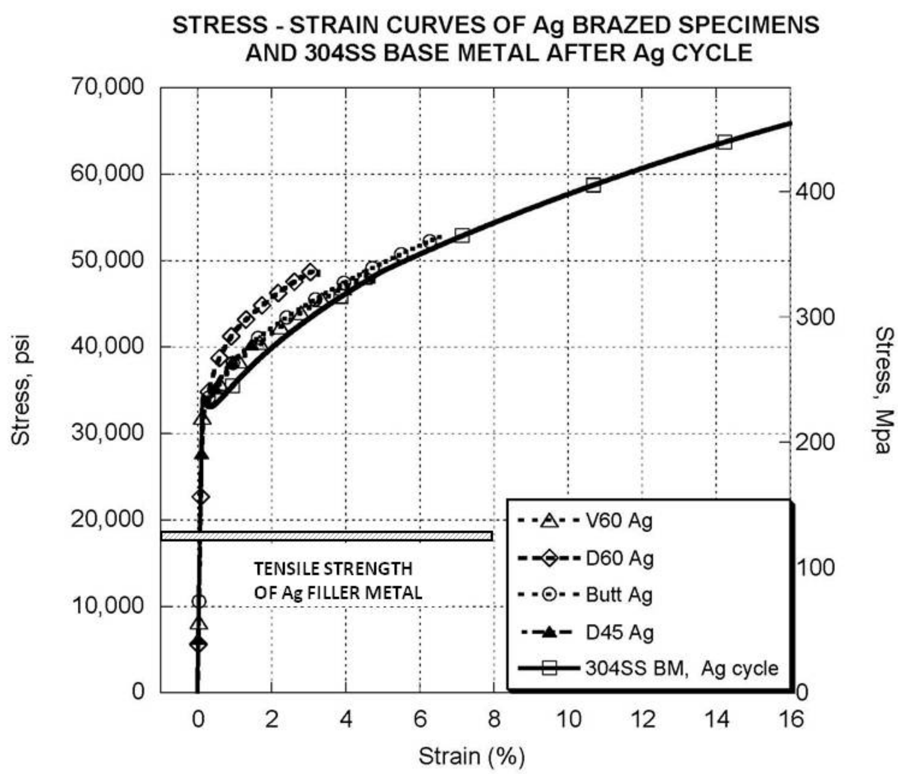

Fig.2.1 Various types of silver-brazed 304SS joints and their behavior vs. base metal during tensile test. Note that strain hardening rates are very similar to the base metal. Reprinted from Flom (2011).

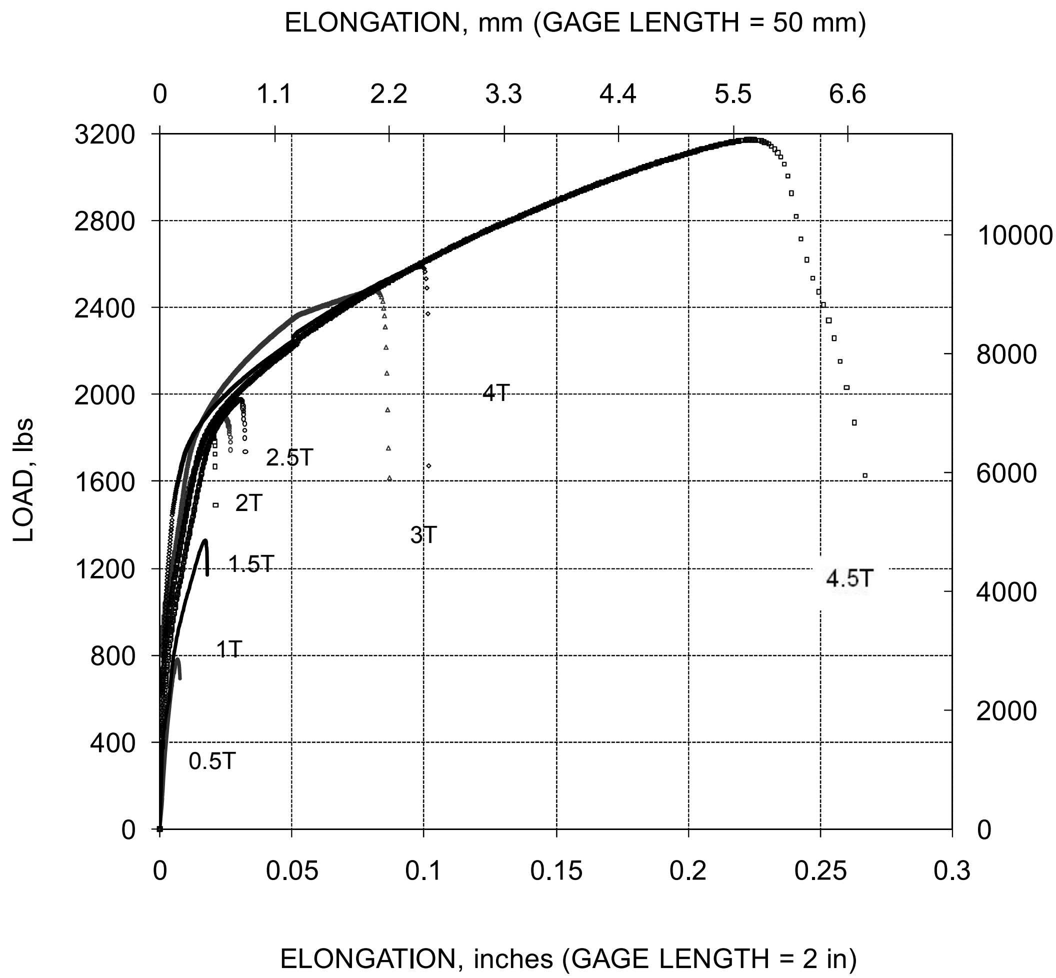

Fig.2.2 Tensile test of 347SS lap shear specimens brazed with Ag filler metal. Load vs. elongation results are plotted for various overlap lengths ranging between 0.5T to 4.5T, where T is thickness of the base metal. Note that strain hardening rate is essentially the same for different overlaps which indicates that plastic deformation within the brazed joint is largely obscured by the plastic deformation of the base metal (Flom, Wang, 2004). Reprinted with permission from Welding Journal.

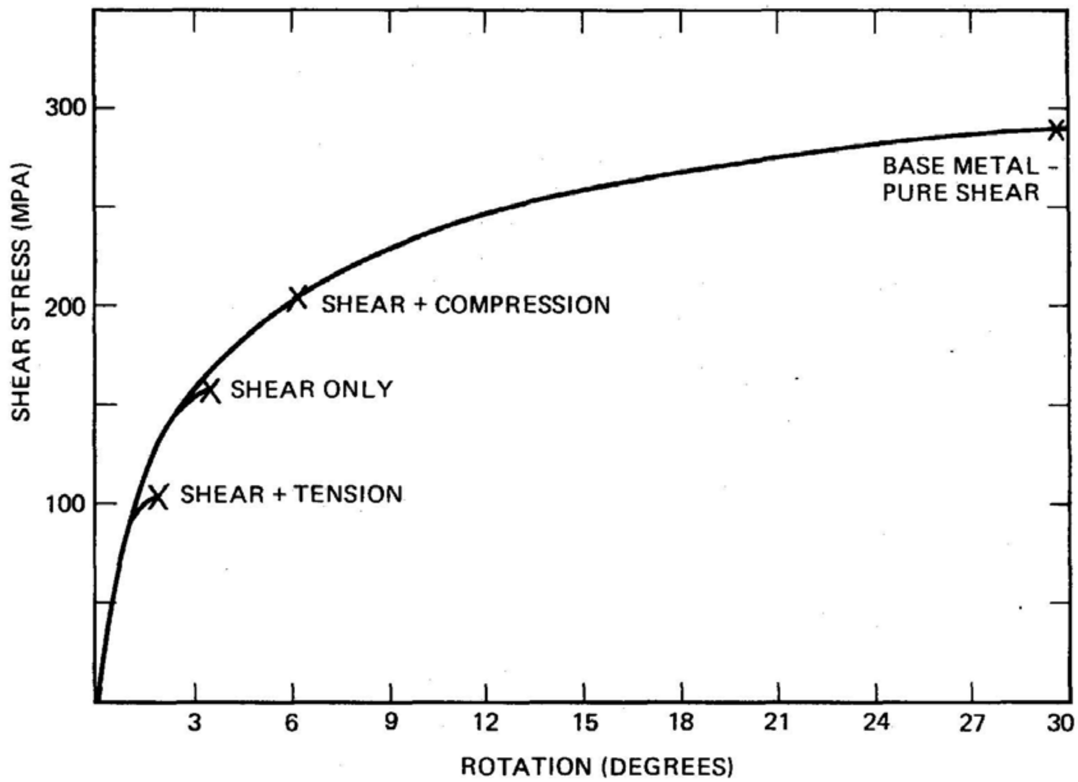

Fig.2.3 Incoloy 800 specimens brazed with Ni-based AWS BNi-8 filler metal and torsion tested at 650°C. Note that the behavior of the brazed joints is very similar to the base metal. Credit to Sandia National Laboratory, Spingarn J. R., et al (1983)

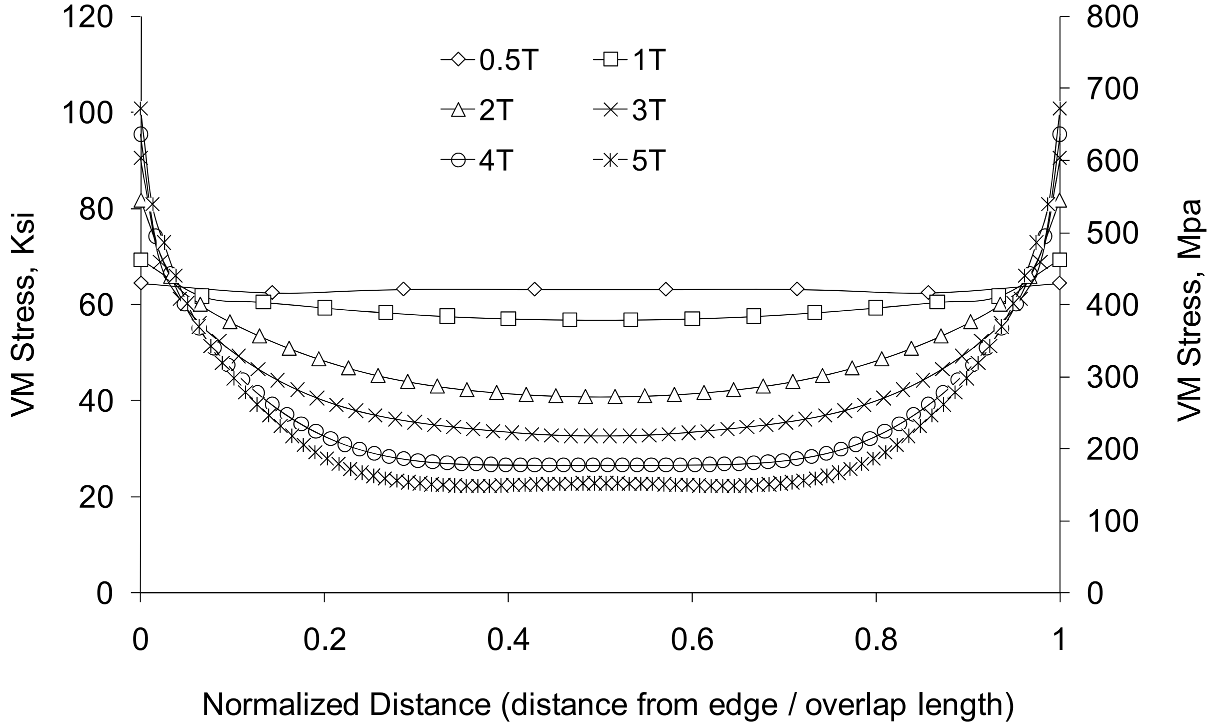

Fig.2.4 Distribution of von Mises (effective) stress within the 347SS/Ag lap shear brazed joints tested to failure. The stress is plotted as a function of the distance from the joint edge for specimens having overlap lengths ranging from 0.5T to 5T, where T is the thickness of the base metal. Note that stresses in many locations, particular near the joint edge exceed, by far, the ultimate strength of the bulk silver, which is about 35 ksi (250 MPa), Flom, Wang (2004). Reprinted with permission from Welding Journal.

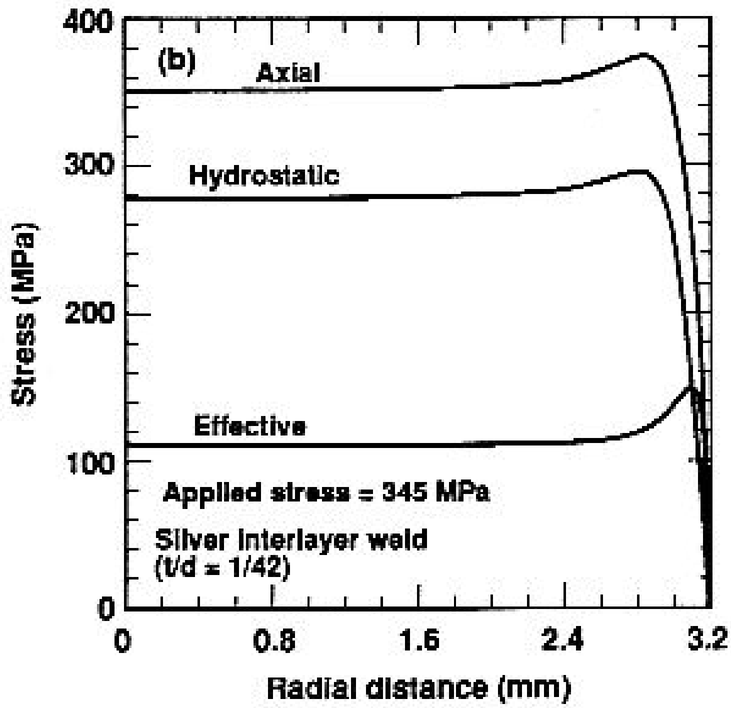

Fig.2.5 Stress distribution in the silver-brazed butt joint determined using FEA. Aspect ratio here is 1/42 or approximately 0.024. Most structural brazed joints have much smaller aspect ratios, in the order of 0.008. In such joints, the axial stresses are even closer to hydrostatic stresses than shown on this plot, Rosen R.S., et al (1993).

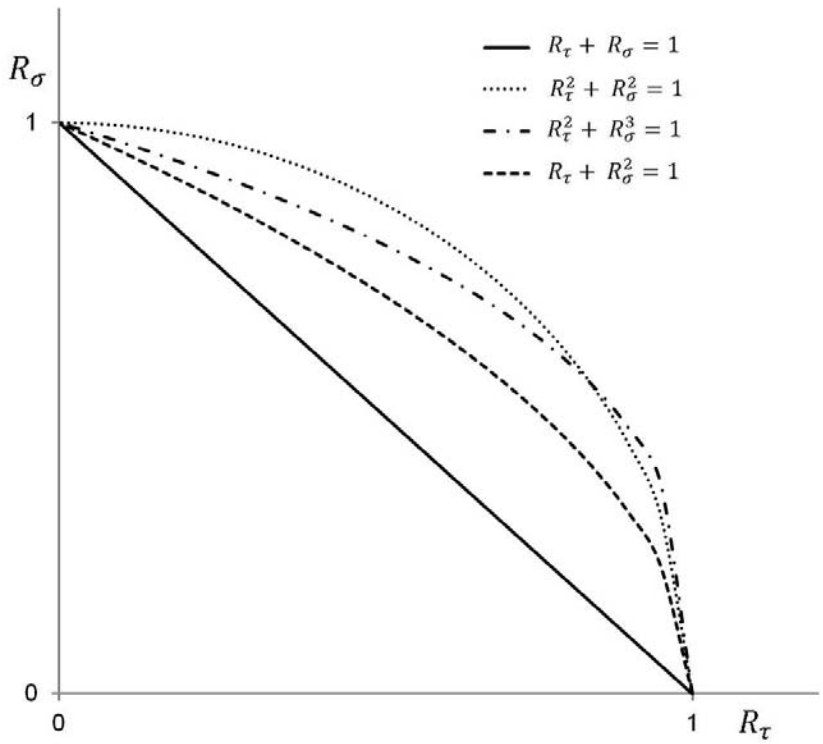

Fig. 2.6 Plots of several interaction equations. Note that straight line represents the most conservative case.

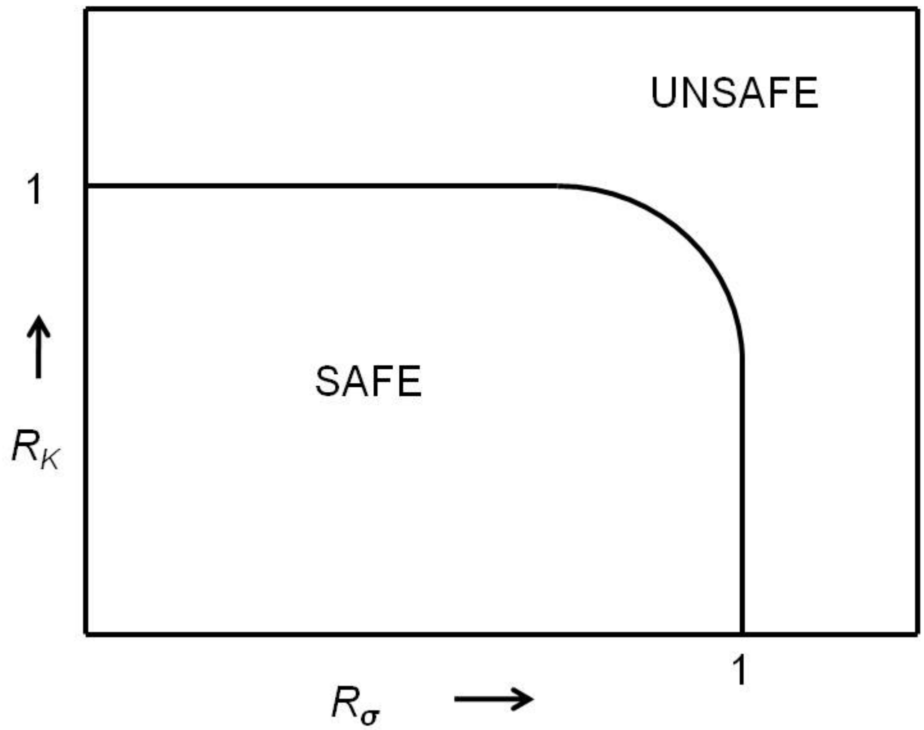

Fig.2.7 An example of FAD used in the welding industry. Vertical axis represents resistance to brittle fracture and horizontal axis represents resistance to plastic collapse, Gordon (1993). Reprinted with permission of ASM International. All rights reserved. www.asminternational.com

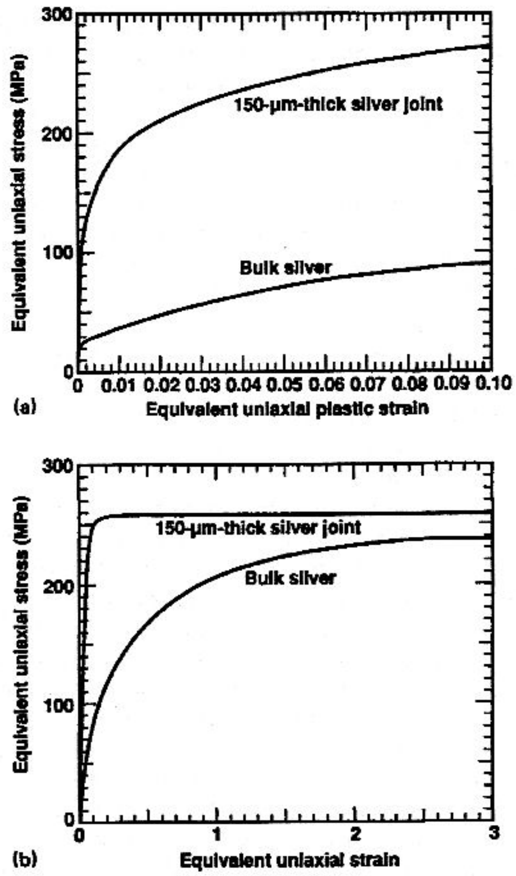

Fig.2.8 Equivalent uniaxial stress vs. equivalent uniaxial strain plot for silver-brazed maraging steel butt brazed specimens tested in torsion. An expanded view of the initial region of the test, up to 0.1 strain is shown in (a). The entire test is captured in (b). Note a significant difference in strain hardening rate between the bulk silver and a silver layer in the brazed joint. Reprinted with permission from Rosen R. S., et al (1980). Copyright 1980, American Vacuum Society.

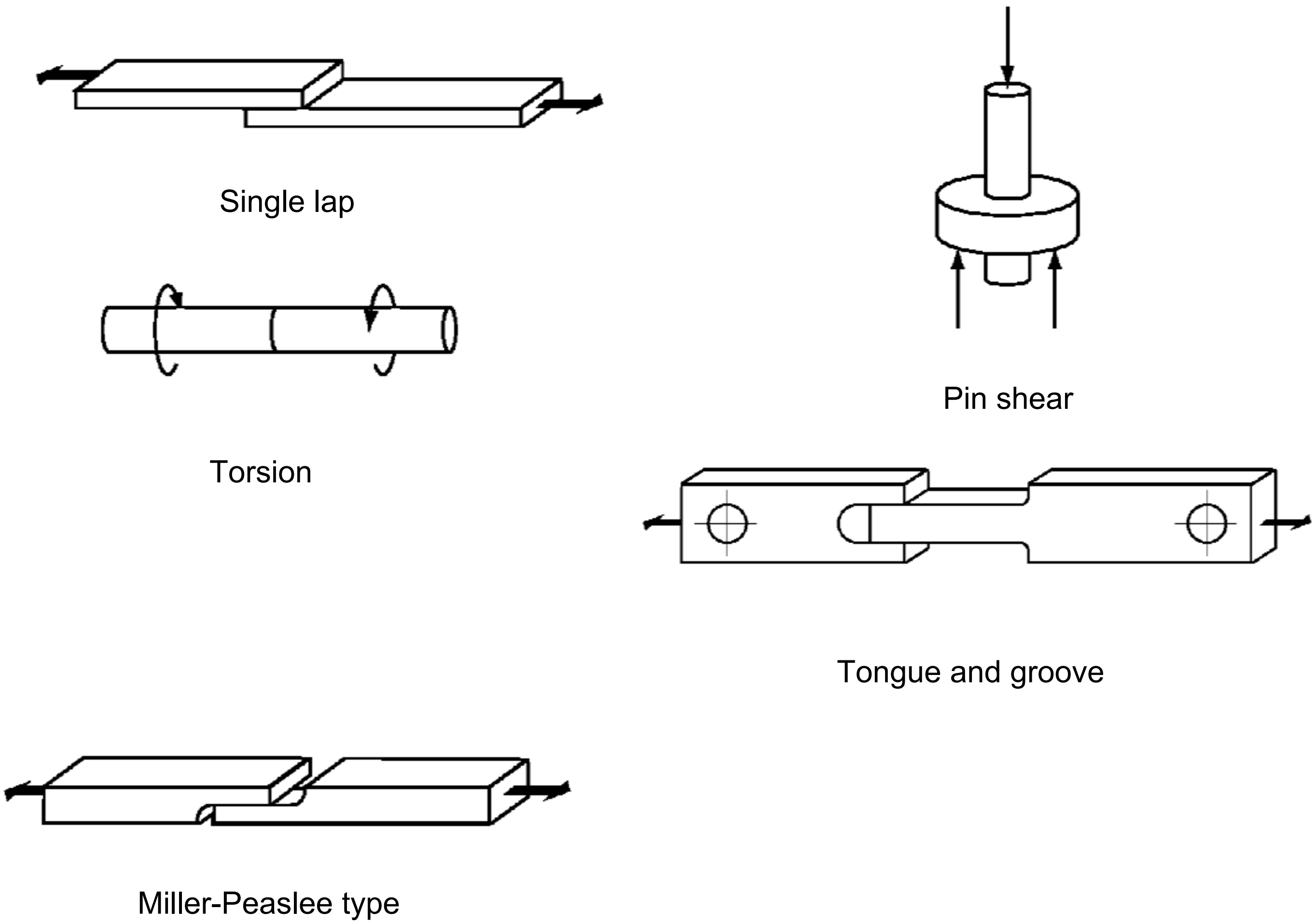

Fig.2.9. Several types of brazed shear specimens single lap used in various studies to determine shear strength of the brazed joints. Effect of eccentricity of the test specimen on average shear strength is much less than the experimental scatter and variability of the brazing process itself (Brazing Handbook, 2007). Consequently, single lap test specimen, described by Peaslee (1976), remains the standard test specimen for measuring shear strength of the brazed joints.

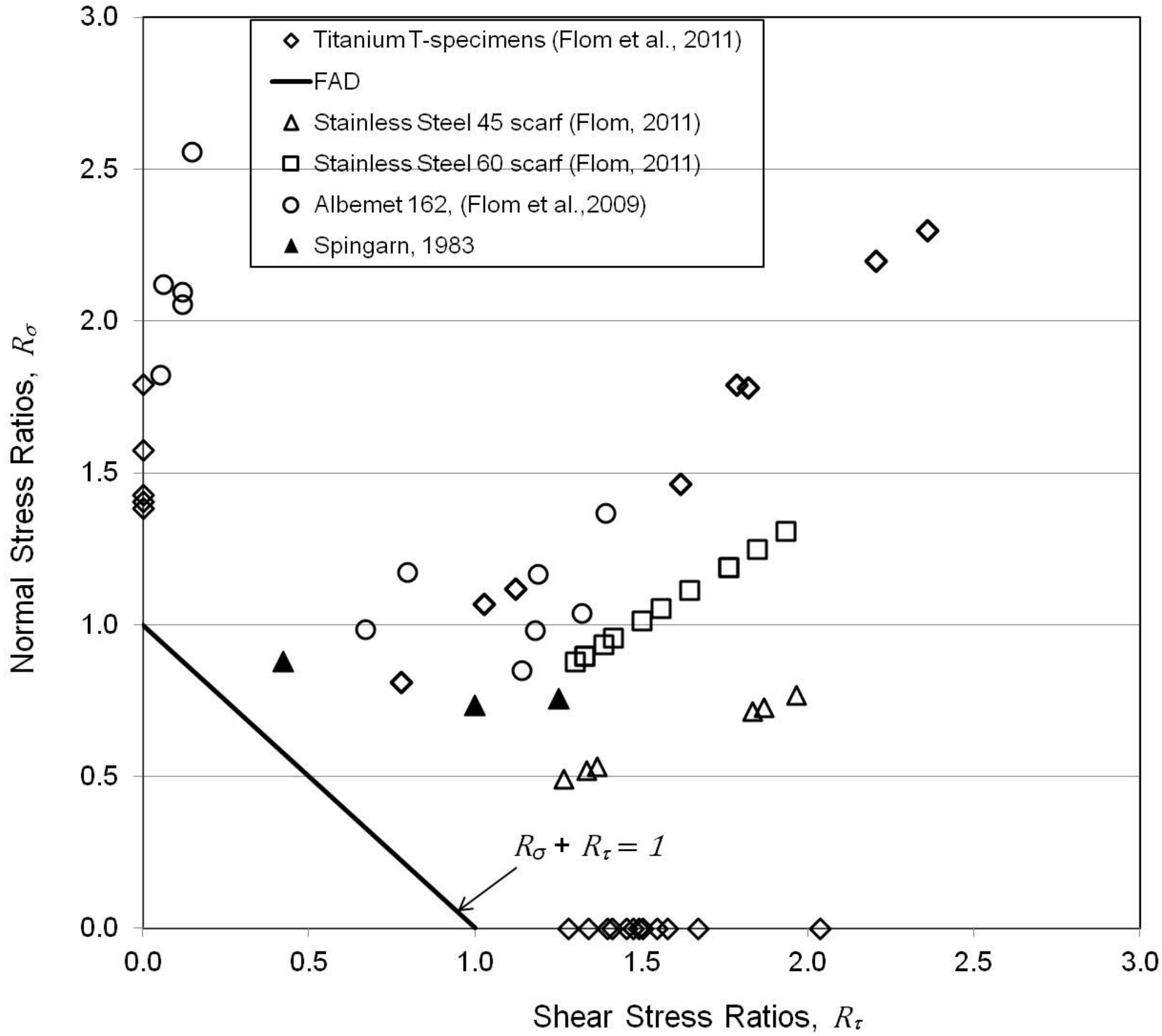

Fig.2. 10 Test results from previous studies plotted as stress ratios. As one can see the FAD line defined by $R_\sigma + R_\tau = 1$ can be used quite conservatively for the lower bound estimate of stress combinations that may cause brazed joint failure. Titanium lap shear and butt brazed specimens (Flom et al., 2011) are also plotted along shear and normal stress axes, respectively.

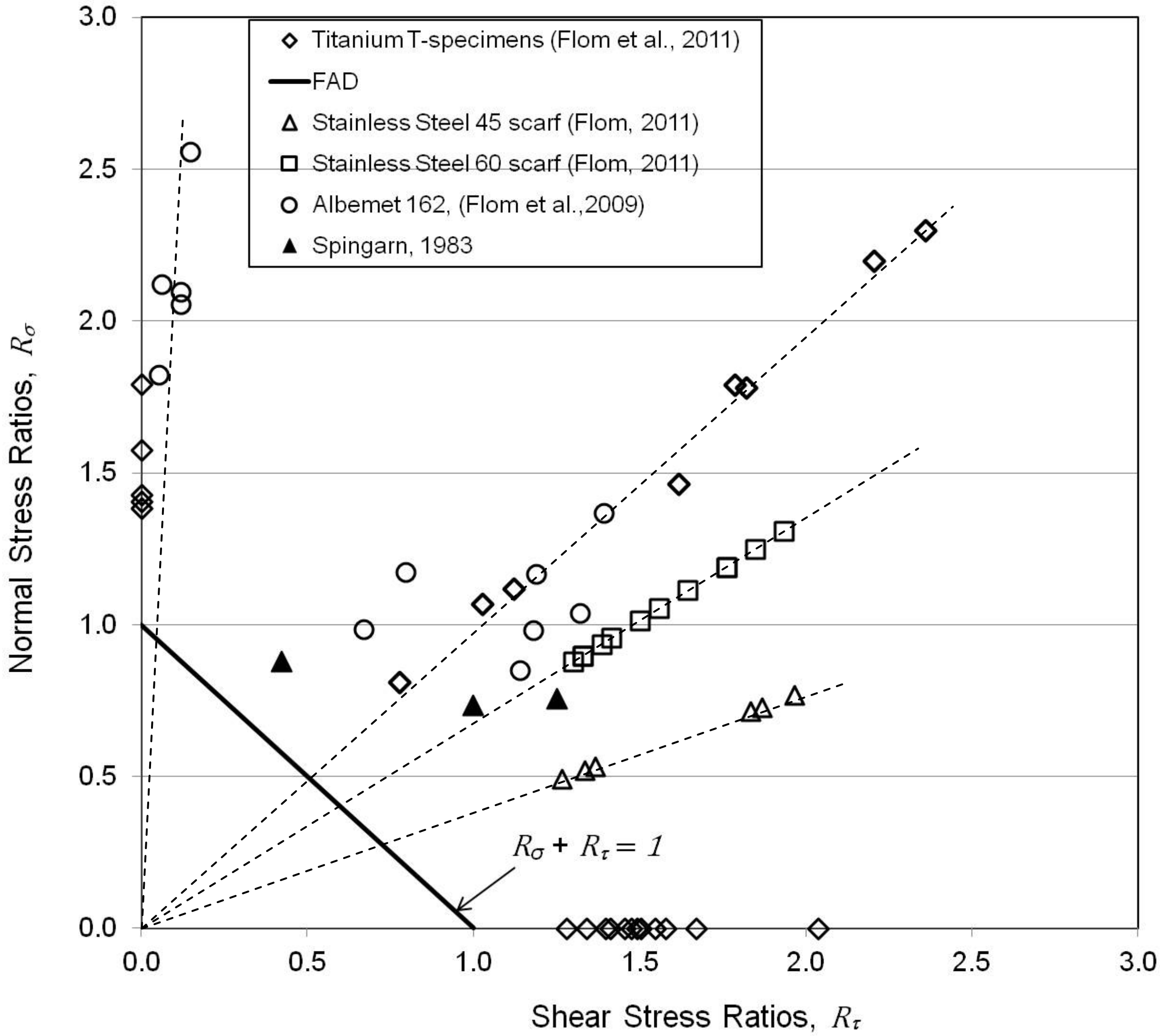

Fig.2. 11 The same results as in Fig.10 shown here with the addition of the trend or brazed joint lines (dashed). Each trend line is associated with a specific braze joint geometry. We can also call them braze joint lines. A position of the data point on such line indicates a particular stresses combination.

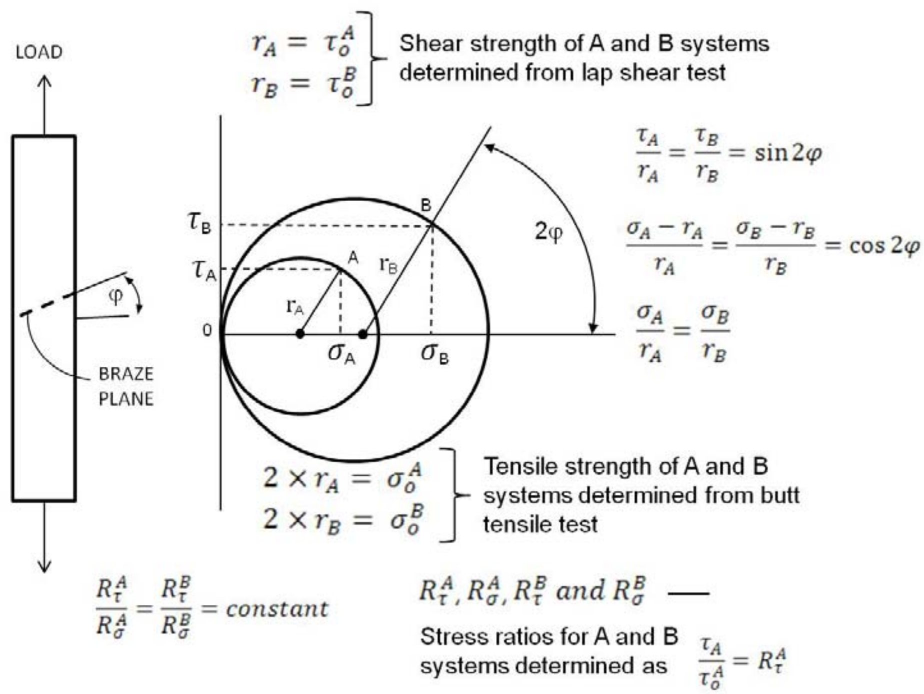

Fig.2.13 Mohr circle construction representing stress state on the braze plane of the scarf joint subjected to uniaxial tension. Smaller circle represents a scarf joint fabricated from the base/filler metal combination, denoted as A system. Large circle represents scarf joint with the identical angle, but fabricated from B system, which is stronger than A. Following the nomenclature above and using simple geometric observations, one can see that shear and normal stress ratios for scarf joint A form the same proportion as the stress ratios for joint B. This explains experimental observation that stress ratios in the identical scarf brazed joints fabricated from different base/filler metals fall on the same trend line.

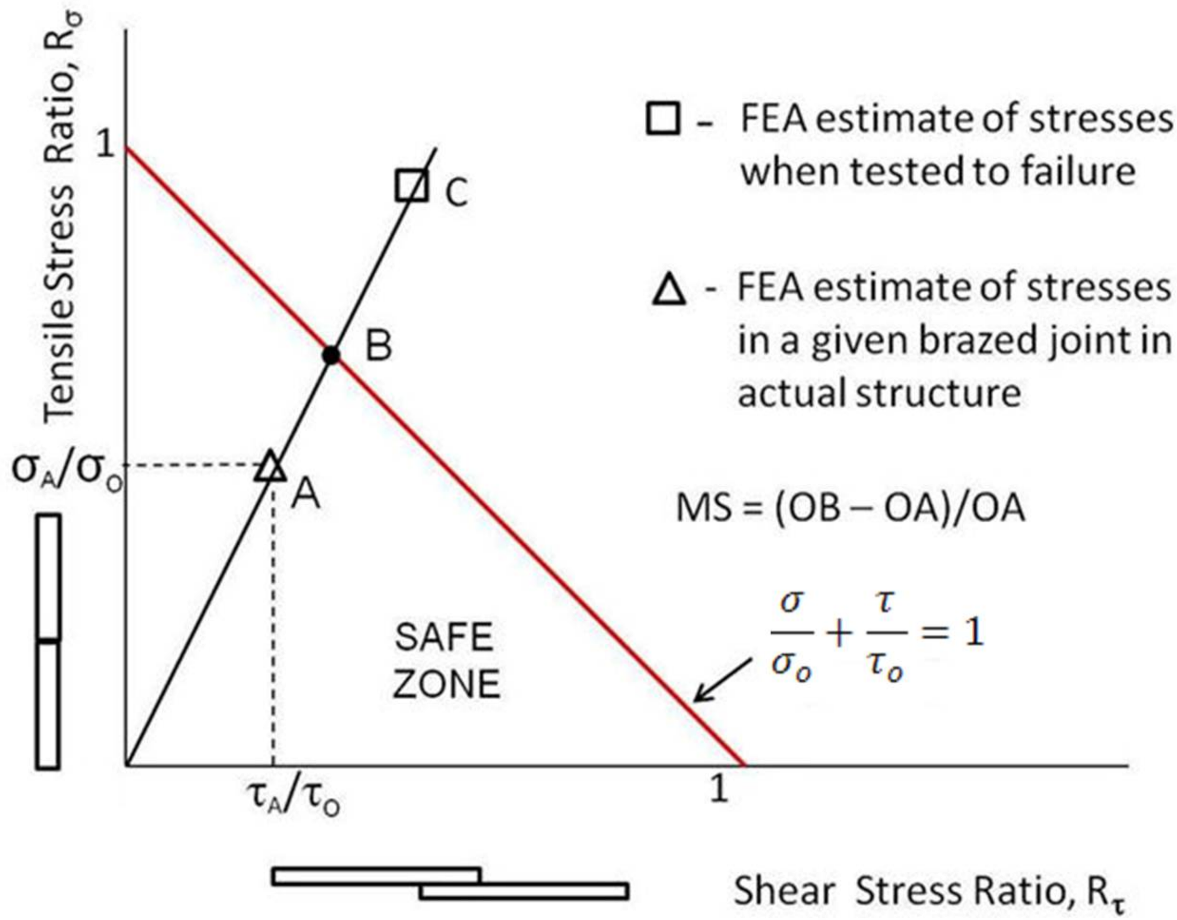

Fig.2. 13 This graph illustrates the process of constructing the braze joint line and determining margins of safety of the brazed joint. Safe zone represents safe combinations of stresses.

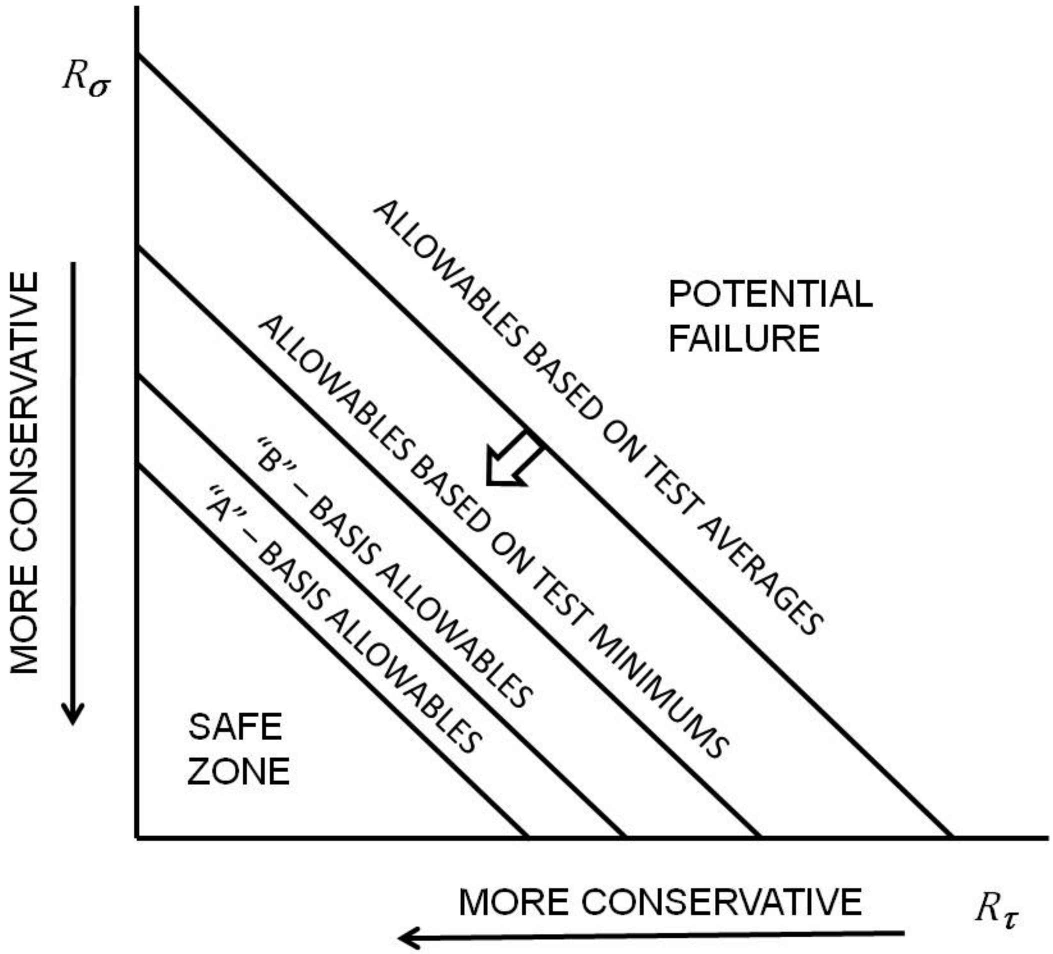

Fig. 2.14 Tensile σ_o and shear τ_o allowables can be determined using various levels of statistical requirements, as illustrated on this graph. More conservative or stringent allowables result in the smaller safe zone. The above graph is showing relative position of FAD depending on the relative value of the allowables. For example, if the test average values of σ_o and τ_o are twice as high as their "B" basis counterparts, it is easy to see that the line $R_\tau + R_\sigma = 1$, representing test averages changes to $R_\tau + R_\sigma = 0.5$, representing "B" – basis results.