

### □ SEMINAR OBJECTIVE



# DISCUSS MARGINS OF SAFETY IN CRITICAL BRAZED STRUCTURES

*The author would like to acknowledge his colleagues Len Wang, Mollie Powell, Diane Kolos and David Puckett, NASA, GSFC as well as Matt Soffa and Monica Rommel from ITT Aerospace, S. R. Lin from Aerospace Corp., Ge Wang from Northrop Grumman and Alexander Shapiro from Titanium Brazing for their contribution to the material presented in this seminar.*

## □ OUTLINE

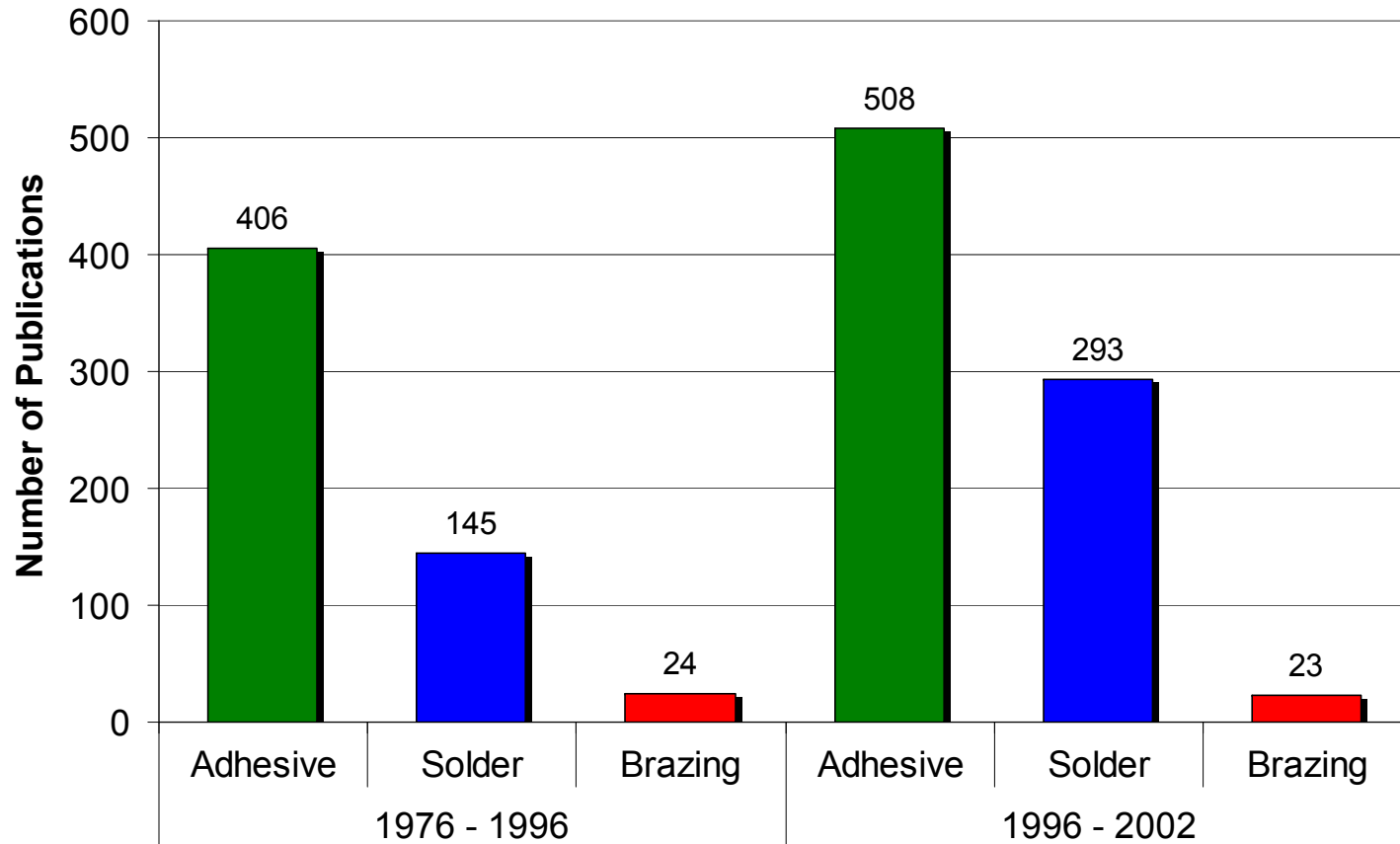
- PRESENT SITUATION
- DEFINITION OF STRENGTH
- MARGINS OF SAFETY
- DESIGN ALLOWABLES
- MECHANICAL TESTING
- FAILURE CRITERIA
- DESIGN FLOWCHART
- BRAZE GAP
- RESIDUAL STRESSES
- DELAYED FAILURES
- FINAL COMMENTS
- REFERENCES

### **PRESENT SITUATION**

-  DESPITE GREAT ADVANCES IN ANALYTICAL TECHNIQUES AVAILABLE TO STRUCTURAL ENGINEERS, DESIGNERS OF BRAZED STRUCTURES HAVE VERY FEW TOOLS TO USE COMPARED TO THEIR COUNTERPARTS WORKING WITH WELDED, FASTENED OR ADHESIVELY BONDED JOINTS.
  
-  INDUSTRY AS A WHOLE HAS BECOME LESS TOLERABLE TO STRUCTURAL FAILURES

## PRESENT SITUATION

### BIBLIOGRAPHY ON FEA AND SIMULATION OF ADHESIVE BONDING, SOLDERING AND BRAZING *(Based on data from Ref.1 & 2)*



## PRESENT SITUATION

### SPACECRAFT STRUCTURES AND MECHANISMS

From Concept to Launch

Thomas P. Sarafin (editor)

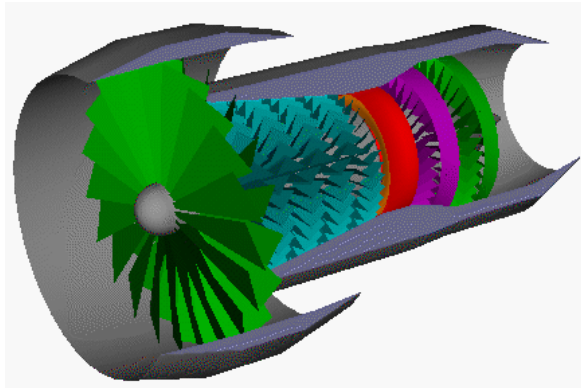


Table 15.18. Comparison of Attachment Options. Brazing and soldering, not listed, are used for small, lightly loaded assemblies.

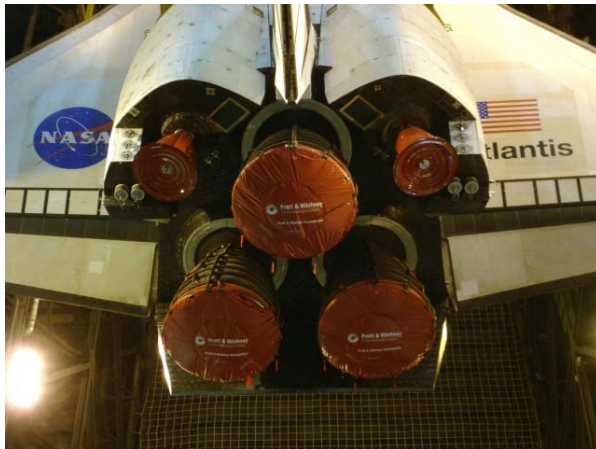
Method	Advantages	Disadvantages	Applications
Mechanical Fasteners	<ul style="list-style-type: none"> <li>- Versatile—many types</li> <li>- Most are readily available</li> <li>- Often inexpensive</li> <li>- Standard sizes and thread geometry</li> <li>- Can be installed in almost any facility without expensive tools or process controls</li> <li>- Good for dissimilar materials</li> <li>- Most are easily disassembled</li> <li>- Adds structural damping</li> </ul>	<ul style="list-style-type: none"> <li>- Weight</li> <li>- Can be expensive</li> <li>- Hard to avoid loss of stiffness</li> <li>- Potential joint shift</li> <li>- Time required for installation</li> <li>- Often requires end fittings to transfer loads from structural members to fasteners</li> <li>- Introduces stress concentrations that can cause premature failure in brittle materials</li> </ul>	<ul style="list-style-type: none"> <li>- Suitable for most structures and mechanisms made of ductile materials</li> </ul>
Welds	<ul style="list-style-type: none"> <li>- Often less expensive than fastening</li> <li>- Maintains stiffness</li> </ul>	<ul style="list-style-type: none"> <li>- Can't disassemble parts</li> <li>- Hard to maintain assembly dimensions (residual stresses cause warping)</li> <li>- Reduces strength of aluminum and certain other materials</li> <li>- Quality varies with processes and workmanship—must develop and demonstrate processes</li> </ul>	<ul style="list-style-type: none"> <li>- Reserved for attaching similar, weldable metals</li> <li>- Stiffness-critical aluminum truss or frame structures</li> <li>- Ground support equipment (steel)</li> <li>- Propellant tanks and lines</li> </ul>
Adhesive Bonds	<ul style="list-style-type: none"> <li>- Lightweight</li> <li>- Can add structural damping</li> <li>- Can be the easiest and most economical method of attachment</li> <li>- Spreads loads out relatively uniformly throughout the joint</li> <li>- Results in smooth surfaces</li> <li>- Effective for dissimilar materials</li> </ul>	<ul style="list-style-type: none"> <li>- Usually can't disassemble</li> <li>- Quality varies extremely with process, materials, and workmanship—must develop and demonstrate processes. Typically need proof testing.</li> <li>- Low tensile (peel) strength</li> <li>- Adhesives have limited shelf life</li> <li>- Some adhesives are brittle</li> <li>- Some are toxic; require good ventilation</li> <li>- Temperature limitations</li> </ul>	<ul style="list-style-type: none"> <li>- Assembly of brittle materials that would crack easily from stress concentrations caused by fasteners</li> <li>- Joining a laminated composite member to a metallic end fitting</li> <li>- Shear joints</li> </ul>

(Ref.3)

## PRESENT SITUATION



JET ENGINE



SSME

## EXAMPLES OF STRUCTURAL APPLICATIONS OF BRAZED JOINTS

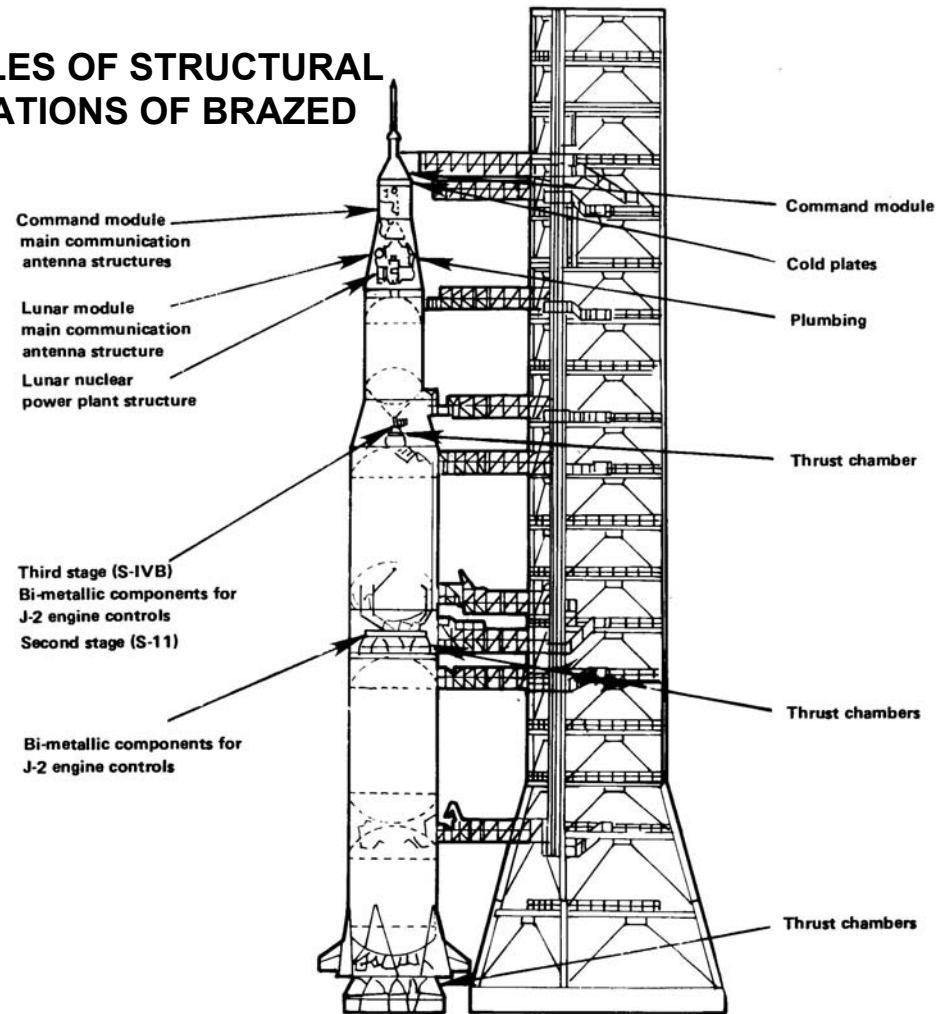
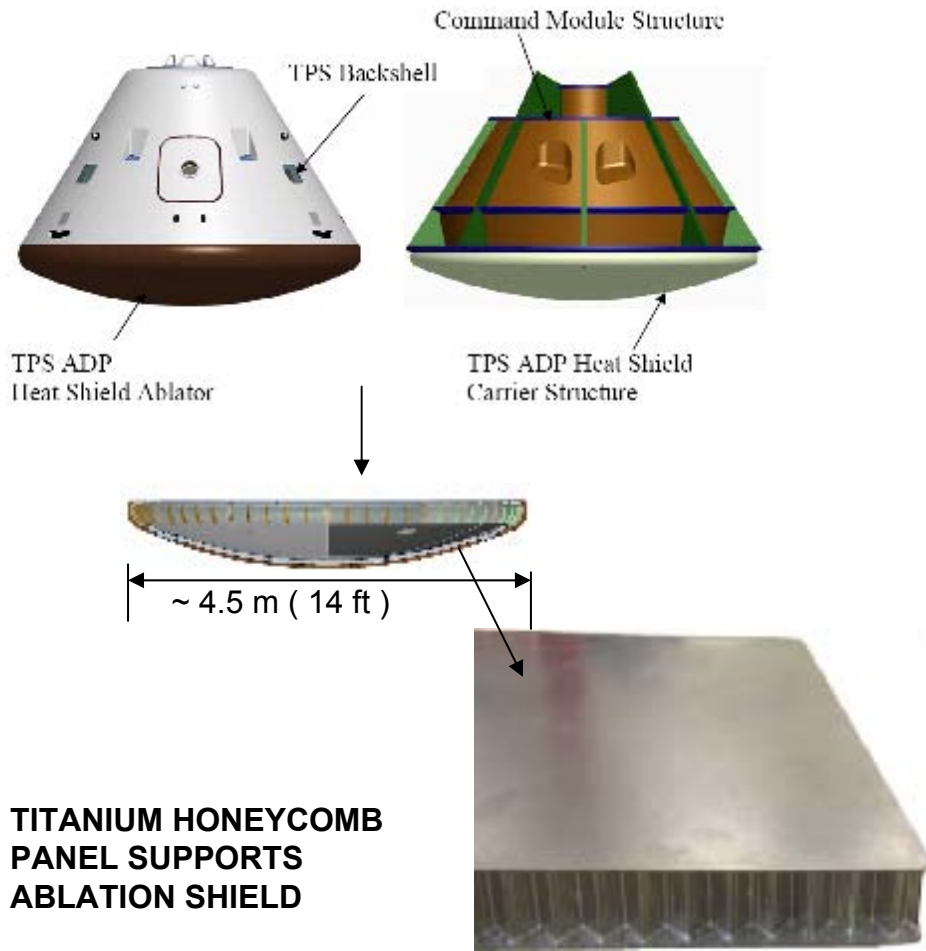


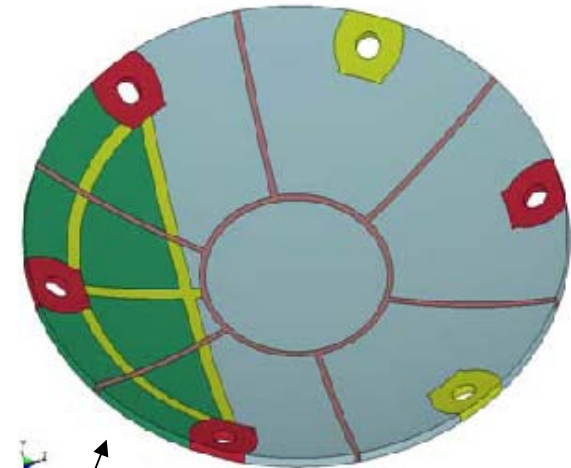
FIGURE 9.56. Hardware brazements in Apollo/Saturn spacecraft

(Ref. 4)

## □ PRESENT SITUATION



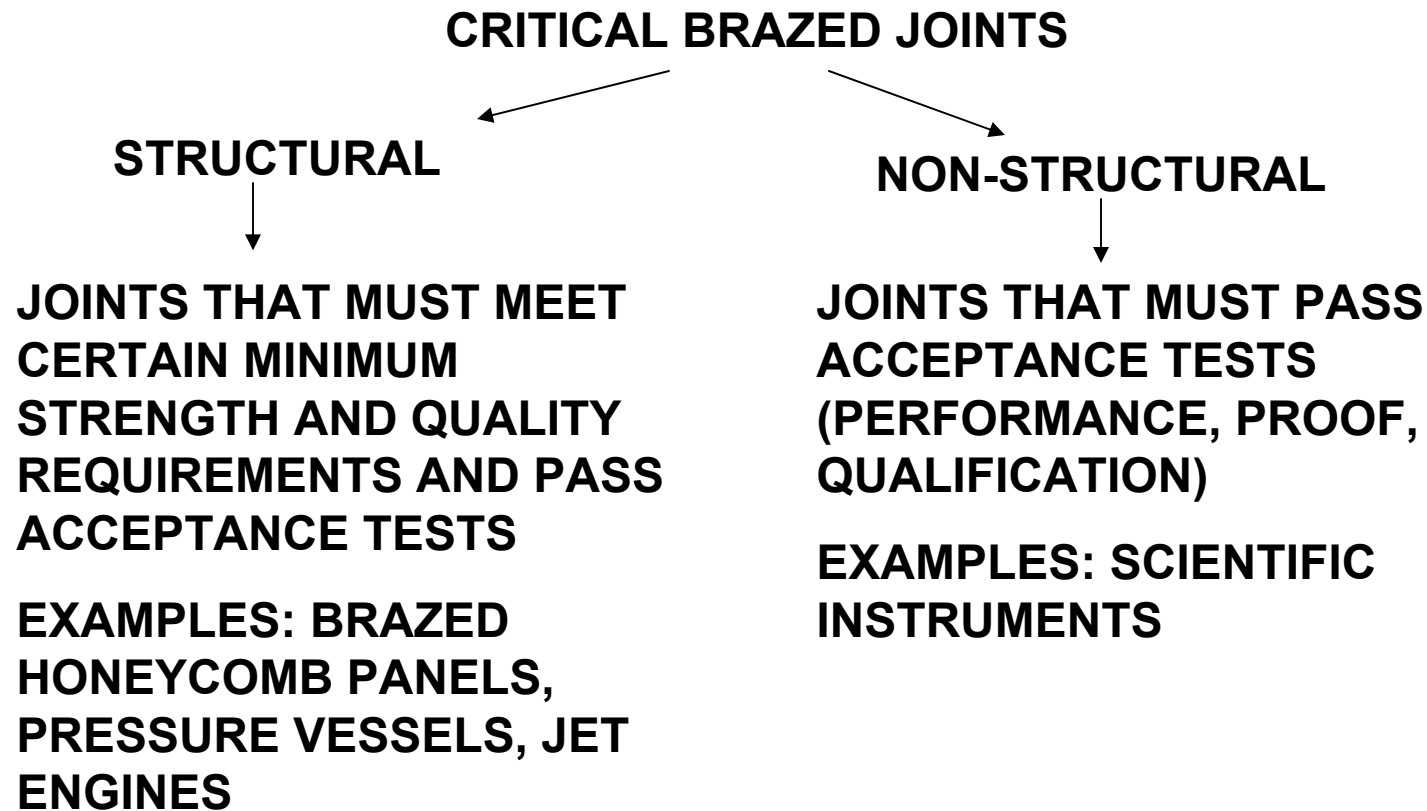
ORION CREW EXPLORATION  
VEHICLE THERMAL PROTECTION  
SYSTEM CONCEPT ( *Ref. 5* )



**SIX BRAZED HONEYCOMB SEGMENTS  
ARE JOINED TOGETHER BY WELDING**

**BRAZED TITANIUM METAL  
MATRIX SANDWICH PANEL**

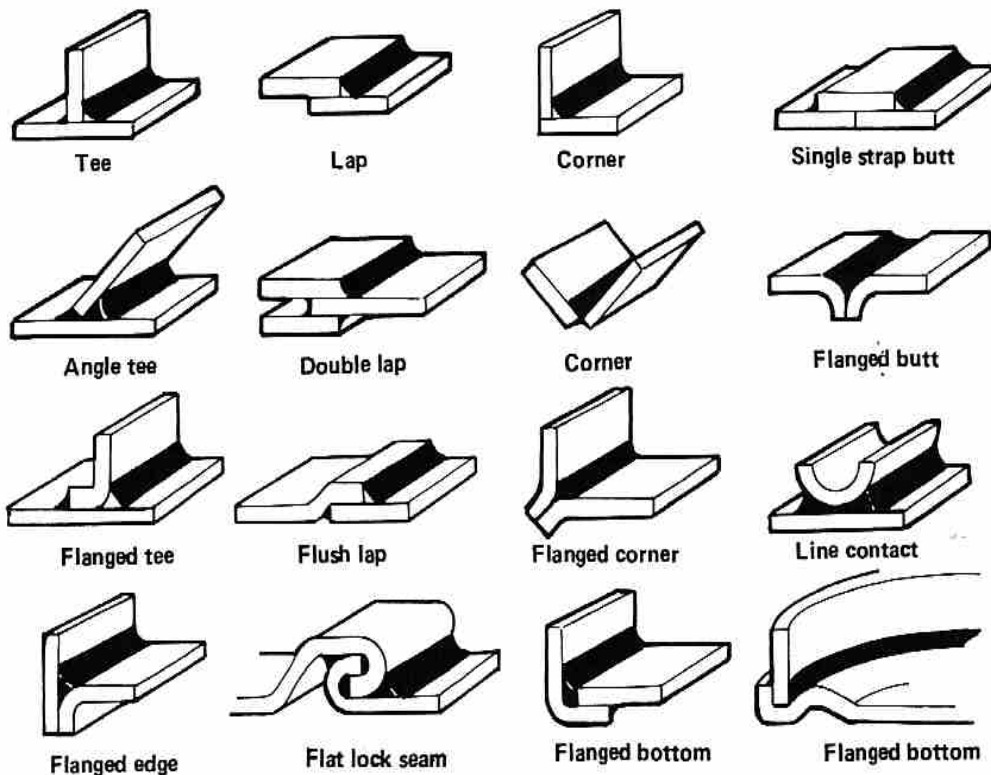
### □ STRENGTH



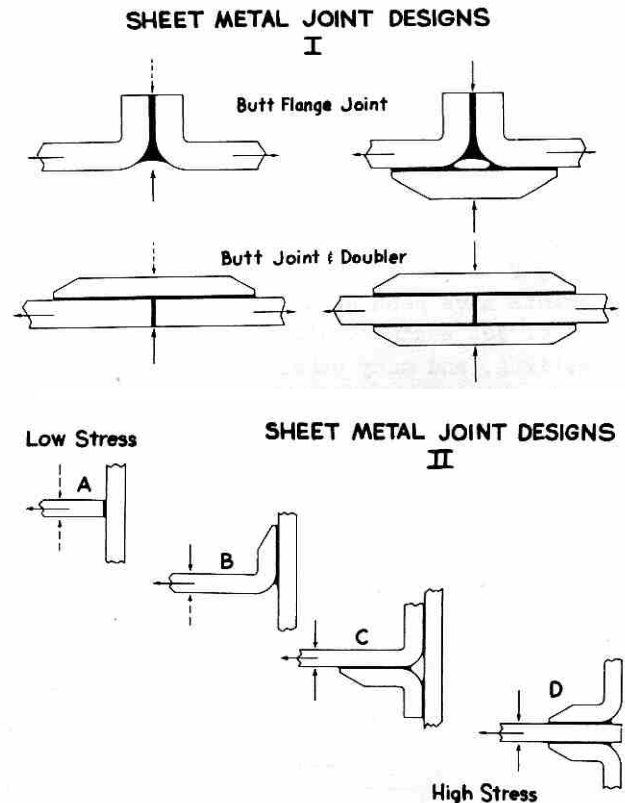


## □ STRENGTH

THERE ARE HUNDREDS OF VARIOUS JOINT DESIGNS USED IN BRAZING. SOME OF THE JOINTS ARE SHOWN BELOW.



( Ref. 4 )



( Ref. 6 )

## □ STRENGTH

MOST OF THE JOINTS CAN BE REPRESENTED BY SOME COMBINATION OF THE TWO FUNDAMENTAL JOINT TYPES: LAP AND BUTT



**SINGLE LAP**



**BUTT JOINT**

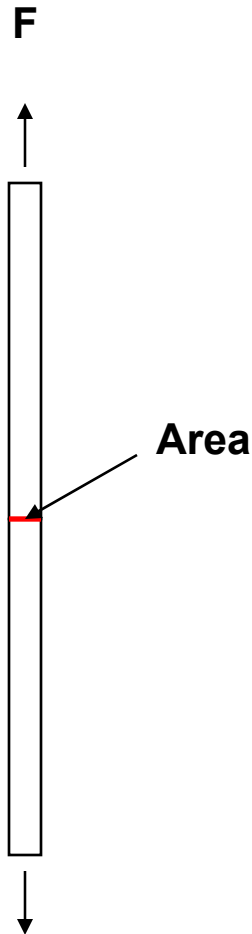
**IDEALLY:**

**LAP JOINTS ARE INTENDED FOR SHEAR LOADS.**

**BUTT JOINTS ARE INTENDED FOR UNIAXIAL TENSILE LOADS**

**IN REAL STRUCTURES BRAZED JOINTS ARE SUBJECTED TO MULTIAXIAL LOADS INCLUDING BENDING**

## □ STRENGTH



BUTT JOINTS ARE RARELY USED IN STRUCTURAL APPLICATIONS.

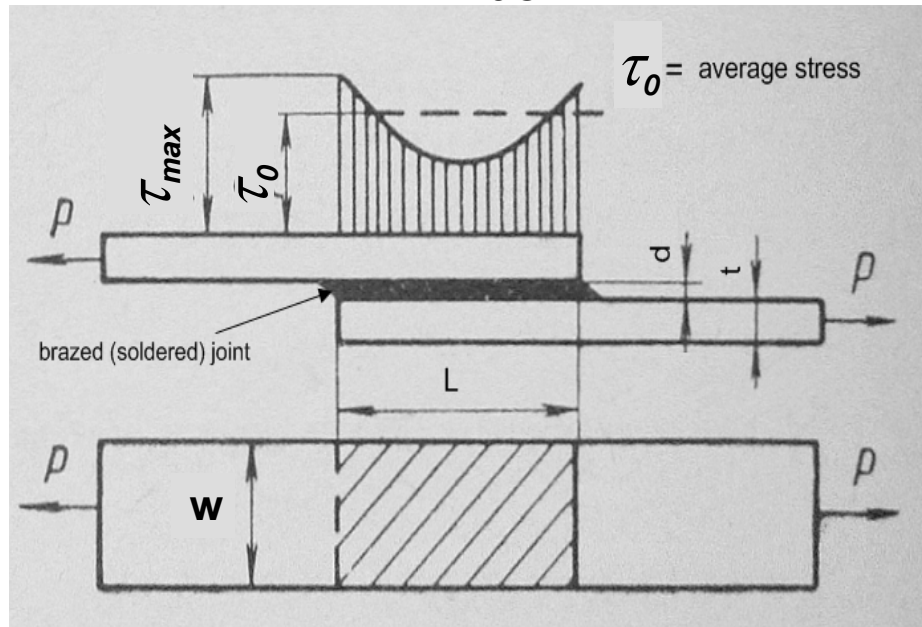
MAIN REASONS FOR THIS ARE:

1. STRENGTH OF THE BUTT JOINT IS GENERALLY LESS THAN THE STRENGTH OF THE BASE METAL;
2. STRENGTH OF THE BUTT JOINT CAN NOT BE TAILORED
3. BUTT JOINTS ARE VERY SENSITIVE TO OFF-AXIAL LOADS

$$\sigma_{JOINT \ TENSILE \ STRENGTH} = \frac{F}{A_{JOINT}}$$

## □ STRENGTH

### LAP JOINT



Distribution of shear stress within the lap joint is not uniform.

We use average value of shear stress because that is what we can determine from test.

$$w \cdot L \cdot \tau_{BR} \geq \sigma_{BM TUS} \cdot w \cdot t \longrightarrow \text{Desirable condition in structural brazed joints}$$

$$w \cdot L \cdot \tau_{BR} \leq \sigma_{BM TUS} \cdot w \cdot t \longrightarrow \text{More realistic situation for mechanical test of brazed joints}$$

$\sigma_{BM}$  - Tensile strength of base metal

$\tau_{BR}$  - Shear strength of joint

## ❑ MARGINS OF SAFETY

$$MS = \frac{\sigma_{ALLOWABLE}}{FS \times \sigma_{MAX}} - 1 > 0$$

MS – Margin of Safety

FS – Factor of Safety - Multiplying factors applied to limit (maximum) loads or stresses for purposes of analytical assessment of design adequacy in strength or stability

$\sigma_{ALLOWABLE}$  - Allowable stress or load – maximum load or stress that can be permitted in the material for a given operating environment without causing rupture or collapse, detrimental deformation or unacceptable crack growth

$\sigma_{MAX}$  - Maximum design stress or load, or Limit Load – maximum stress or load expected to act on a structure in a given operating environment.

**CRITICAL BRAZED JOINTS MUST DEMONSTRATE POSITIVE MARGIN OF SAFETY**

## ❑ MARGINS OF SAFETY

EXAMPLE OF FACTORS OF SAFETY USED IN DESIGN OF NASA LIFTING DEVICES  
AS PART OF GROUND SUPPORT EQUIPMENT ( *Ref. 7* )

Item	Design Load Factor G's		Factor of Safety		Proof Test Factors	
	Vertical	Lateral	Ultimate	Yield	Initial	Periodic
<b>Alloy Steel Chain</b>	<b>1.0*</b>	<b>0.0*</b>	<b>5.0</b>		<b>2</b>	<b>1</b>
<b>Wire Rope</b>	<b>1.0*</b>	<b>0.0*</b>	<b>5.0</b>		<b>2</b>	<b>1</b>
<b>Metal Mesh</b>	<b>1.0*</b>	<b>0.0*</b>	<b>5.0</b>		<b>2</b>	<b>1</b>
<b>Synthetic Rope</b>	<b>1.0*</b>	<b>0.0*</b>	<b>10.0</b>		<b>2</b>	<b>1</b>
<b>Synthetic Web</b>	<b>1.0*</b>	<b>0.0*</b>	<b>5.0**</b>		<b>2</b>	<b>1</b>
<b>Linear Fiber</b>	<b>1.0*</b>	<b>0.0*</b>	<b>5.0**</b>		<b>2</b>	<b>1</b>
<b>Shackles, D-Rings, Turnbuckles, Eye Bolts, Hoist Rings</b>	<b>1.0*</b>	<b>0.0*</b>	<b>5.0</b>		<b>2</b>	<b>1</b>
<b>Structural Slings</b>	<b>1.0*</b>	<b>0.0*</b>	<b>5.0</b>	<b>3.0</b>	<b>2</b>	<b>1</b>

Each industry (aerospace, aircraft, nuclear, automotive, medical ) works under a strict system of codes and standards which require a certain level of quality and strength of the structural components they use, including structural joints (welded, adhesive and brazed). The industrial regulations define various Factors of Safety (FS) imposed on the structures. Depending on the consequences of the failure FS could be anywhere between 1 and 10.

## ❑ MARGINS OF SAFETY

### MORE EXAMPLES OF Factors of Safety

#### Structural design and test factors of safety for spaceflight hardware ( Ref. 8 )

Table 1—Minimum Design and Test Factors for Metallic Structures

Verification Approach	Ultimate Design Factor	Yield Design Factor	Qualification Test Factor	Acceptance or Proof Test Factor
Prototype	1.4	1.0*	1.4	NA or 1.05**
Protoflight	1.4	1.25	NA	1.2***

**NOTES:**

\* Structure must be assessed to prevent detrimental yielding during flight, acceptance, or proof testing.

\*\* Propellant tanks and SRM cases only.

\*\*\* Protoflight level testing is required for the first article of a multiple article build. A workmanship level test is required for all subsequent copies of the first article. The workmanship test shall be approved by the responsible Technical Authority.

Table 2—Minimum Design and Test Factors for Fasteners and Preloaded Joints\*\*

Verification Approach	Design Factors			Test Factors	
	Ultimate Strength	Joint Separation		Qualification	Acceptance or Proof
		Safety Critical *	Other		
Prototype	1.4	1.4	1.2	1.4	NA
Protoflight	1.4	1.4	1.2	NA	1.2

**NOTE:**

\* Joints where structural failure could cause a catastrophic event. Examples of a catastrophic event include, but are not limited to, loss of life, disabling injury, or loss of a major national asset such as the Space Shuttle or Space Station.

\*\* Factors of safety on yield are not specified for fasteners.

### ❑ MARGINS OF SAFETY

Factor of Safety is used to account for design uncertainties that cannot be analyzed or accounted for in a rational manner.

Does FS account for **all** design uncertainties? In homogeneous metallic materials, FS accounts for most of the uncertainties resulting from the designer's inability to predict complex stress distribution or because fabrication process cannot be controlled to produce ideal or identical structures.

Brazed joints introduce a number of additional design uncertainties such as:

- mechanical properties of the filler metal within the joint
- amount of internal discontinuities and their effect on the properties of the joint
- amount of residual stresses present in the brazed joint
- our ability to perform and interpret non-destructive examination of the joints
- metallurgical and microstructural characteristics of the brazed joint
- sensitivity to misalignment and/or brazed gap variations
- other “undefined” uncertainties



## ❑ MARGINS OF SAFETY

$$MS = \frac{\sigma_{ALLOWABLE}}{FS \times \sigma_{MAX}} - 1 > 0$$

If FS becomes inclusive of various knock downs due to uncertainties in design and fabrication of the brazed structures, its value is going to increase. In order to keep MS positive, we would have to decrease the maximum operating stress (load) or increase allowable stress (load).

In real applications, it is very unlikely for designers to be able to reduce the maximum operating loads. Those are dictated by the requirements imposed by the customer.

Therefore, it is important to determine the correct or realistic value for allowable load or stress applicable to a given brazed joint. Unreasonably high value of allowable stress will lead to a false sense of security.

## □ DESIGN ALLOWABLES

MMPDS-02  
1 April 2005

### 8.2.3 BRAZING

**8.2.3.1 Copper Brazing** — The allowable shear strength for copper brazing of steel alloys shall be 15 ksi, for all conditions of heat treatment. Higher values may be allowed upon approval of the procuring or certifying agency.

The effect of the brazing process on the strength of the parent or base metal of steel alloys shall be considered in the structural design. Where copper furnace brazing is employed, the calculated allowable strength of the base metal which is subjected to the temperatures of the brazing process shall be in accordance with the following:

Material	Allowable Strength
Heat-treated material (including normalized) used in "as-brazed" condition	Mechanical properties of normalized material
Heat-treated material (including normalized) reheated during or after brazing	Mechanical properties corresponding to heat treatment performed

**8.2.3.2 Silver Brazing** — Silver-brazed areas should not be subjected to temperatures exceeding 900°F. Silver brazing alloys are listed in specification QQ-B-654. Deviation from this specification may be allowed upon approval of the procuring or certifying agency.

The allowable shear strength for silver brazing of steel alloys shall be 15 ksi, provided that clearances or gaps between parts to be brazed do not exceed 0.010 in. Deviation from this specified allowable value may be allowed upon approval of the procuring or certifying agency.

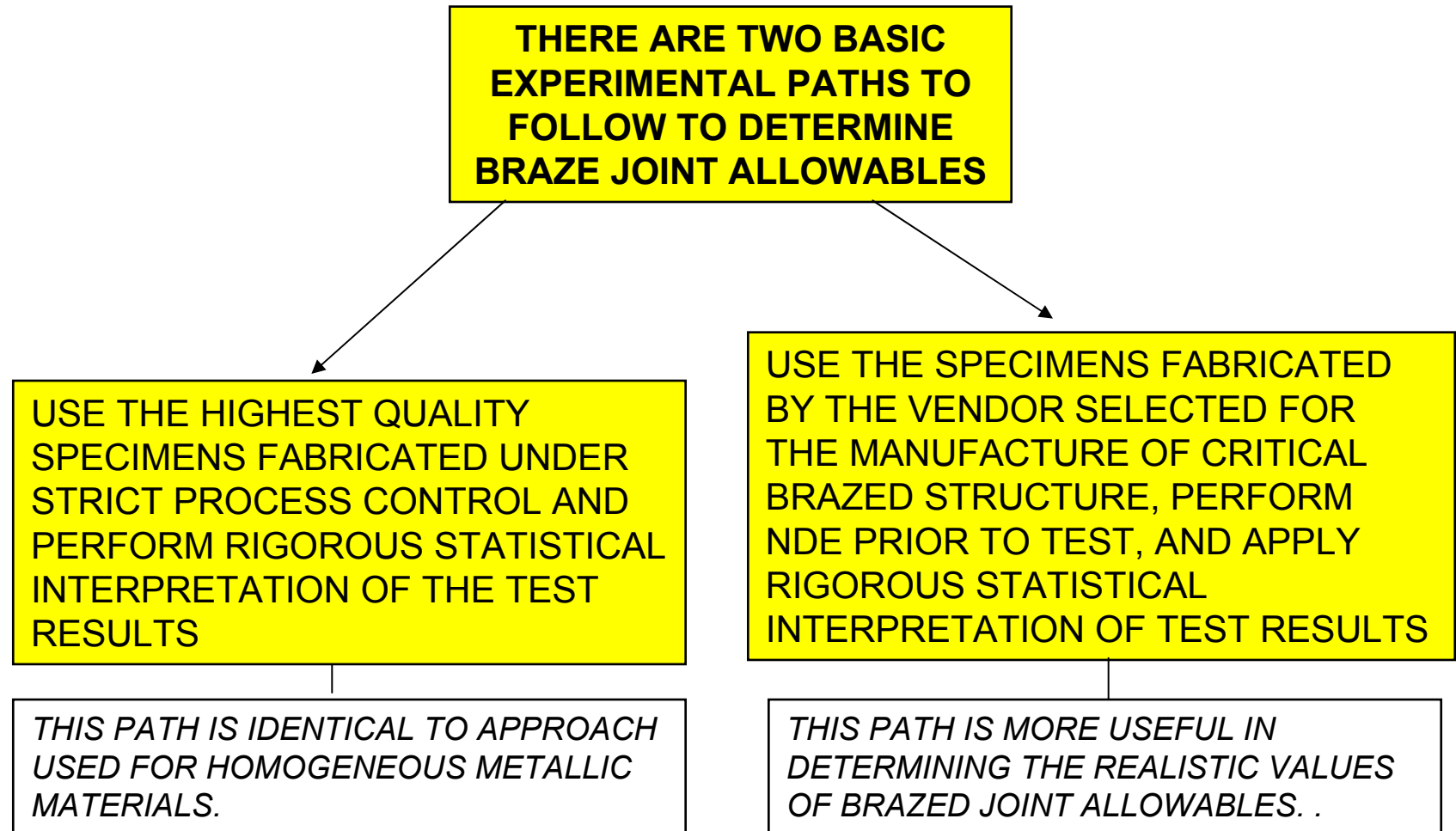
( Ref. 9 )

The most common source for design allowables in aerospace industry for homogeneous metallic materials is MMPDS (formerly MIL-HDBK-5). Unfortunately, information available on the brazed joints is very limited, as shown on the left.

Design allowables are determined experimentally by testing the standard specimens.

Since there are two fundamental types of brazed joints (lap shear and butt) we have two fundamental types of allowables: shear and tensile strength design allowables.

### ❑ DESIGN ALLOWABLES



### ❑ DESIGN ALLOWABLES

#### WHAT IS THE MOST STRAIGHT FORWARD USE OF SHEAR AND TENSILE STRENGTH ALLOWABLES?

- ❑ SHEAR STRENGTH ALLOWABLES ARE USED TO ESTIMATE THE OVERLAP DISTANCE NEEDED TO ACHIEVE FULL STRENGTH IN BRAZED JOINTS WITH VERY SIMPLE GEOMETRY AS WELL AS MARGINS OF SAFETY IN LAP JOINTS.
- ❑ TENSILE STRENGTH ALLOWABLES ARE USED TO DETERMINE THE CROSS SECTIONAL AREA OF THE BUTT JOINT AS WELL AS MARGIN OF SAFETY IN BUTT JOINTS.

**IN ORDER TO BE ABLE TO USE SHEAR AND TENSILE STRENGTH ALLOWABLES FOR DESIGN OF COMPLEX JOINTS UNDER MULTIAXIAL LOADING CONDITIONS, ONE NEEDS TO ESTABLISH FAILURE CRITERIA OR INTERACTION EQUATIONS BASED ON SHEAR AND TENSILE ALLOWABLES OBTAINED BY TEST**




### ❑ MECHANICAL TESTING

#### WHY DO WE NEED TO TEST BRAZED JOINTS?

THERE ARE THREE BASIC REASONS:

- ❑ MEASURE / TEST FUNDAMENTAL PROPERTIES (**DESIGN ALLOWABLES**) OF THE JOINTS AND USE THEM FOR DESIGN OF COMPLEX BRAZED ASSEMBLIES
- ❑ VERIFY QUALITY OF THE BRAZING PROCESS  
(witness samples)
- ❑ VERIFY LOAD CARRYING CAPABILITY OF THE BRAZED COMPONENT OR STRUCTURE (PROOF TEST)

### MECHANICAL TESTING

-  FOCUS OF THIS SEMINAR IS ON TESTING FUNDAMENTAL PROPERTIES OF THE BRAZED JOINTS LEADING TO DEVELOPMENT OF DESIGN ALLOWABLES.
-  FUNDAMENTAL PROPERTIES OF THE BRAZED JOINTS ARE DETERMINED BY TESTING **STANDARD** TEST SPECIMENS.
-  PROCESS VERIFICATION (WITNESS SAMPLES) AND PROOF TESTING USUALLY INVOLVE NON-STANDARD OR APPLICATION-SPECIFIC SPECIMENS.

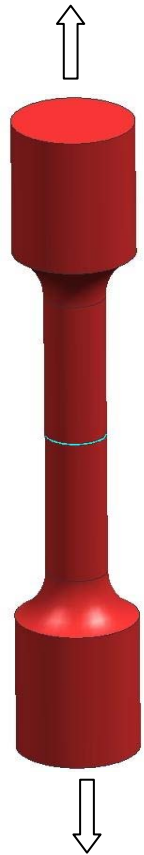
## □ MECHANICAL TESTING

THE FOLLOWING STANDARDS PROVIDE INFORMATION ON BRAZED SPECIMENS DESIGN AND TESTING PROCEDURES

STANDARD*	TEST TYPE	TEST OBJECTIVE
ISO 5187	TENSILE, SHEAR, CREEP SHEAR	FUNDAMENTAL PROPERTIES
EN 12797 (European Std)	TENSILE, SHEAR, 3-pt BEND, PEEL	FUNDAMENTAL & PROCESS VERIFICATION
AWS C3.2 (USA)	TENSILE, SHEAR, 4-pt BEND, CREEP	FUNDAMENTAL PROPERTIES
GOST 28830-90 GOST 24167-80 GOST 23046-78 GOST 26446-85 (Russian Federation)	TENSILE, SHEAR, CREEP SHEAR 3-pt BEND IMPACT FATIGUE	FUNDAMENTAL & PROCESS VERIF. FUNDAMENTAL FUNDAMENTAL FUNDAMENTAL

\* - *THIS LIST MAY NOT BE COMPLETE*

### □ MECHANICAL TESTING



TENSILE



SHEAR

WE WILL FOCUS ON TWO MOST FUNDAMENTAL TESTS: TENSILE AND SHEAR. THESE TESTS ARE PERFORMED ON BUTT JOINT AND LAP SHEAR BASIC CONFIGURATIONS SHOWN ON THE LEFT.

IT IS RECOGNIZED THAT VARIOUS STANDARDS ADDRESSING DESTRUCTIVE TESTING OF THE BRAZED JOINTS OFFER DIFFERENT TYPES OF TEST SPECIMENS TO MEASURE SHEAR STRENGTH OF THE BRAZED JOINTS.

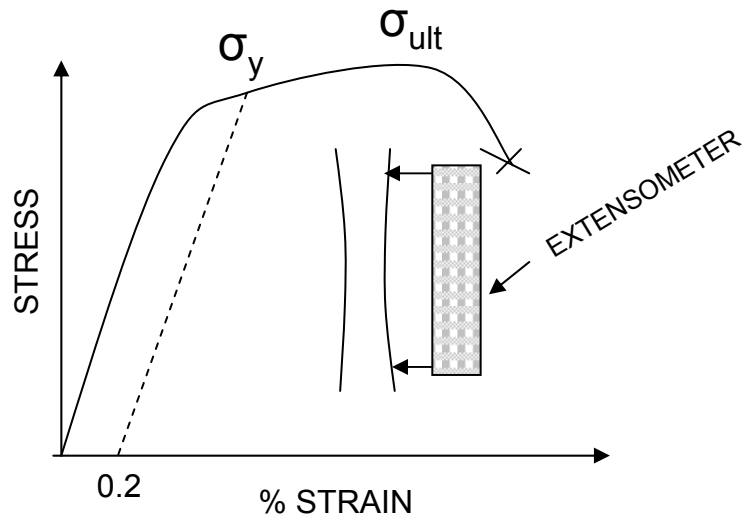
THE PRACTICE SHOWS, HOWEVER, THAT THE SIMPLEST “DOGBONE” GEOMETRY (ASTM E8) SHOWN ON THE LEFT ALLOWS MEASUREMENT OF THE VALUES OF THE AVERAGE SHEAR STRENGTH AS WELL AS THE OTHER, MORE SOPHISTICATED SPECIMENS.



## MECHANICAL TESTING

### TENSILE TEST

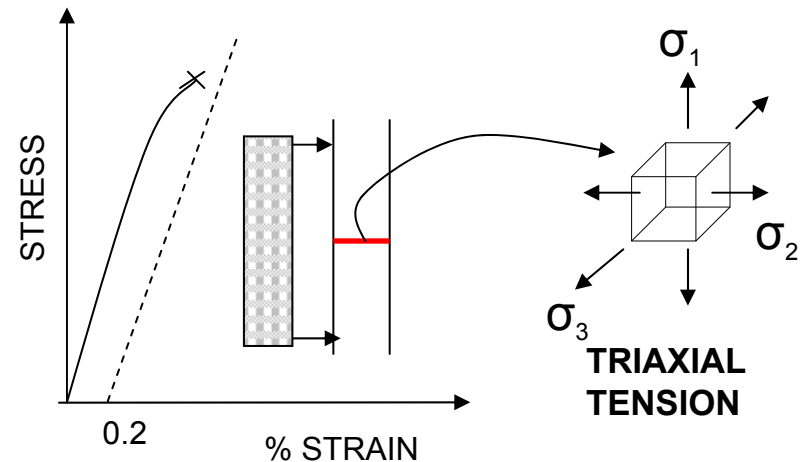
#### HOMOGENEOUS DUCTILE BASE METAL



#### PROPERTIES OBTAINED:

- YIELD STRENGTH
- TENSILE ULTIMATE STRENGTH
- ELONGATION TO FAILURE
- ELASTIC MODULUS
- AREA REDUCTION

#### BUTT JOINT W/ DUCTILE FILLER METAL



#### PROPERTIES OBTAINED:

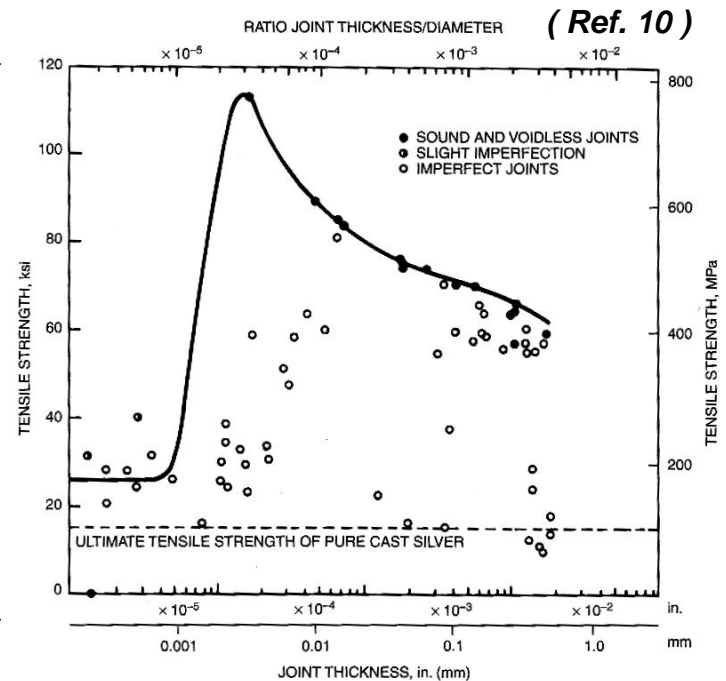
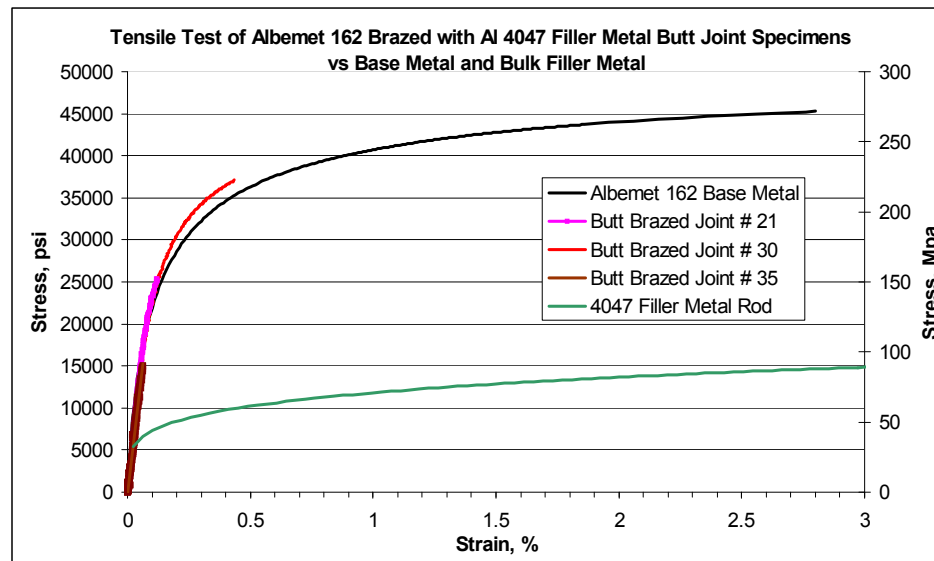
- TENSILE ULTIMATE STRENGTH

YIELD STRENGTH (0.2 % OFFSET) IS NOT DEFINED OR IDENTICAL TO BASE METAL; ELONGATION TO FAILURE IS VERY SMALL (BRITTLE-LIKE); MODULUS IS IDENTICAL TO BASE METAL; THE ONLY DUCTILE CHARACTERISTIC IS FRACTURE SURFACE MORPHOLOGY (DIMPLES).

## MECHANICAL TESTING

### TENSILE TEST

DUCTILE FILLER METAL IS IN THE STATE OF TRIAXIAL TENSION WITHIN THE MAIN PORTION OF THE BUTT JOINT. THIS GREATLY REDUCES THE ABILITY TO PLASTICALLY DEFORM (HYDROSTATIC COMPONENT OF STRESS STATE IS MUCH GREATER THAN DEVIATORIC). CONSEQUENTLY, BUTT BRAZED SPECIMENS ARE MUCH STRONGER THAN THE FILLER METALS TESTED IN THE BULK, UNRESTRAINED FORM IN ANNEALED CONDITION.



## □ MECHANICAL TESTING

### TENSILE TEST

#### □ DUCTILE FILLER METAL / STRONG BASE METAL COMBINATION:

$$E_{BM} > E_{FM} \quad \sigma_{TUS}^{BM} > \sigma_{TUS}^{FM}$$

EXPECT TO HAVE  $\sigma_{TUS}^{BM} > \sigma_{ALLOWABLE} > \sigma_{TUS}^{FM}$

#### □ STRONG FILLER METAL / STRONG BASE METAL COMBINATION:

$$E_{BM} \sim E_{FM} \quad \sigma_{TUS}^{BM} \sim \sigma_{TUS}^{FM}$$

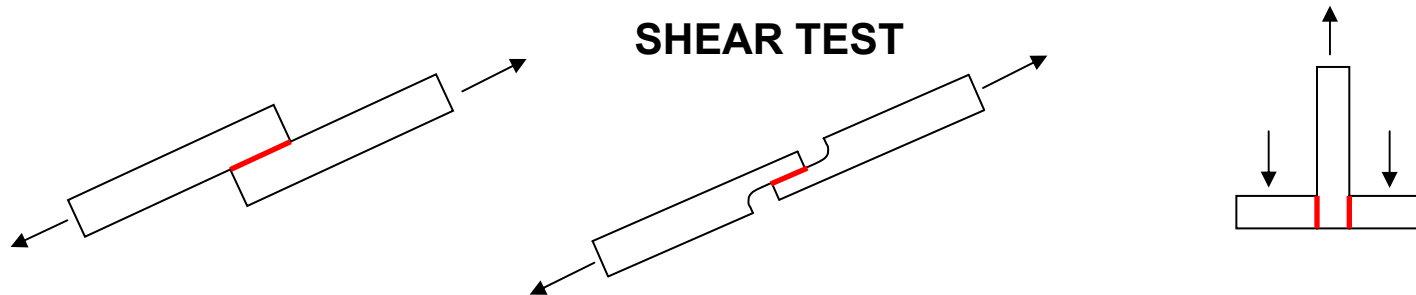
EXPECT TO HAVE  $\sigma_{ALLOWABLE} \sim \text{WEAKER OF TWO.}$

### ☐ MECHANICAL TESTING

#### TENSILE TEST

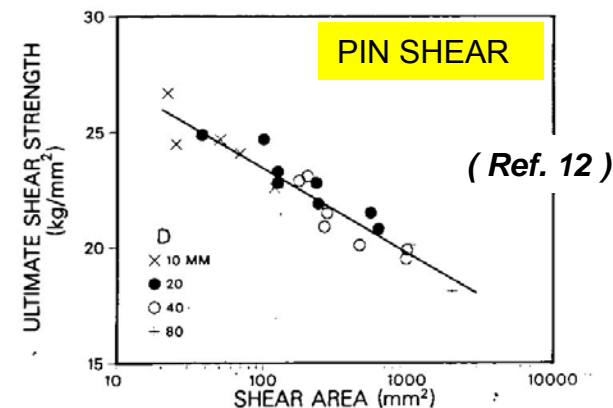
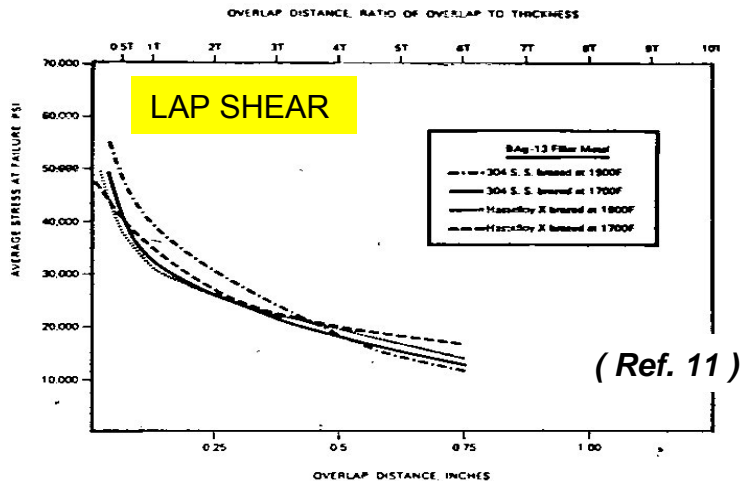
- ☐ THE MAIN BENEFIT OF TENSILE TESTING IS ESTABLISHING THE TENSILE ALLOWABLE FOR STATIC LOADING.
- ☐ UNFORTUNATELY, NO OTHER MECHANICAL PROPERTIES OF THE FILLER METAL INTERLAYER ( **YIELD STRENGTH, ELONGATION TO FAILURE, STRESS-STRAIN CURVE**) CAN BE OBTAINED FROM THE STANDARD BUTT JOINT TENSILE TESTS.
- ☐ YIELD STRENGTH AND STRESS-STRAIN CURVE THAT ACCURATELY REPRESENT THE PROPERTIES OF THE FILLER METAL INTERLAYER ARE IMPORTANT FOR ANALYTICAL ASSESSMENT OF CREEP, LOW CYCLE FATIGUE, RESIDUAL STRESSES, RESISTANCE TO CRACK GROWTH AND OTHER PROPERTIES OF THE BRAZED JOINTS, PARTICULARLY WHEN FINITE ELEMENT ANALYSIS IS EMPLOYED.

## MECHANICAL TESTING



DESPITE THE VARIETY OF THE TEST SPECIMEN GEOMETRIES, THE COMMON TREND IS THAT THE AVERAGE SHEAR STRENGTH OF THE LAP JOINT DECREASES WITH THE INCREASE IN THE OVERLAP LENGTH.

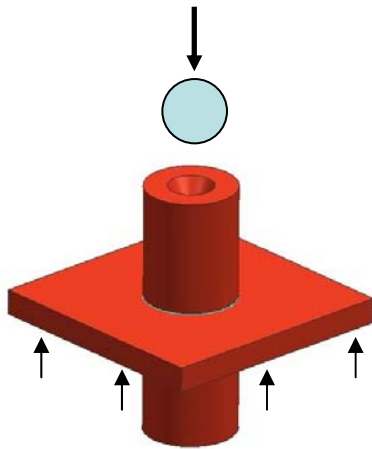
AN EFFORT TO DESIGN “PURE” SHEAR BRAZED TEST SPECIMENS IS NOT PRODUCTIVE: - “PURE” SHEAR LOADING CONDITIONS ARE SELDOM ENCOUNTERED IN PRACTICE;



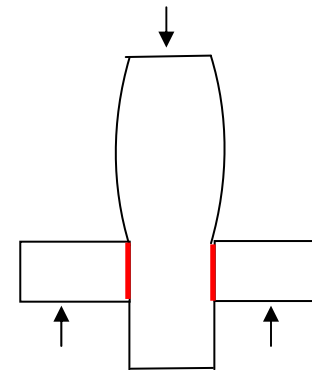
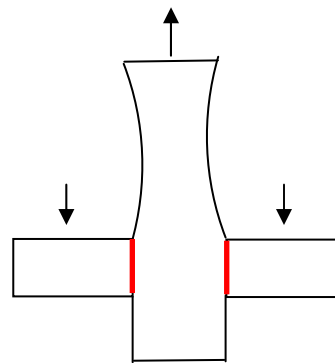
## MECHANICAL TESTING

### SHEAR TEST

- WHEN SELECTING PIN SHEAR TEST GEOMETRY, PLEASE BE AWARE THAT **PULL  $\neq$  PUSH**



BECAUSE OF IT'S RELATIVE SIMPLICITY VENDORS SOMETIMES LIKELY TO PERFORM A PUSH-TYPE TEST ON PIN SHEAR SPECIMENS.



EXAGGERATED DEFORMATION DURING PULL & PUSH TESTS

## MECHANICAL TESTING

### SHEAR TEST

**Table 1 — Shear Strength Values Obtained for Brazed Joints**

Pull type test, Fig. 3 (a)

Specimen no.	d <sub>0</sub> , mm	d, mm	Braze area, mm <sup>2</sup>	Ult. shear str., τ <sub>B</sub> , kg/mm <sup>2</sup>	ksi
1	35	24	678	14.3	20.3
2	35	23	579	12.8	18.2
3	35	22	518	14.5	20.6
4	35	21	462	14.3	20.3
5	35	20	427	13.1	18.6
6	35	17	321	15.0*	21.3
7	35	16	277	14.6*	20.7
				Avg 14.1	20.0

Push type test, Fig. 3(b)

8	17	10	299	22.3*	31.7
9	17	10	295	22.0*	31.2
10	20	10	289	21.7*	30.8
11	20	10	286	23.1*	32.8
12	22	10	283	21.8*	30.9
13	22	10	280	22.1*	31.4
14	27	10	277	21.8*	30.9
15	35	24	422	22.6	32.1
16	35	24	399	21.8	31.1
17	35	24	377	21.9	31.4
				Avg 22.1	

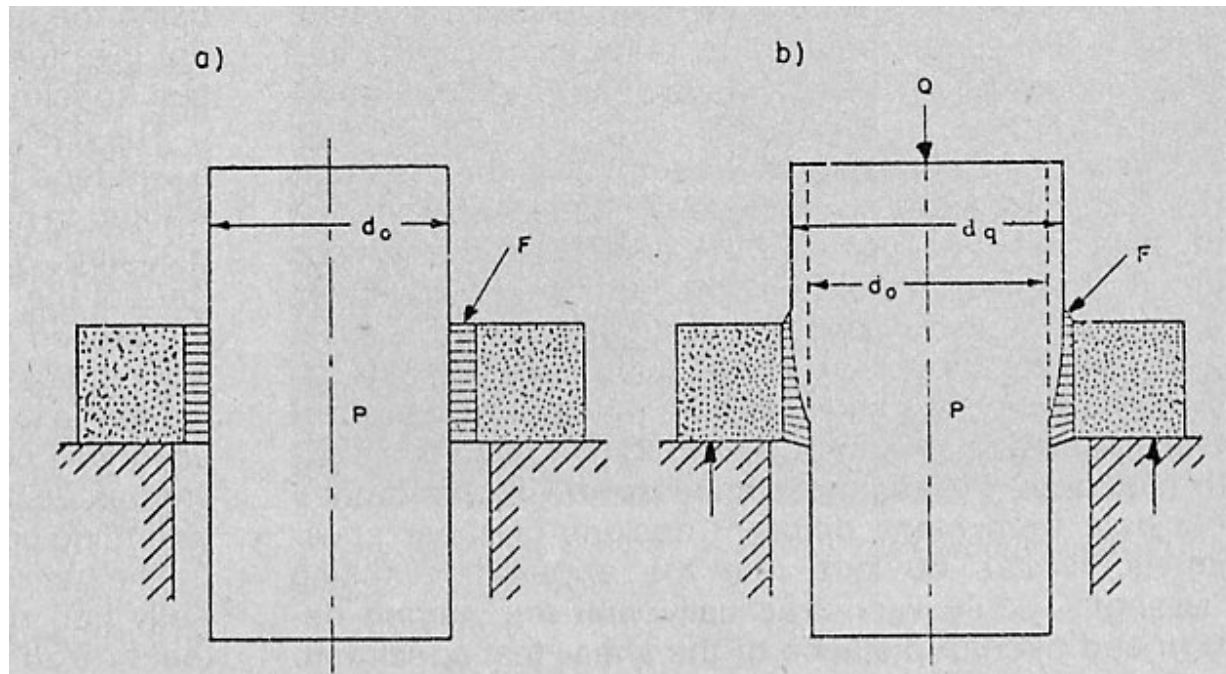
$$\tau_{PUSH} \sim 1.5 \tau_{PULL}$$

EXPERIMENTAL RESULTS DEMONSTRATE THAT SHEAR STRENGTH OBTAINED IN THE PUSH TEST EXCEEDS THE STRENGTH MEASURED IN PULL TEST.

( Ref. 13 )

## MECHANICAL TESTING

### SHEAR TEST



( Ref. 14 )

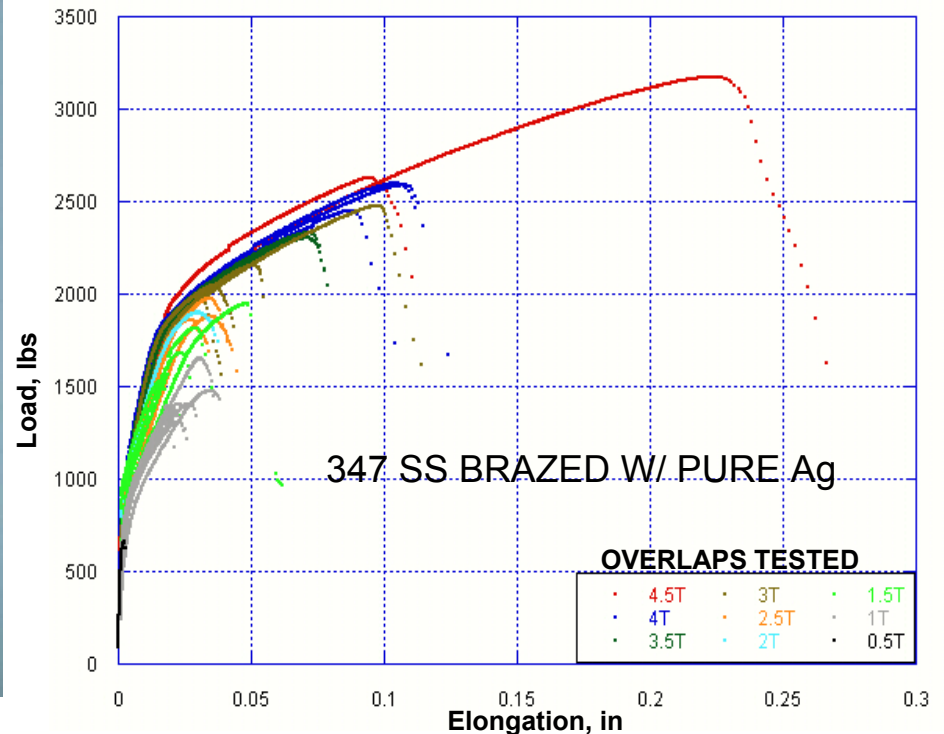
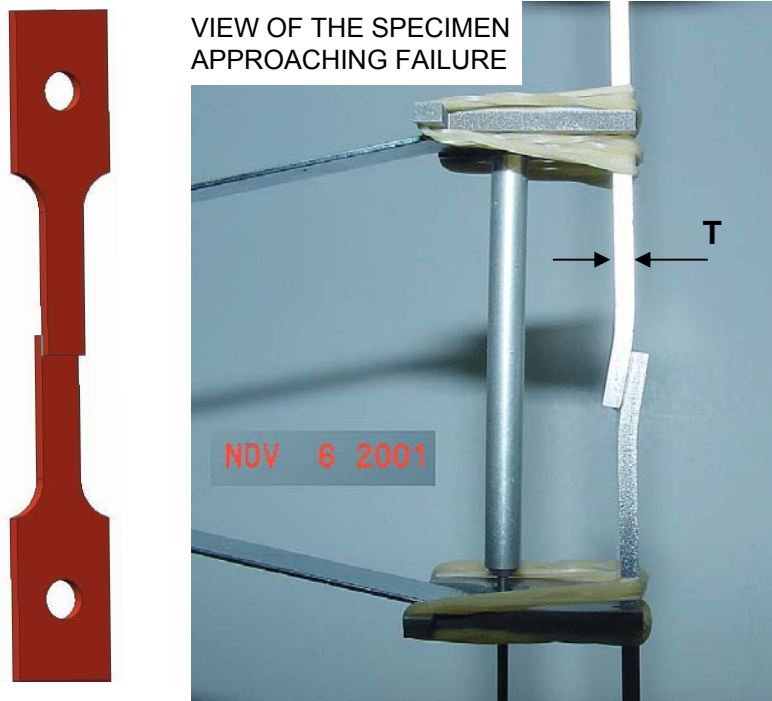
*Fig. 5 — Plug and ring device (compression) for shear-strength determination in brazed joints: (a) Before loading and (b) after loading. Due to the expansion of the plug, P, under the load, Q, the diameter of the plug increases from  $d_o$  to  $d_q$ . This expansion results in a combination of compression and shear stresses in the filler-metal layer, F. The compressive stresses are especially large in the upper part of the filler-metal layer. (Courtesy Frankford Arsenal)*



## MECHANICAL TESTING

### SHEAR TEST

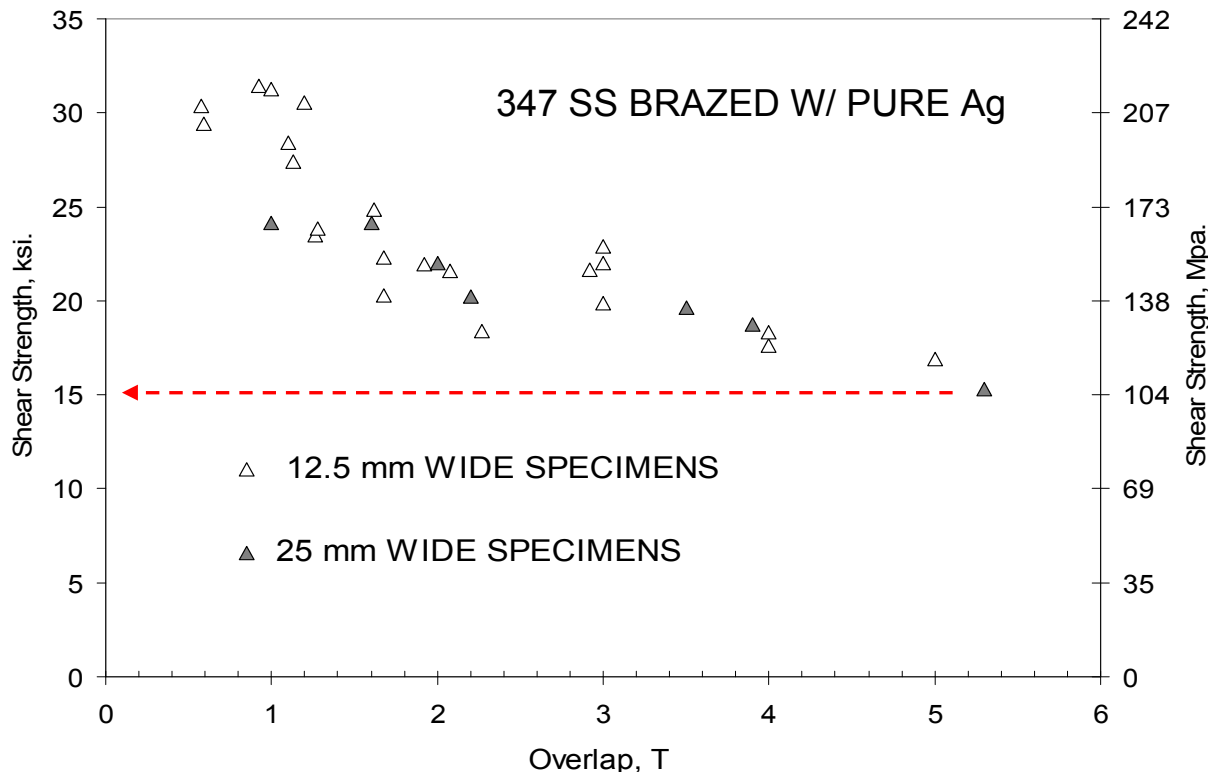
WHAT CAN WE LEARN FROM STANDARD SHEAR TESTS (AWS C3.2)?



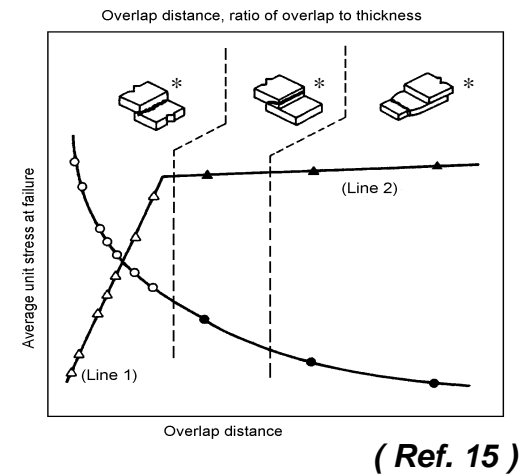
IT IS NOT ESSENTIAL TO USE EXTENSOMETER. IT MAY HELP TO VISUALIZE THE THREE DIFFERENT PHASES OF DEFORMATION [ a) initial loading; b) realignment and c) final stretching ] IN LAP SHEAR SPECIMENS COMPRISED OF DUCTILE BASE & FILLER METALS COMBINATION.

## MECHANICAL TESTING

### SHEAR TEST



**ACTUAL EXPERIMENTAL RESULTS FROM SHEAR TESTING OF SINGLE LAP SHEAR SPECIMENS PER AWS C 3.2 STANDARD. NOTE THE LOWEST SHEAR STRENGTH ~ 15 ksi (104 Mpa)**



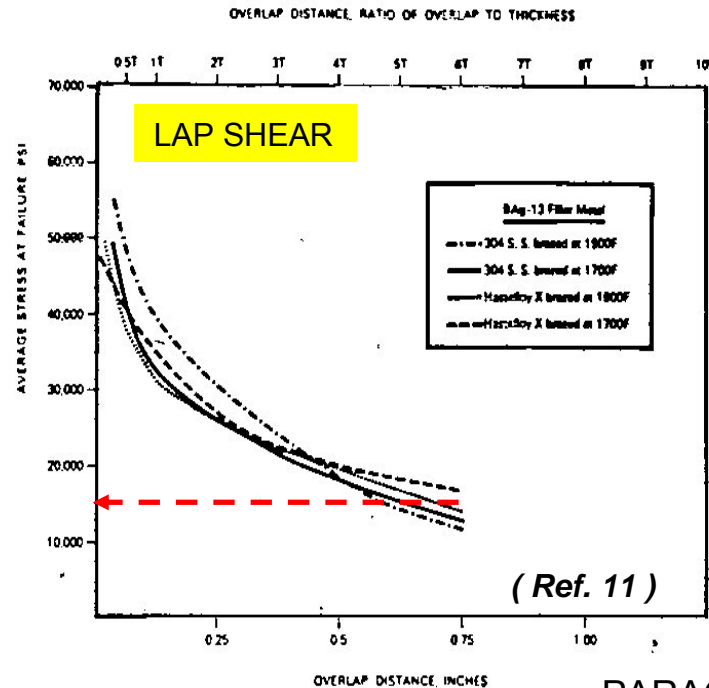
**IDEALIZED PLOT OF SHEAR STRENGTH VS. OVERLAP DISTANCE GIVEN AS A GUIDE IN STANDARD AWS C 3.2**

$$\tau_{AVG} = f(L)$$

Where  $L$  is overlap distance

## MECHANICAL TESTING

### SHEAR TEST



AS WE CAN SEE, THE SHEAR STRENGTH ALLOWABLE SELECTED BY MMPDS (MIL-HDBK-5) FOR SILVER BRAZED STEEL LAP JOINTS IS CLOSE TO THE LOWEST SHEAR STRENGTH OBTAINED EXPERIMENTALLY FROM THE SHEAR TESTS.

IT APPEARS THAT DESIGNER DOES NOT BENEFIT FROM THE HIGHER SHEAR STRENGTHS AT SHORTER OVERLAPS!!!

AS OVERLAP DISTANCE DECREASES SHEAR STRESS DISTRIBUTION BECOMES MORE UNIFORM APPROACHING PURE SHEAR

PARAGRAPH TAKEN FROM MMPDS-02

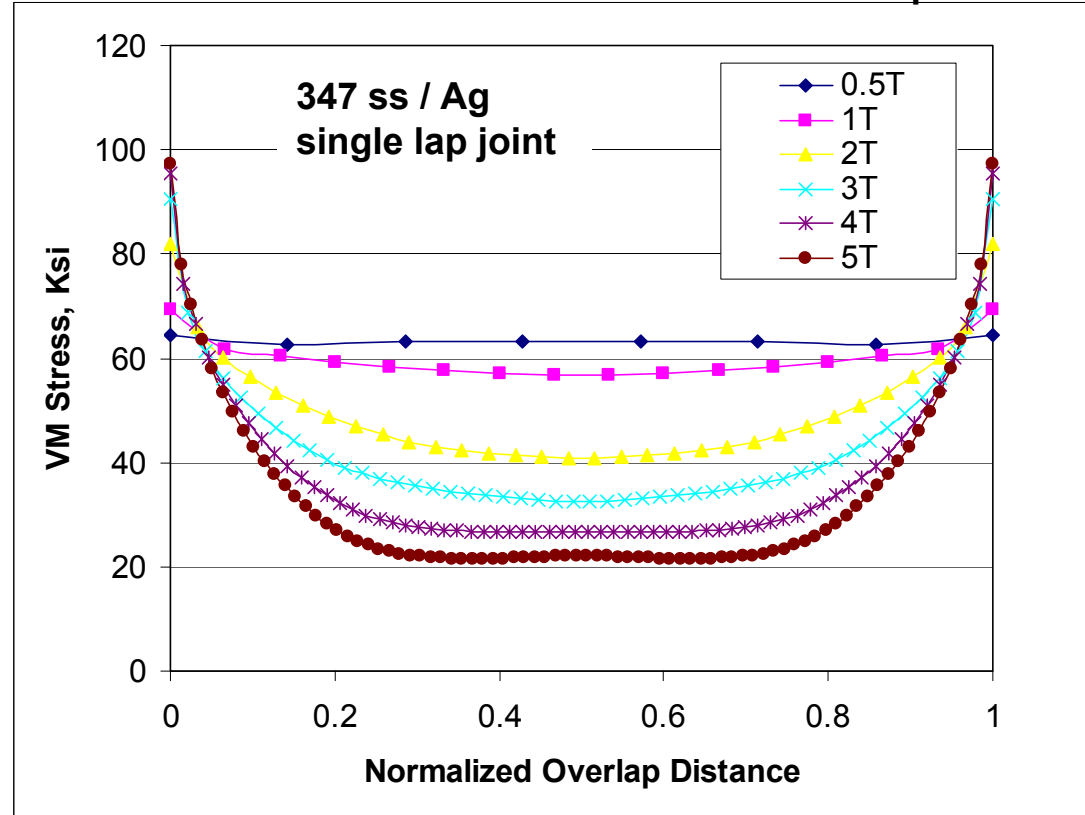
**8.2.3.2 Silver Brazing** — Silver-brazed areas should not be subjected to temperatures exceeding 900°F. Silver brazing alloys are listed in specification QQ-B-654. Deviation from this specification may be allowed upon approval of the procuring or certifying agency.

The allowable shear strength for silver brazing of steel alloys shall be 15 ksi, provided that clearances or gaps between parts to be brazed do not exceed 0.010 in. Deviation from this specified allowable value may be allowed upon approval of the procuring or certifying agency.

## MECHANICAL TESTING

### SHEAR TEST

Von Mises Stress Distribution for Various Overlap Distances

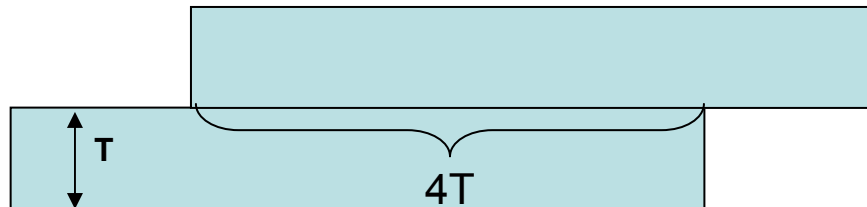
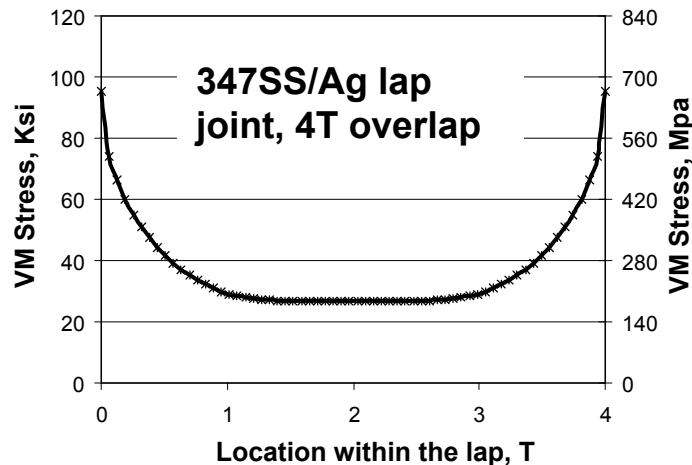


( Ref. 16 )

AS OVERLAP DISTANCE INCREASES ( STARTING AROUND 4T) THE VM STRESS DISTRIBUTION IN THE MIDDLE PORTION OF THE LAP BECOMES MORE UNIFORM

NOTE THAT VM STRESS IN UNIFORM REGION IS QUITE LOW, SOMEWHERE BETWEEN 20 AND 30 ksi.

## MECHANICAL TESTING



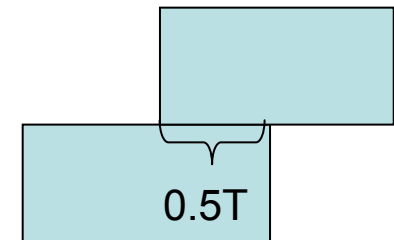
The longer the overlap, the larger the region of constant  $\sigma_{vm}$  or  $\tau$

## SHEAR TEST

$$\tau = \frac{1}{\sqrt{3}} \cdot \sigma_{vm} = 0.577 \cdot \sigma_{vm}$$

For  $\sigma_{vm} = 27$  ksi,  $\tau = 15.6$  ksi = very close to 15 ksi shear strength for silver-base BFM given in MMPDS (former MIL-HDBK-5) !

VERY SHORT OVERLAPS HAVE UNIFORM, ALMOST "PURE" SHEAR STRESS, BUT THAT VALUE IS NOT USED IN ENGINEERING ANALYSIS



### □ MECHANICAL TESTING

□ WE HAVE DISCUSSED BOTH TENSILE AND SHEAR TESTS AND WHAT ALLOWABLES CAN BE OBTAINED FROM THESE TESTS. BEFORE WE START TALKING ABOUT THE USE OF THESE ALLOWABLES IN COMPLEX, MULTIAXIAL LOADING CONDITIONS AND JOINT GEOMETRIES, WE STILL NEED TO ADDRESS AN IMPORTANT ASPECT OF THE BRAZED SPECIMEN TESTING

□ IT IS IMPORTANT TO DECIDE VERY EARLY IN THE PROJECT WHETHER THE FUNDAMENTAL (ALLOWABLES DEVELOPMENT) TEST SPECIMENS


□1) REPRESENT A TYPICAL PRODUCTION QUALITY AND PRODUCTION FIXTURES OF THE SPECIFIC VENDOR SELECTED FOR THE PROJECT OR

□2) REPRESENT THE BEST QUALITY AVAILABLE FOR THIS BRAZING PROCESS REGARDLESS OF WHETHER IT CAN BE ACHIEVED FOR YOUR ASSEMBLY.


□ MY RECOMMENDATION IS TO USE THE SAME CONDITIONS (ESSENTIAL VARIABLES) IN PREPARATION OF THE FUNDAMENTAL TEST SPECIMENS AS WILL BE USED IN FABRICATION OF THE MAIN BRAZED ASSEMBLY. BY DOING SO, YOU WILL CAPTURE THE EFFECTS OF FIXTURING, INTERNAL QUALITY (TRAPPED FLUX, VOIDS, LACK OF BRAZE), ETC. ON BRAZED JOINT ALLOWABLES. IT IS IMPORTANT THAT THE ALLOWABLES REPRESENT THE ACTUAL BRAZED JOINTS BEING DESIGNED.

## □ MECHANICAL TESTING

□ TENSILE AND SHEAR ALLOWABLES SHOULD CAPTURE THE INFLUENCE OF THE BRAZING PROCESS ESSENTIAL VARIABLES, JOINT GEOMETRY AND THE INTERNAL QUALITY ON THE RESULTANT MECHANICAL PROPERTIES OF THE PRODUCTION JOINT.

□ FROM TENSILE TEST:  $\sigma = f(\sigma^{FM}, \frac{\delta}{D}, Q)$   TENSILE ALLOWABLE

$\sigma^{FM}$  – strength of the filler metal (bulk) ,  $\delta / D$  – aspect ratio,  $Q$  – quality factor

□ FROM SHEAR TEST:  $\tau = f(\sigma^{FM}, \frac{\delta}{W}, L, Q)$   SHEAR ALLOWABLE

$\delta / W$  – aspect ratio,  $L$  – overlap distance,  $Q$  – quality factor

### **❑ FAILURE CRITERIA**

- ❑ AFTER FUNDAMENTAL MECHANICAL TESTING OF THE BRAZED SPECIMENS IS COMPLETED AND TENSILE AND SHEAR ALLOWABLES ARE ESTABLISHED THE NEXT QUESTION TO ANSWER IS HOW TO USE THESE ALLOWABLES FOR DESIGN OF THE ACTUAL BRAZED JOINTS?
- ❑ IF THERE WERE BRAZED JOINT FAILURE CRITERIA APPLICABLE TO BRAZED ASSEMBLIES AND CONSISTING OF SOME KIND OF INTERACTION BETWEEN THE TENSILE AND SHEAR ALLOWABLES, WE COULD ESTIMATE THE MARGINS OF SAFETY OF THE BRAZED JOINTS.
- ❑ UNFORTUNATELY, AT THE PRESENT TIME THERE ARE NO STANDARD FAILURE CRITERIA FOR BRAZED JOINTS, EXCEPT FOR THE VERY BASIC OR SIMPLE JOINTS SUCH AS LAP OR BUTT JOINTS SUBJECTED TO UNIAXIAL LOADS.
- ❑ CONSEQUENTLY, IT BECOMES THE DESIGNER'S TASK TO ESTABLISH THE FAILURE CRITERION FOR THE TYPE(S) OF BRAZED JOINTS CONSIDERED FOR FABRICATION OF THE CRITICAL BRAZED STRUCTURE. THIS TASK SHOULD BE INITIATED VERY EARLY IN THE LIFE OF THE PROJECT.



## ❑ FAILURE CRITERIA

❑ ISOTROPIC METALLIC MATERIALS HAVE REASONABLY WELL DEFINED FAILURE CRITERIA THAT ARE USED BY STRUCTURAL ENGINEERS TO DETERMINE THE “HEALTH” OF THE COMPONENT SUBJECTED TO STATIC LOADS.

GENERAL FORM  $\rightarrow f(\sigma_1, \sigma_2, \sigma_3) = \sigma_c$  AT FAILURE

❑ THE STRUCTURAL COMMUNITY GENERALLY ACCEPTS USE OF **TRESCA (SHEAR)** OR **VON MISES** CRITERIA TO DETERMINE THE ONSET OF YIELDING IN DUCTILE MATERIALS. YIELDING IN THE MAJORITY OF STRUCTURES IS CONSIDERED TO BE A FAILURE EVENT. FOR THE PURPOSE OF THIS SEMINAR WE ARE GOING TO IGNORE SUCH FAILURES AS INSTABILITY, BUCKLING, CRACK PROPAGATION, ETC.

<u>TRESCA</u>	( Ref. 17 )	<u>VON MISES</u>
$\tau_{MAX} = \frac{\sigma_1 - \sigma_3}{2} = \tau_0$	$\sigma_0 = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}$	
OR		
$\sigma_1 - \sigma_3 = \sigma_0$	$\sigma_0 = \text{yield strength in uniaxial test} = \sigma_{TYS}$	
	$\tau_0$ — CRITICAL VALUE OF SHEAR STRESS; $\sigma_0$ - MATERIAL PROPERTY	

## ❑ FAILURE CRITERIA

❑ FOR LESS DUCTILE ISOTROPIC MATERIALS (ELONGATION IS < 2%) STRUCTURAL ANALYSTS DETERMINE FIRST (LARGEST) PRINCIPAL STRESS IN THE COMPONENT AND COMPARE IT TO THE UNIAXIAL YIELD OR ULTIMATE STRENGTH.

$$\sigma_1 = \sigma_{TYS} \quad or \quad \sigma_1 = \sigma_{TUS}$$

❑ THERE IS ANOTHER FAILURE CRITERION CALLED COULOMB - MOHR WHICH IS CONSISTENT WITH TYPICAL BEHAVIOR OF BRITTLE MATERIALS AND ASSUMES THAT FRACTURE OCCURS ON A GIVEN PLANE IN THE MATERIAL WHEN A COMBINATION OF SHEAR AND NORMAL STRESSES REACH CERTAIN CRITICAL LEVELS.

(Ref. 17)  $\tau + \mu\sigma = C$       Where  $\mu$  and  $C$  are constants for a given material.

❑ THE COULOMB – MOHR FRACTURE CRITERION APPEARS TO BE VERY PROMISING FOR PREDICTION FAILURE IN BRAZED JOINT. IT CAPTURES SEVERAL IMPORTANT CHARACTERISTICS OF THE BRAZED JOINT BEHAVIOR:

- UNLESS FRACTURE IS TRANSITIONED INTO THE BASE METAL, TYPICAL BRAZED JOINT FAILURES OCCUR WITHIN THE THIN INTERLAYER;
- ON MACROSCALE FRACTURE OF BRAZED JOINT IS BRITTLE

- FOR BUTT JOINT TENSILE TEST  $\tau = 0; \mu\sigma = C \quad or \quad \sigma = \frac{C}{\mu} = \sigma_{ALLOWABLE}$
- FOR LAP SHEAR TEST  $\sigma = 0; \tau = C = \tau_{ALLOWABLE}$

## ❑ FAILURE CRITERIA

❑ WITH RESPECT TO THE BRAZED JOINT, COULOMB – MOHR FAILURE CRITERION CAN BE MODIFIED AS FOLLOWS:

$$C = \tau_{ALLOW}; \quad \frac{\tau_{ALLOW}}{\mu} = \sigma_{ALLOW}; \quad \mu = \frac{\tau_{ALLOW}}{\sigma_{ALLOW}}; \quad \tau + \frac{\tau_{ALLOW}}{\sigma_{ALLOW}} \sigma = \tau_{ALLOW} \quad \text{or} \quad \frac{\tau}{\tau_{ALLOW}} + \frac{\sigma}{\sigma_{ALLOW}} = 1$$

❑ THIS IS A VERY SIMPLE, UNDERSTANDABLE AND PRACTICAL FAILURE CRITERION. IT'S USE, HOWEVER, IS LIMITED TO BRAZED JOINTS WHICH CAN BE ANALYZED BY HAND CALCULATIONS BASED ON THE AVERAGE STRESSES ACTING IN THE BRAZE INTERLAYER. KNOWLEDGE OF THE BEAM THEORY AND CROSS-SECTIONAL PROPERTIES WOULD ENABLE TO ESTIMATE THE TOTAL TENSILE AND SHEAR STRESSES ACTING WITHIN CERTAIN CROSS SECTION THROUGH THE BRAZED JOINT.

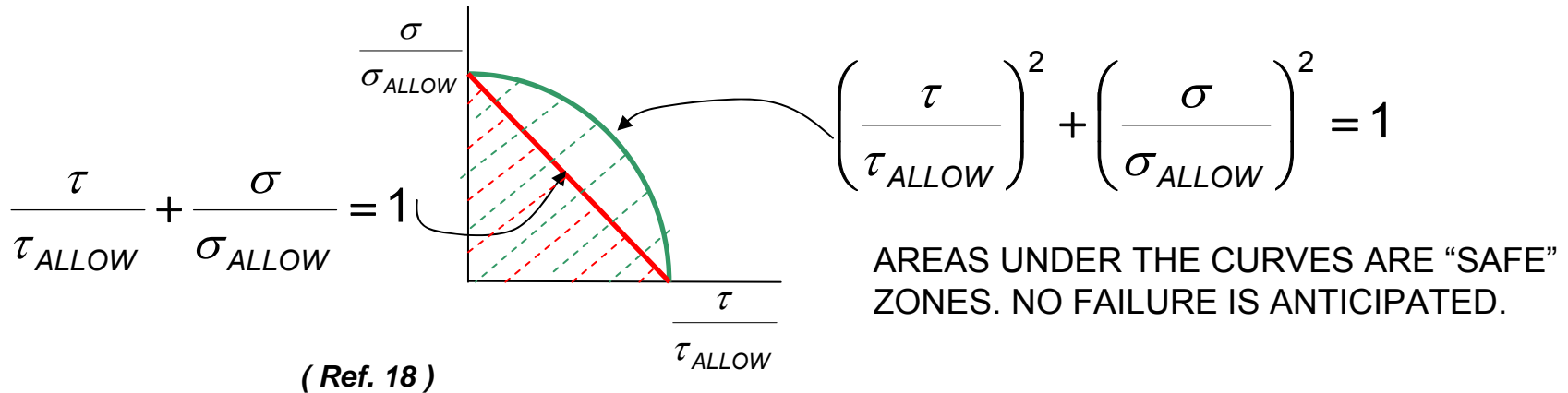
❑ IT IS INTERESTING TO NOTE THAT THE INTERACTION EQUATION ASSESSING THE STRENGTH OF THE ISOTROPIC METALLIC MATERIAL HAS A FORM OF  $R_a^x + R_b^y = 1$

WHERE R's ARE THE RATIOS OF DESIGN STRESSES (SHEAR OR NORMAL) TO CORRESPONDING ALLOWABLE STRESSES. FOR TWO-DIMENSIONAL STRESS STATE THIS INTERACTION EQUATION BECOMES:

(Ref. 3)  $R_s^2 + R_T^2 = 1$  WHERE  $R_s^2 = \frac{\tau}{\tau_{ALLOW}}$  and  $R_T^2 = \frac{\sigma}{\sigma_{ALLOW}}$

## FAILURE CRITERIA

MODIFIED COULOMB-MOHR BRAZED JOINT FAILURE CRITERION IS MORE CONSERVATIVE THAN THE INTERACTION EQUATIONS, AS ONE CAN SEE BELOW:



IN ORDER TO USE THIS COULOMB – MOHR FAILURE CRITERION FOR DESIGN, WE NEED TO ADD A FACTOR OF SAFETY (FS):

$$\frac{1}{FS} \times \left( \frac{\tau}{\tau_{ALLOW}} + \frac{\sigma}{\sigma_{ALLOW}} \right) \leq 1$$

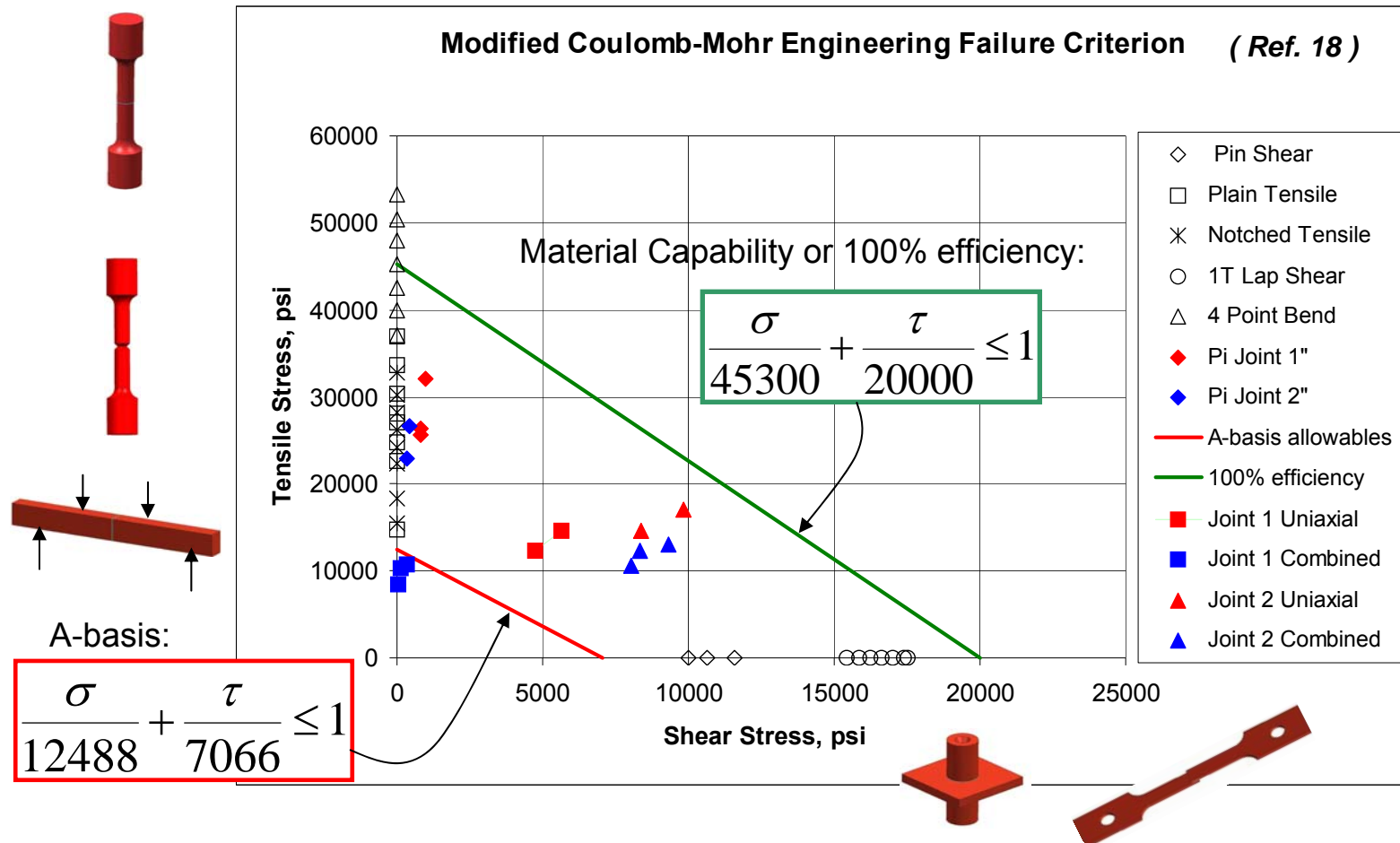
and

$$MS = \frac{1}{FS} \times \left( \frac{\tau}{\tau_{ALLOW}} + \frac{\sigma}{\sigma_{ALLOW}} \right) - 1$$

*MS – Margin of Safety*

## FAILURE CRITERIA

EXAMPLE OF USING MODIFIED COULOMB-MOHR FAILURE CRITERION IN ANALYSIS OF BRAZED JOINTS IS SHOWN BELOW. *BASE METAL – ALBEMET 162 (62% Be, 38% Al) FILLER METAL – AL 4047 (88% Al, 12% Si)*

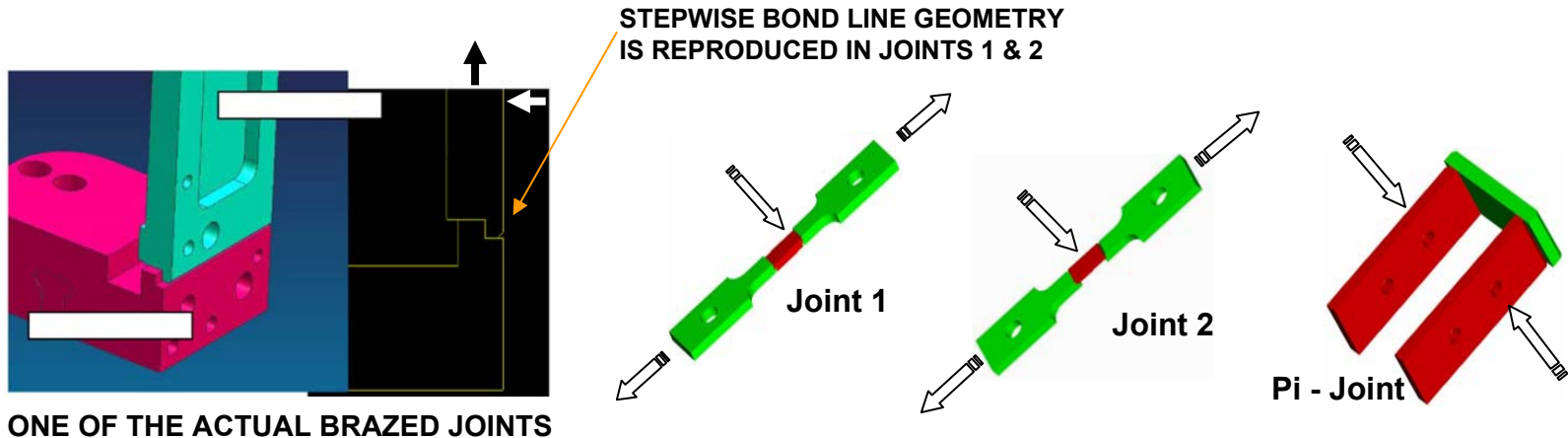


**Material capability line intercepts axes at points that correspond to the strength of the base metal!**

**In other words, the brazed joint is 100% efficient when the failure is transitioned into the base metal.**

## ❑ FAILURE CRITERIA

❑ COLORED DATA SYMBOLS FROM PREVIOUS SLIDE REPRESENT EXPERIMENTAL RESULTS OF TESTS TO FAILURE OF VERIFICATION OR “GEOMETRY-SPECIFIC” TEST SPECIMENS IDENTIFIED AS “Pi – Joint, Joint 1 and Joint 2 AS SHOWN BELOW: (Ref. 18)



❑ IT IS INTERESTING TO NOTE THAT BY INTRODUCING A FACTOR OF SAFETY OF  $\approx 4$  WE CAN “DOWN GRADE” THE FAILURE CRITERION FROM THE “MATERIAL CAPABILITY” OR 100% EFFICIENCY THRESHOLD (GREEN LINE) TO A MORE REALISTIC, PRACTICAL LEVEL (ALMOST A-BASIS), THAT DESIGNER CAN USE TO PREDICT STRENGTH MARGINS!

$$\frac{\sigma}{12488} + \frac{\tau}{7066} \approx \frac{1}{4} \times \left( \frac{\sigma}{45300} + \frac{\tau}{20000} \right) \quad 4 \text{ is a Factor of Safety}$$

## ❑ FAILURE CRITERIA

- ❑ IN SITUATIONS WHERE STRENGTH OF MATERIALS HAND CALCULATIONS ARE TOO COMPLICATED TO PERFORM, STRUCTURAL ENGINEERS USE VERY POWERFUL TOOLS BASED ON FINITE ELEMENT ANALYSIS (FEA). THESE ANALYSES ALLOW ONE TO DETERMINE STRESS STATE AT A SINGLE POINT WITHIN THE STRUCTURE.
- ❑ IN THIS CASE MODIFIED COULOMB-MOHR CRITERION IS NO LONGER APPLICABLE, SINCE IT IS BASED ON THE AVERAGE STRESSES.
- ❑ FOR FEA ANOTHER FAILURE CRITERION HAS BEEN DEVELOPED AND USED AT GSFC. THIS CRITERION IS BASED ON CHRISTENSEN WORK (*Ref. 19*) AND WE CALL IT MODIFIED CHRISTENSEN FAILURE CRITERION.

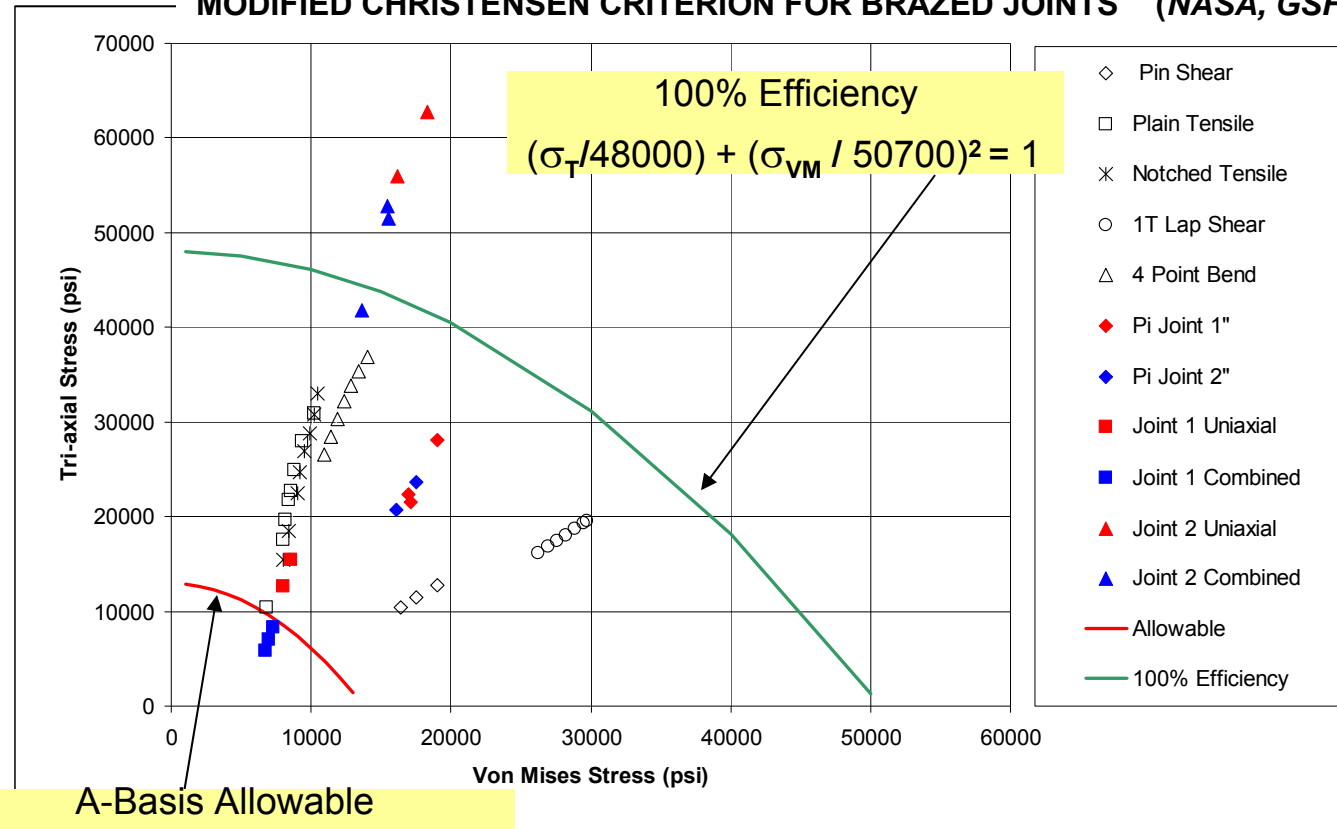
$$\left( \frac{\sigma_{VM}}{\sigma_{VM MAX}} \right)^2 + \frac{\sigma_T}{\sigma_{T MAX}} \leq 1 \quad \sigma_T = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$

$\sigma_T = \text{TRIAXIAL STRESS}$

## FAILURE CRITERIA

MODIFIED CHRISTENSEN FAILURE CRITERION WAS APPLIED TO THE SAME BRAZED JOINTS IN ALBEMET 162 STRUCTURE BRAZED WITH AWS BAI4 (Al 4047).

MODIFIED CHRISTENSEN CRITERION FOR BRAZED JOINTS (NASA, GSFC)

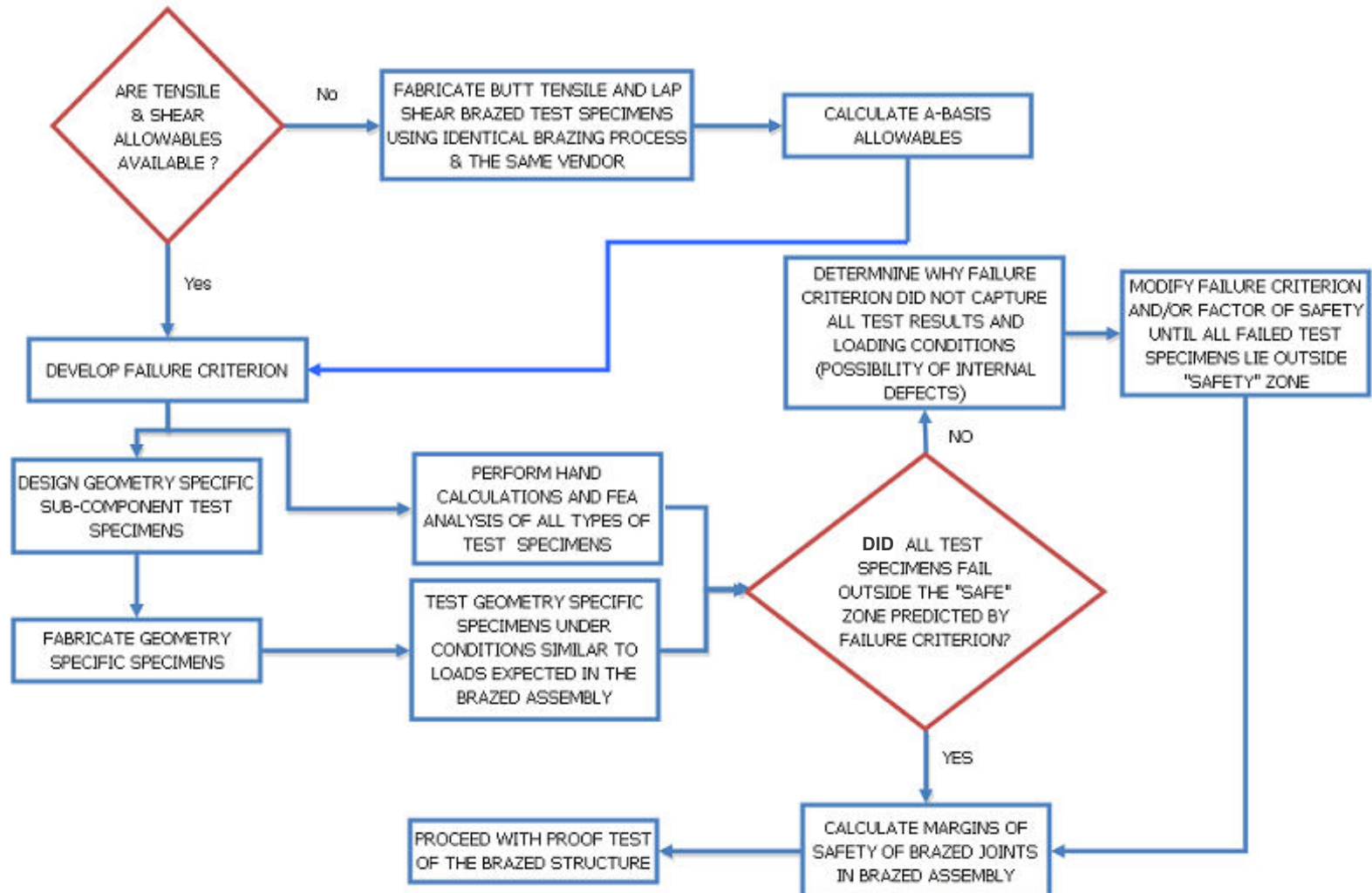


COLORED SYMBOLS REPRESENT THE SAME "GEOMETRY-SPECIFIC" TEST SPECIMENS USED IN COULOMB- MOHR ANALYSIS.


AGAIN COMPARING 100% EFFICIENCY THRESHOLD WITH A-BASIS RESULTS POINTS TO  $\approx 4$  AS A ROUGH ESTIMATE OF SAFETY FACTOR



## □ DESIGN FLOWCHART



## BRAZE GAP

 PERHAPS ONE OF THE MOST FREQUENT QUESTIONS ASKED BY MECHANICAL ENGINEERS DESIGNING A BRAZED ASSEMBLY IS WHAT BRAZE GAP THEY SHOULD SPECIFY ON THE ASSEMBLY DRAWINGS. BASED FOR THE MOST PART ON THE PRACTICAL KNOWLEDGE ACCUMULATED OVER MANY YEARS OF BRAZING VARIOUS BASE METAL / FILLER METAL COMBINATIONS, THE BRAZING INDUSTRY HAD DEVELOPED AND PUBLISHED CERTAIN GUIDE LINES, AS SHOWN BELOW:

26 CHAPTER 2—BRAZEMENT DESIGN

AWS BRAZING

**Table 2.1**  
**Recommended Joint Clearance (Gap) at the Brazing Temperature**

AWS Brazing Filler Metal Classification	Joint Clearance (Gap),* in. (mm)
BAISi group	0.000–0.002 (0.000–0.051) for furnace brazing in vacuum atmosphere and clad brazing sheet 0.002–0.008 (0.051–0.20) for a length of lap less than 0.25 (6.35) 0.008–0.010 (0.20–0.25) for a length of lap greater than 0.25 (6.35)
BCuP group	0.001–0.005 (0.025–0.127) no flux and for flux brazing for joint length under 1.0 (25.4) 0.007–0.015 (0.178–0.38) no flux and for flux brazing for joint length greater than 1.0 (25.4)
BAG group	0.002–0.005 (0.025–0.127) flux brazing 0.000–0.002 (0.000–0.051) atmosphere brazing†
BAu group	0.002–0.005 (0.051–0.127) flux brazing 0.000–0.002 (0.000–0.051) atmosphere brazing†
BCu group	0.000–0.002 (0.000–0.051) atmosphere brazing†
BCuZn group	0.002–0.005 (0.051–0.127) flux brazing
BMg	0.004–0.010 (0.102–0.254) flux brazing
BNI group	0.002–0.005 (0.051–0.127) general applications (flux/atmosphere) 0.000–0.002 (0.000–0.051) free-flowing types, atmosphere brazing

(Ref. 10)

**Table 5.1** Recommended gap sizes for braze families. After BS 1723

Braze	Gap at brazing temperature (mm)
Al alloys	0.050 → 0.250
Ag alloys	0.050 → 0.150 (fluxed) 0.025 → 0.125 (controlled atmosphere)
Cu	–0.050* → 0.100 (controlled atmosphere)
Cu-P alloys	0.025 → 0.150 (in air) 0.050 → 0.150 (fluxed)
Cu-Zn alloys	0.050 → 0.150 (fluxed)
Ni	0.000 → 0.125 (controlled atmosphere)
Au	0.025 → 0.125 (controlled atmosphere)

(Ref. 20)

### □ BRAZE GAP

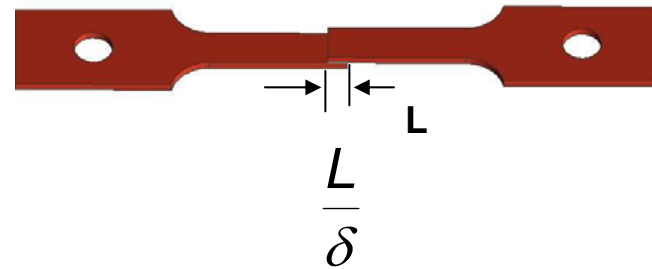
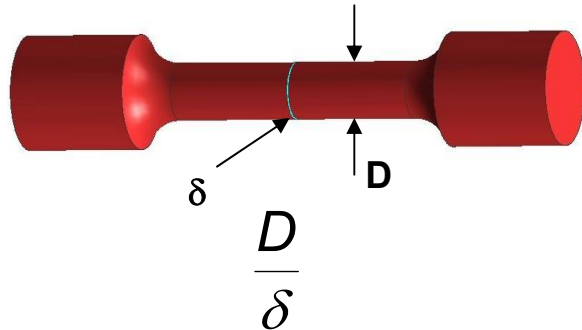
□ EVERYBODY IS HAPPY AS LONG AS THE JOINT GAP IS FOUND TO CONFORM TO THE RECOMMENDED GUIDELINES. BUT WHAT HAPPENS WHEN THE RESULTANT BRAZED JOINT, DUE TO A MANUFACTURING ANOMALY, HAS CLEARANCE THAT EXCEEDS THE DRAWING TOLERANCES? FOR EXAMPLE, BRAZED GAP IN STAINLESS STEEL STRUCTURE VACUUM BRAZED WITH SILVER-BASED FILLER METAL (AWS BAg8) IS MEASURED TO BE 0.25 mm (0.010 inch)? OR INCONEL 718 ASSEMBLY VACUUM BRAZED WITH AWS BAu4 ALLOY HAS A BRAZED JOINT WITH THE GAP = 0.2 mm (0.008 inch)?

□ IN ORDER TO DECIDE WHAT TO DO WITH THIS NONCONFORMING BRAZED ASSEMBLY, (*Accept as-is, Scrap, De-rate the joint strength, Reinforce the “bad” joint – those are some of the options*) IT WOULD HELP TO UNDERSTAND THE IMPACT OF THE BRAZED JOINT GAP ON JOINT STRENGTH.

□ IT TURNS OUT, THAT WHAT MATTERS IS NOT JUST THE JOINT GAP TAKEN BY ITSELF, REGARDLESS OF OTHER JOINT DIMENSIONS. IT IS THE **ASPECT RATIO** THAT AFFECTS THE PROPERTIES OF THE BRAZED JOINT. CONSEQUENTLY, IT WOULD BE VERY USEFUL TO THINK IN TERMS OF THE **ASPECT RATIO** WHEN DISCUSSING THE PROPERTIES OF THE BRAZED JOINTS.

## □ BRAZE GAP

□ ASPECT RATIOS OF THE CYLINDRICAL BUTT BRAZED JOINT AND A LAP JOINT ARE SHOW BELOW:



- THE ABILITY TO PLASTICALLY DEFORM GREATLY DEPENDS ON AN AMOUNT OF CONSTRAINT OR TRIAXIALITY OF THE STRESS STATE WITHIN THE BRAZE INTERLAYER, NO MATTER HOW DUCTILE THE FILLER METAL IS IN IT'S UNRESTRAINED OR BULK FORM.
- RECALL THAT THE STRESS TENSOR CONSISTS OF DEVIATORIC (RESPONSIBLE FOR SHEAR, I.E. PLASTIC DEFORMATION OR DISTORTION) AND HYDROSTATIC COMPONENTS (RESPONSIBLE FOR VOLUMETRIC CHANGE OR DILATATION).
- IN THE CASE OF PURE HYDROSTATIC TENSION (difficult to instrument) or COMPRESSION, NO PLASTIC DEFORMATION (e.g. yielding) TAKES PLACE AND THE MATERIAL APPEARS MUCH STRONGER AND MACROSCOPICALLY BEHAVES IN A BRITTLE MANNER.

## □ BRAZE GAP

□ THERE HAD BEEN SEVERAL THEORETICAL ATTEMPTS TO PREDICT AN INCREASE IN STRENGTH OF THE DUCTILE LAYER AS A FUNCTION OF IT'S ASPECT RATIO. THE MOST PROMINENT OF THEM ARE SHOWN BELOW:

$$\sigma_r = \sigma_y \times \left( \frac{1}{2} \times \frac{D}{\delta} - \frac{r}{\delta} \right) \quad (\text{Ref. 21})$$

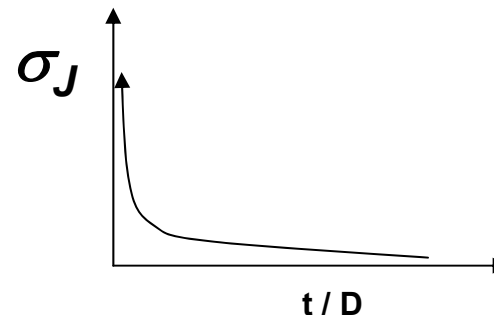
$$\sigma_J = \sigma_y \times \left( 1 + \frac{D}{\delta} \times \frac{1}{6} \right) \quad (\text{Ref. 22})$$

$$\sigma_J = 0.5\sigma_y \times \left( \frac{L}{\delta} + 3 \right) \quad (\text{Ref. 23})$$

$$\sigma_J = \sigma_y \times \left( 1 + \frac{D}{\delta} \times \frac{1}{\sqrt{3}} \right) \quad (\text{Ref. 24})$$

Where  $\sigma_r$  is the radial stress in the butt joint;  $\sigma_y$  is the yield strength of the braze interlayer;  $\sigma_J$  is the tensile strength of the brazed joint.

□ ALL THESE EXPRESSIONS PREDICT HYPERBOLIC INCREASE IN JOINT STRENGTH AS THE ASPECT RATIO BECOMES SMALLER



## BRAZE GAP

EXPERIMENTAL RESULTS SHOW THE SAME TREND BUT DON'T QUITE FIT THE THEORETICAL PREDICTIONS, PARTICULAR FOR THE VERY HIGH ASPECT RATIOS.

APTER 2—BRAZEMENT DESIGN

AND BRAZING HAN

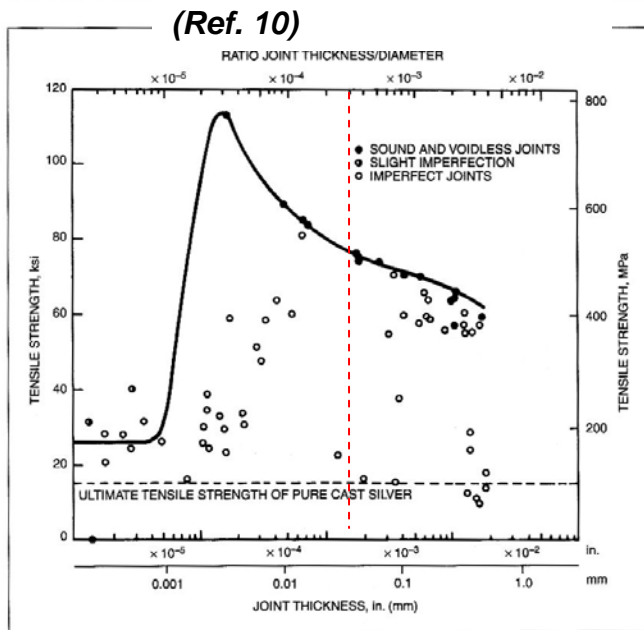


Figure 2.5—Tensile Strength of Silver Brazed Butt Joints 0.5 in. (12.7 mm) in Diameter as a Function of Joint Thickness

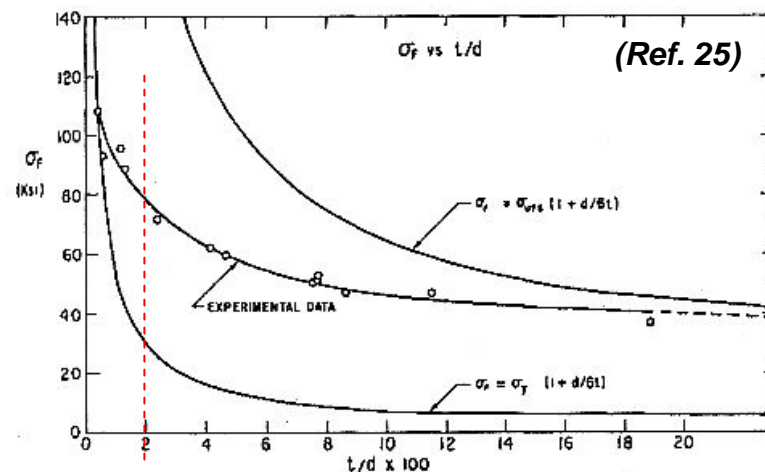
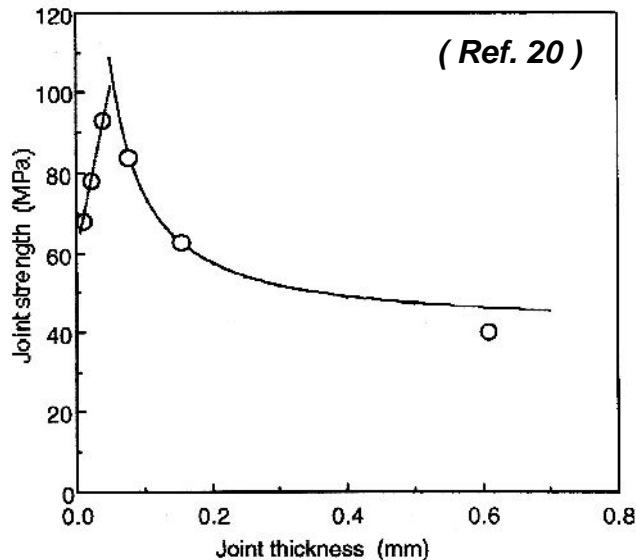


Fig. 3—The variation of  $\sigma_F$  with joint geometry  $t/d$  for maraging steel-Ag-4 pct Pd brazed joints along with the bounds for the Orowan theory assuming maximum and minimum strain hardening.

THE RECOMMENDED BRAZE GAPS FALL WITHIN THE RANGE OF ASPECT RATIOS RESULTING IN THE HIGHEST JOINT STRENGTHS. FOR EXAMPLE THE GAP FOR Ag-BASED FM OF 0.13 mm (0.005 inch) IN 6 mm (0.250 inch) DIA TENSILE BUTT SPECIMEN (AWS C3.2) RESULTS IN  $(\delta/D) = 0.02$  (see dashed red lines above). IF THE TEST SPECIMEN DIA IS REDUCED (for the same  $\delta$ ) THE MEASURED STRENGTH WILL BE LOWER. WHEN  $\delta \rightarrow 0$ , IT MAY BE DIFFICULT FOR FM TO PENETRATE ENTIRE BRAZED JOINT. THIS MAY RESULT IN DEFECTS THAT WILL REDUCE JOINT STRENGTH (LEFT PLOT)

## BRAZE GAP



16 The tensile strengths of butt joints between austenitic stainless-steel with a fluxed Ag-Cu-Zn-Cd alloy. After Udin *et al.* (1954)

IN SOME BM / FM COMBINATIONS EXPERIMENTAL RESULTS CORRELATE WELL W/ THEORY, PARTICULARLY FOR SMALLER ASPECT RATIOS (TOP). WHEN STRENGTH OF FM IS SIMILAR TO BM, THE JOINT STRENGTH DOES NOT SEEM TO DEPEND ON THE GAP SIZE OR ASPECT RATIO, AS SHOWN ON THE RIGHT (Until the joint gaps become too small for proper brazing process)

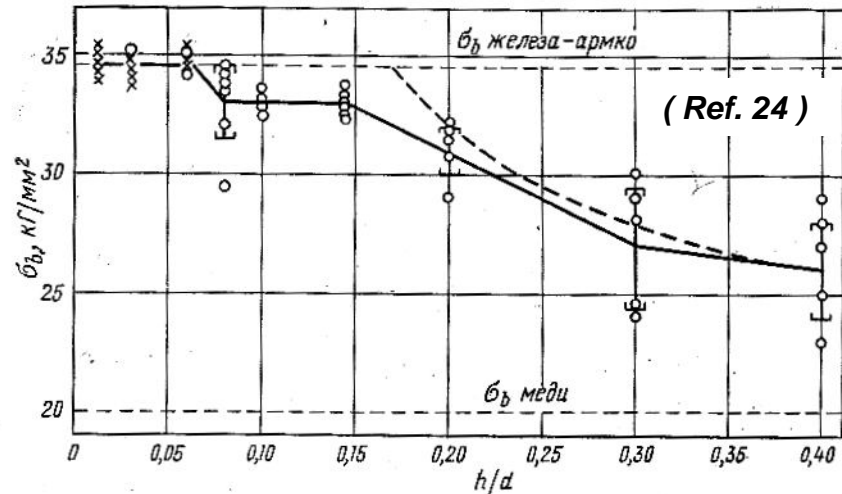


Рис. 85. Зависимость предела прочности от величины зазора при пайке железа Армко медью встык:

O — разрушение по шву; X — разрушение по основному металлу

(Pure iron butt joints brazed w/ Cu.

X - failure in BM; O – failure in the interlayer)

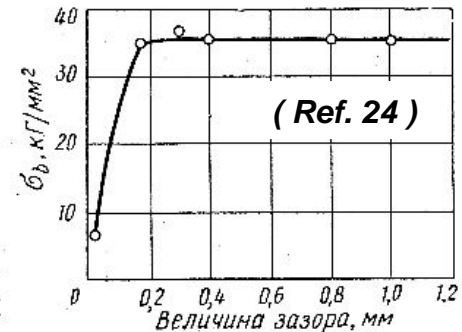


Рис. 86. Зависимость прочности стыковых соединений от величины зазора при пайке стали марки Ст.3 припоем на железной основе

(ISI 1020 Steel butt specimen brazed w/ iron-based FM.)



## BRAZE GAP

IT IS IMPORTANT TO BE AWARE OF THE ASPECT RATIO WHEN EITHER GENERATING DESIGN DATA, USING HERITAGE DATA OR COMPARING THE TEST RESULTS FROM VARIOUS SOURCES. FOR EXAMPLE, FOR  $\delta = 0.1$  mm (0.004 inch) and  $D = 6$  mm (0.250 inch), JOINT STRENGTH  $\approx 77$  ksi, BUT IF THE DIA OF TEST SPECIMEN IS REDUCED TO, SAY, 3 mm (0.130 inch),  $\delta / D = 0.033$  AND THE JOINT STRENGTH WILL BE ABOUT 65 ksi !

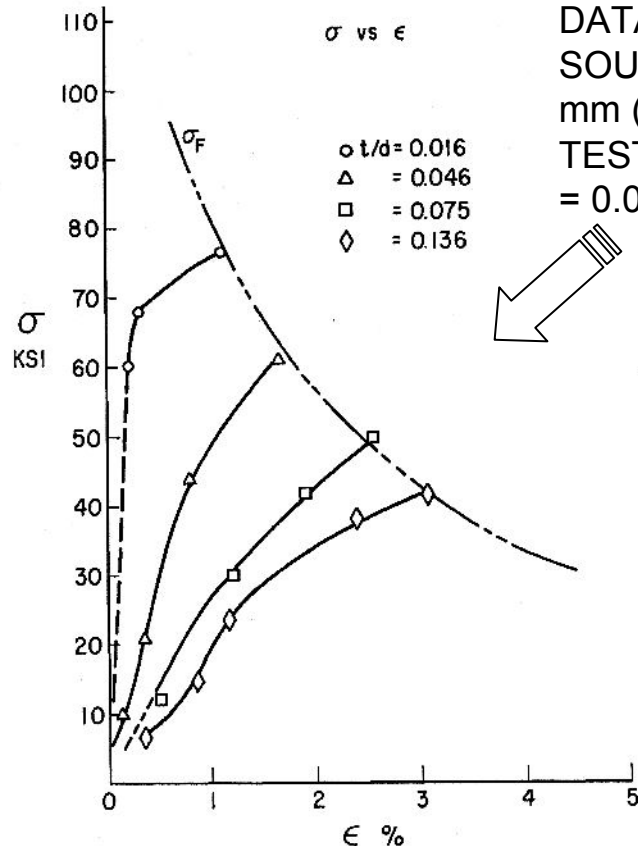


Fig. 12—The influence of  $t/d$  ratio on the joint stress-strain behavior of maraging steel—Ag-4 pct Pd brazed joints.

( Ref. 25 )

LAP SHEAR JOINTS SHOW SIMILAR RELATION BETWEEN SHEAR STRENGTH & JOINT GAP.

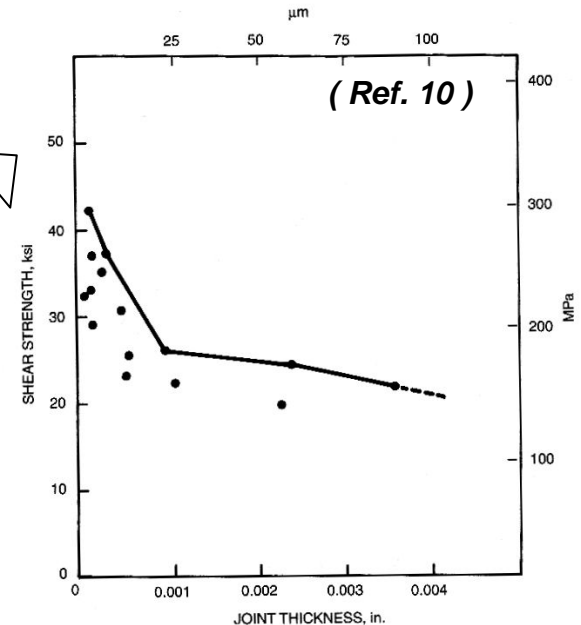


Figure 2.4—Relationship of Shear Strength to Joint Thickness for Pure Silver Joints in 0.5 in. (12.7 mm) Diameter Drill Rod Induction Brazed in a Dry Atmosphere of 10%  $H_2$ -90%  $N_2$  (No Flux Used)



### □ BRAZE GAP

- IMPORTANT POINTS TO REMEMBER WHEN DISCUSSING THE JOINT GAP:
  - TRY TO USE THE SAME ASPECT RATIOS WHEN COMPARING THE TEST RESULTS OR DEVELOPING DESIGN DATA;
  - IT MAY BE HELPFUL TO CONSIDER TESTING BUTT TENSILE SPECIMENS HAVING AT LEAST TWO DIAMETERS, SAY 6 mm (0.250 in) AND 3 mm. A STRAIGHT LINE CAN CONNECT TWO DATA POINTS OBTAINED FROM THESE TESTS. IT WILL HELP TO DETERMINE “**SENSITIVITY**” OF YOUR BM / FM SYSTEM TO VARIATIONS OF THE BRAZE GAP DURING MANUFACTURING OF THE BRAZED ASSEMBLY.
  - IF THE PRODUCTION BRAZED JOINTS DESIGNED TO OPERATE PREDOMINANTLY IN SHEAR, A VARIABLE GAP TEST SHOULD BE PERFORMED ON SHEAR SPECIMENS. IT IS RECOMMENDED TO USE THE OVERLAP DISTANCE RESULTING IN EQUAL STRENGTH JOINTS AND TEST TWO BRAZE GAPS: THE DESIGN GAP FOR ONE SET OF SPECIMENS AND TO DOUBLE ITS VALUE FOR ANOTHER SET.
  - IDEALLY, THE ASPECT RATIOS OF THE TEST SPECIMENS SHOULD ENVELOPE THE ASPECT RATIOS OBSERVED ON THE ACTUAL BRAZED JOINTS IN THE BRAZED ASSEMBLY

## RESIDUAL STRESS

ANOTHER FACTOR AFFECTING THE STRENGTH OF THE BRAZED JOINTS IS RESIDUAL STRESSES PRESENT IN THE BRAZED JOINT AT ROOM TEMPERATURE.

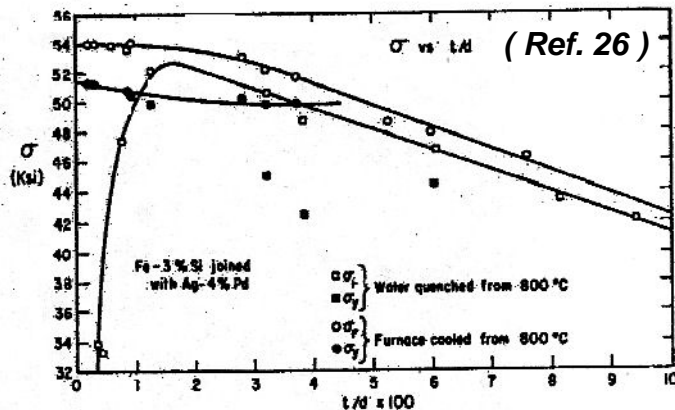


Fig. 1—The influence of cooling rate upon the tensile strength of butt brazed joints as a function of thickness to diameter,  $t/d$ , ratio.

AN EXAMPLE OF THE ADVERSE EFFECT OF THE RESIDUAL STRESS ON THE STRENGTH OF THE BRAZED JOINT IS SHOWN ON THE LEFT. NOTICE A SHARP DROP-OFF IN STRENGTH IN QUENCHED JOINT FOR ASPECT RATIOS CORRESPONDING TO RECOMMENDED BRAZE GAPS.

IT IS QUITE CLEAR THAT THE MAIN REASON FOR HAVING RESIDUAL STRESSES IN THE BRAZED JOINTS IS THE DIFFERENCE IN CTE BETWEEN THE JOINT CONSTITUENTS. OTHER REASONS ARE NON-UNIFORM COOLING AND ASSEMBLY STRESSES.

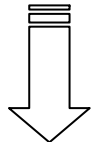
THE SUBJECT OF RESIDUAL STRESSES IN BRAZED JOINTS IS COVERED IN A NUMBER OF RESEARCH PAPERS AND REMAINS TO BE STUDIED MORE, PARTICULARLY IN TERMS OF ENGINEERING APPLICATIONS. WE WILL FOCUS ON JUST A FEW PRACTICAL ASPECTS.

### □ RESIDUAL STRESS

□ IN TERMS OF SEVERITY OF THE RESIDUAL STRESSES AND THEIR EFFECT ON INTEGRITY OF THE BRAZED JOINTS, THE BRAZED JOINTS CAN BE LISTED IN THE FOLLOWING ORDER :

- METAL / CERAMIC JOINTS WITHOUT STRESS COMPENSATORS
- METAL / METAL JOINTS WITH LARGE CTE DIFFERENCE BETWEEN BMs
- CERAMIC / CERAMIC JOINTS
- METAL / METAL JOINTS WITH LARGE CTE MISMATCH BETWEEN BM & FM

**MOST SEVERE**



**LEAST**

□ ANOTHER TWO KEY FACTORS AFFECTING THE LEVEL OF RESIDUAL STRESSES ARE:

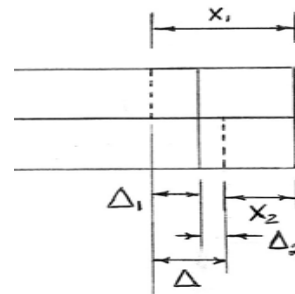
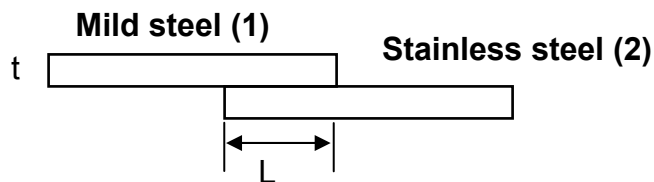
- JOINT GEOMETRY – THE HIGHER THE LEVEL OF CONSTRAINT (HENCE TRIAXIALITY) IN THE JOINT DESIGN – THE HIGHER THE RESIDUAL STRESS
- COOLING RATE

THESE TWO FACTORS ARE RELATED TO THE DEGREE OF STRESS RELAXATION BY CREEP.

## RESIDUAL STRESS

AMOUNT OF RESIDUAL STRESS ACCUMULATED IN THE BRAZED JOINT BETWEEN TWO MATERIALS WITH DIFFERENT CTEs CAN BE APPROXIMATELY ESTIMATED USING ELASTIC PROPERTIES OF EACH MATERIAL AS A FUNCTION OF TEMPERATURE. FOR EXAMPLE, CONSIDER LAP JOINT BETWEEN MILD STEEL AND STAINLESS STEEL.

(Ref. 24)



$$\Delta = \Delta_1 + \Delta_2 = X_1 - X_2$$

$X_1$  - Free contraction of plate 1

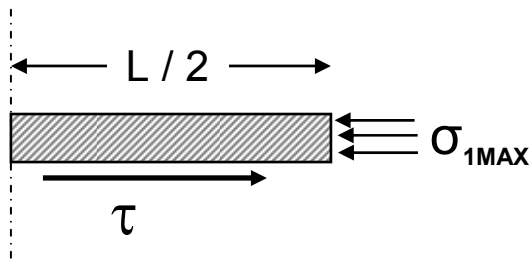
$X_2$  - Free contraction of plate 2

$$\varepsilon_{1\max} = 1.5 \frac{\Delta_1}{L} \quad \varepsilon_{2\max} = 1.5 \frac{\Delta_2}{L}$$

$$\sigma_{1\max} = \frac{1.5 \frac{\Delta \cdot E_1}{L}}{1 + \frac{E_1}{E_2}} = \frac{1.5 \frac{\Delta \cdot E_2}{L}}{1 + \frac{E_2}{E_1}} = \sigma_{2\max}$$

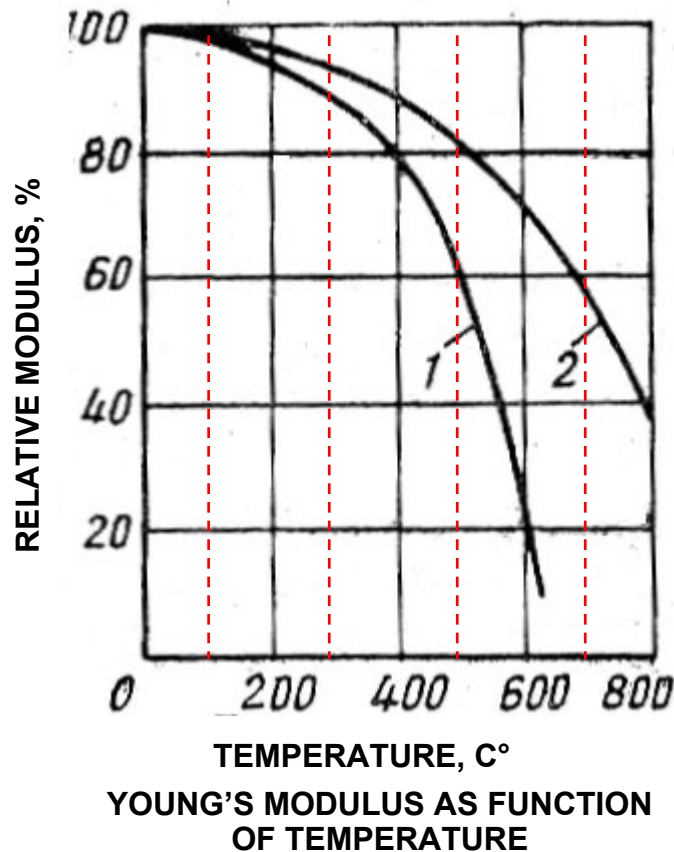
FROM EQUILIBRIUM CONDITION AND ASSUMING EQUAL CROSS SECTIONS.

FREE BODY EQUILIBRIUM OF ONE PLATE. FORCE DUE TO NORMAL STRESS WITHIN THE PLATE IS EQUALIZED BY FORCE DUE TO SHEAR STRESS  $\tau$  IN FM.  $W$  - WIDTH OF THE PLATE;



$$\sigma_{1\max} \cdot t \cdot w - \tau \cdot \frac{L}{2} \cdot w = 0 \quad \tau = \frac{2 \cdot \sigma_{1\max} \cdot t}{L}$$

## RESIDUAL STRESS



$$\left. \begin{aligned} \alpha_1 &= 14.1 \times 10^{-6} / \text{C}^\circ \\ \alpha_2 &= 19 \times 10^{-6} / \text{C}^\circ \end{aligned} \right\} \text{AVERAGE CTEs FOR BASE METALS FOR } 20^\circ \text{ TO } 740^\circ \text{ TEMPERATURE RANGE}$$

$$E_1 = E_2 = 206 \text{ Gpa}; - \text{YOUNG'S MODULUS AT R.T.}$$

$$X_1 = \alpha_1 (T_{BR} - 20) \cdot L = 14.1 (740 - 20) 10^{-6} L = 1.02 \cdot 10^{-2} \cdot L$$

$$X_2 = \alpha_2 (T_{BR} - 20) \cdot L = 19 (740 - 20) 10^{-6} L = 1.37 \cdot 10^{-2} \cdot L$$

$$\Delta = X_2 - X_1 = 0.35 \cdot 10^{-2} \cdot L$$

$$E_{1AVG} = (0 + 0.30 + 0.60 + 0.80 + 0.90 + 0.95 + 0.98) \cdot \frac{E}{7} \sim 0.65E$$

$$E_{2AVG} = (0.60 + 0.72 + 0.82 + 0.88 + 0.94 + 0.96 + 0.98) \cdot \frac{E}{7} \sim 0.84E$$

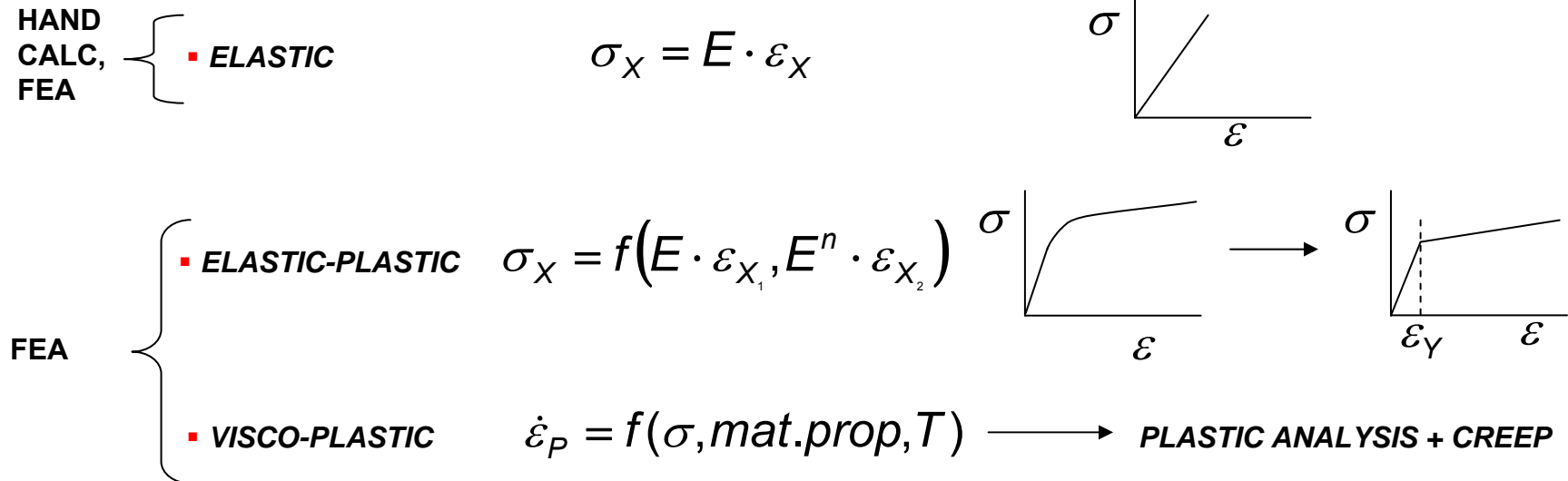
$$\sigma_{1max} = \sigma_{2max} = \frac{1.5 \cdot 0.35 \cdot 10^{-2} \cdot 0.65 \cdot 206}{1 + \frac{0.65 \cdot E}{0.84 \cdot E}} = 397 \text{ Mpa} \quad (58 \text{ ksi})$$

$$\tau = \frac{2 \cdot \sigma_{1max} \cdot t}{L} = \frac{2 \cdot 397 \cdot 1}{4} = 198 \text{ Mpa} (28 \text{ ksi}) \quad \text{FOR } t/L = 4$$

## RESIDUAL STRESS

- THE PROBLEM WITH SUCH A CLASSIC ELASTICITY-BASED ESTIMATE IS THAT IT OVERESTIMATES RESIDUAL STRESS, BY IGNORING THE COOLING RATE. IN OTHER WORDS, THIS ESTIMATES DOES NOT CONSIDER CREEP.
- IN ORDER TO HAVE A MORE REALISTIC ESTIMATE OF RESIDUAL STRESSES IN THE BRAZED JOINTS, A DIFFERENT CONSTITUTIVE RELATIONSHIP MUST BE DEVELOPED TO ACCOUNT FOR CREEP WITHIN THE BRAZE INTERLAYER.

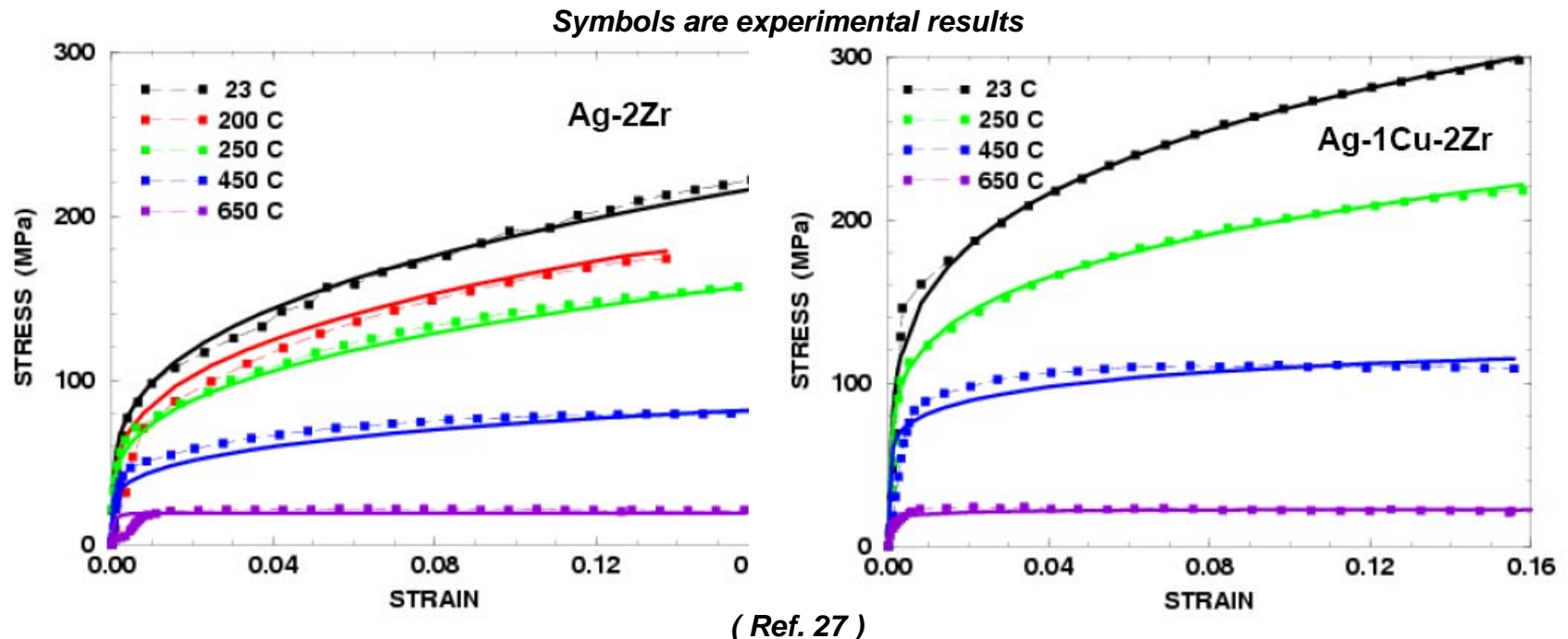
### EVOLUTION OF BRAZED JOINT ANALYSIS



### PLASTIC DEFORMATION + CREEP INDUCED STRESS RELAXATION

## RESIDUAL STRESS

- SIGNIFICANT ADVANCEMENTS IN DEVELOPING VISCO-PLASTIC CONSTITUTIVE EQUATIONS FOR METAL / CERAMIC BRAZED JOINTS HAVE BEEN MADE AT SANDIA NATIONAL LABS (J. Stevens, S. Burchett, M. Nielsen, M. Hosking, etc)
- THE SANDIA VISCOPLASTIC UNIFIED CREEP AND PLASTICITY MODEL (UCP) CAPTURES PLASTICITY + CREEP. THEY HAVE DEVELOPED FEA CODES FOR Cu, Ag and Au – based FMs. PLOTS BELOW SHOW A GOOD CORRELATION BETWEEN THE EXPERIMENTS AND SIMULATIONS USING UCP MODEL





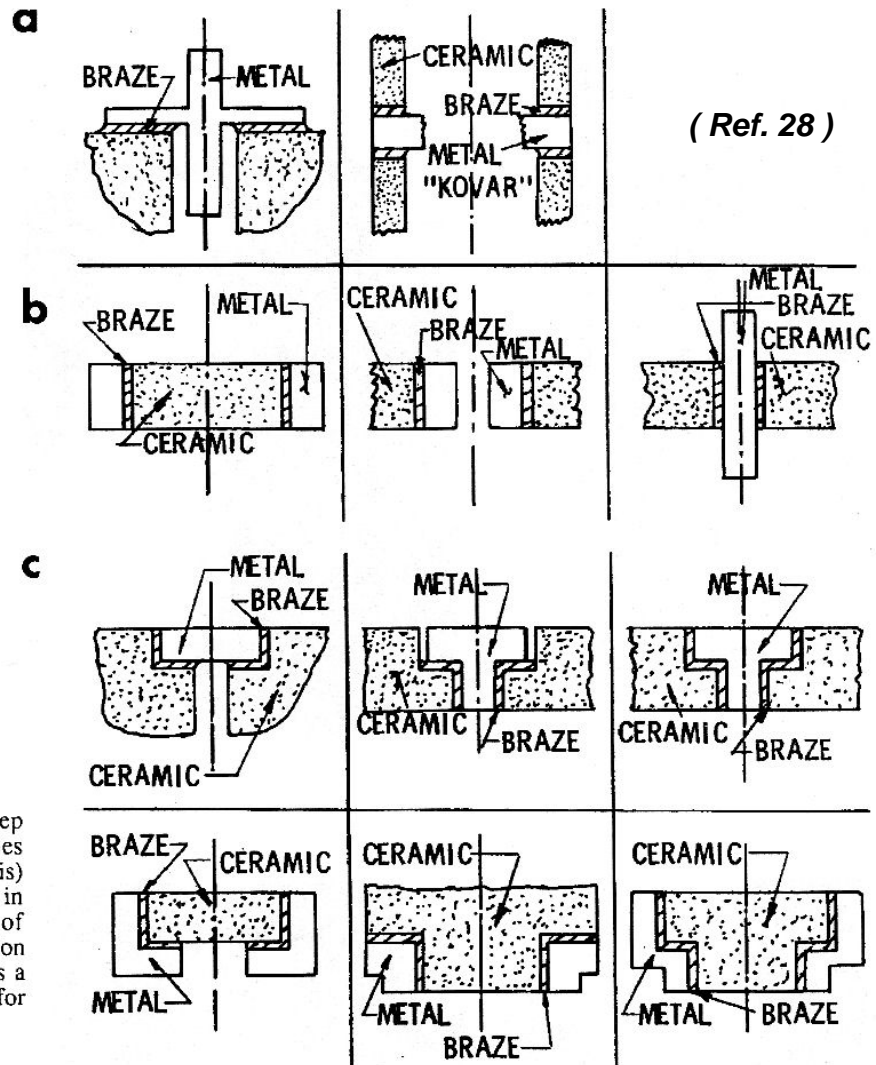
## RESIDUAL STRESS

PROLONGED COOL DOWNS OR DWELLS AT ELEVATED TEMPERATURES MAY OR MAY NOT HELP TO REDUCE CTE MISMATCH INDUCED RESIDUAL STRESSES.

CREEP ONLY REDUCES DEVIATORIC (DISTORTION) STRESSES PLASTIC DEFORMATION CAUSES DISTORTION THUS RELIEVING DEVIATORIC STRESS.

IF JOINT GEOMETRY RESULTS IN HIGH TRIAXIALITY (DILATATION STRESSES) – THEY WILL NOT BE RELIEVED BY CREEP.

Generic metal/ceramic braze joints, grouped according to their potential for creep induced stress relaxation during cooldown from the brazing cycle. All sketches depict components with cylindrical symmetry, with the axis of symmetry (z-axis) indicated. (a) Two types of "Shear" braze joints, where the dominant loading is in shear, with good potential for stress relaxation. (b) Three types of "Tension/Compression" braze joints with more limited potential for stress relaxation relative to (a). (c) Six types of "Tortuous Path" braze joints, where there is a significant hydrostatic stress component and correspondingly little potential for stress relaxation.

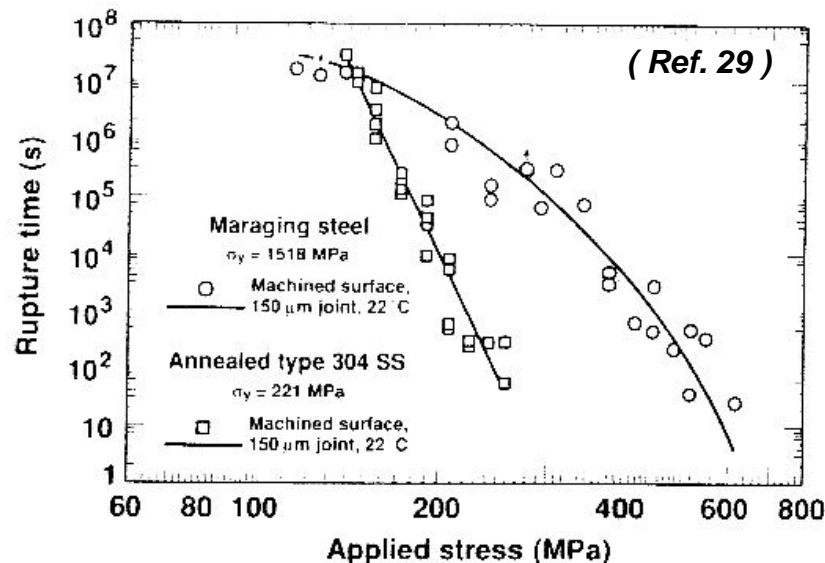




## □ DELAYED FAILURES

□ THE LAST SUBJECT OF THIS SEMINAR IS BEHAVIOR OF THE BRAZED JOINTS UNDER SUSTAINED LOADS. THE TENSILE AND SHEAR ALLOWABLES WE HAVE DISCUSSED SO FAR WERE BASED ON MECHANICAL TESTS PERFORMED ON THE BRAZED JOINTS USING TYPICAL LOADING RATES. THERE ARE REALLY TWO QUESTIONS TO CONSIDER:

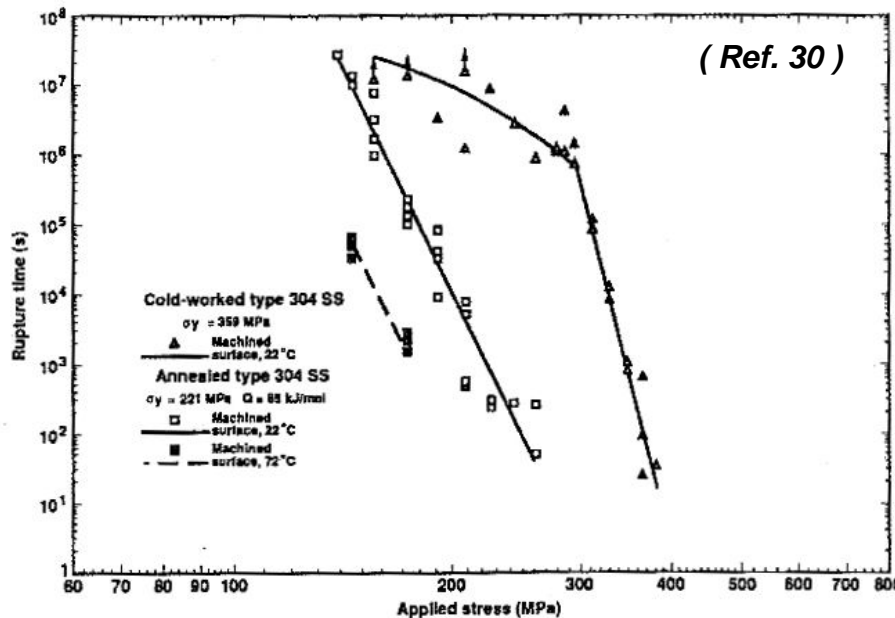
- ARE THERE ANY REPORTED CASES / STUDIES INDICATING THAT BRAZED JOINTS CAN FAIL UNDER SUSTAINED LOADS AT STRESSES SUBSTANTIALLY LESS THAN THE ULTIMATE TENSILE STRENGTH OF THE BUTT BRAZED TEST SPECIMENS?
- IF YES, WHAT ARE THE SAFE LEVELS OF SUSTAINED LOADS?



□ IT APPEARS THAT SILVER BRAZED JOINTS EXHIBIT DELAYED FAILURES, AS SHOWN ON THIS GRAPH. GRAPH IS BASED ON DATA GENERATED BY KASSNER, 1989.

## □ DELAYED FAILURES

□ EXPERIMENTAL DATA INDICATE THAT BUTT JOINTS BRAZED WITH PURE SILVER HAVE FAILED AT LOWER STRESSES IN CASE OF DUCTILE BASE METALS AS COMPARED TO THE STRONGER ONES. SAME TREND APPLIES TO THE DELAYED FAILURE AS SHOWN BELOW.

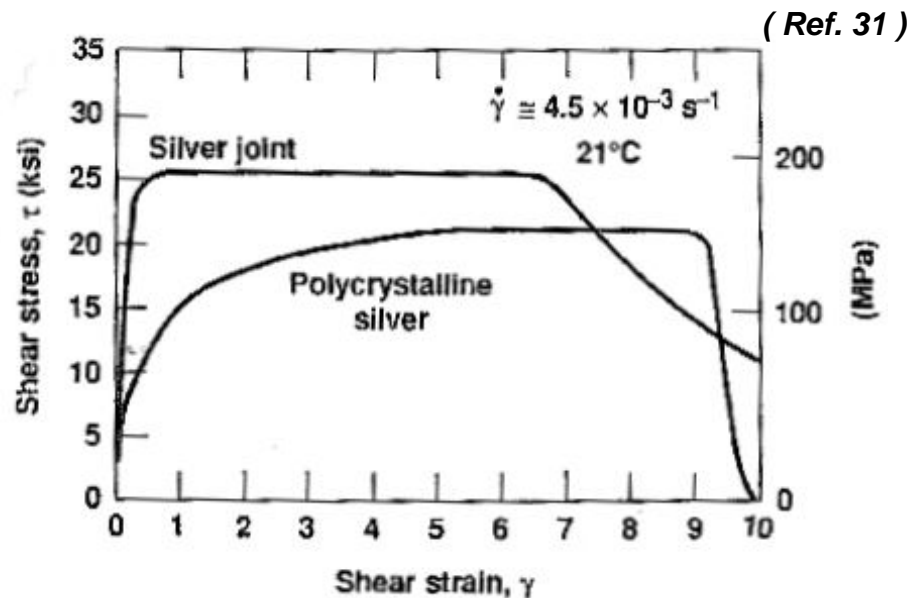


□ NON-DEFORMING BASE METAL RESTRICTS TRANSVERSE CONTRACTION OF THE SOFT INTERLAYER TO A GREATER EXTENT THAN THE DUCTILE BM. CONSEQUENTLY THIS CONSTRAINT PRODUCES MORE TRIAXIALITY IN STRESS STATE WHICH RESULTS IN THE STRENGTHENING EFFECT AS DEMONSTRATED BY THESE TEST RESULTS.

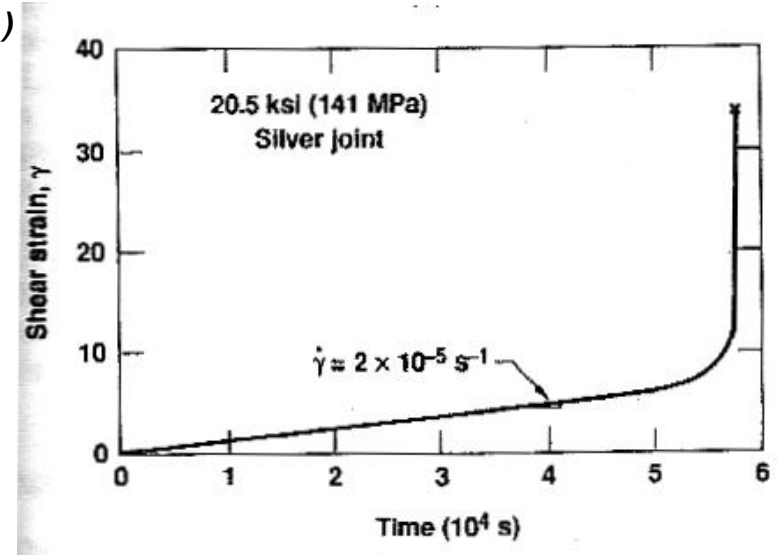
**SILVER-INTERLAYER DIFFUSION BRAZED BUTT JOINTS BETWEEN ANNEALED AND COLD WORKED 304 SS BASE METALS.**

## □ DELAYED FAILURES

□ SHEAR STRESSES IN PURE SILVER BRAZED JOINTS MAY ALSO CAUSE DELAYED FAILURES AS SHOWN BELOW. AS ONE CAN SEE DELAYED FAILURE (RIGHT PLOT) IS TAKING PLACE UNDER SHEAR STRESS OF ONLY 141 MPa (20.5 ksi) WHICH IS LESS THAN THE SHEAR STRENGTH OF 182 MPa (26 ksi) MEASURED ON THE THE SAME JOINTS



**SHEAR STRENGTH OF THE SILVER-INTERLAYER DIFFUSION BRAZED JOINT VS. BULK SILVER**



**TORSIONAL CREEP CURVE FOR SILVER IN SILVER-INTERLAYER DIFFUSION BRAZED JOINT.**

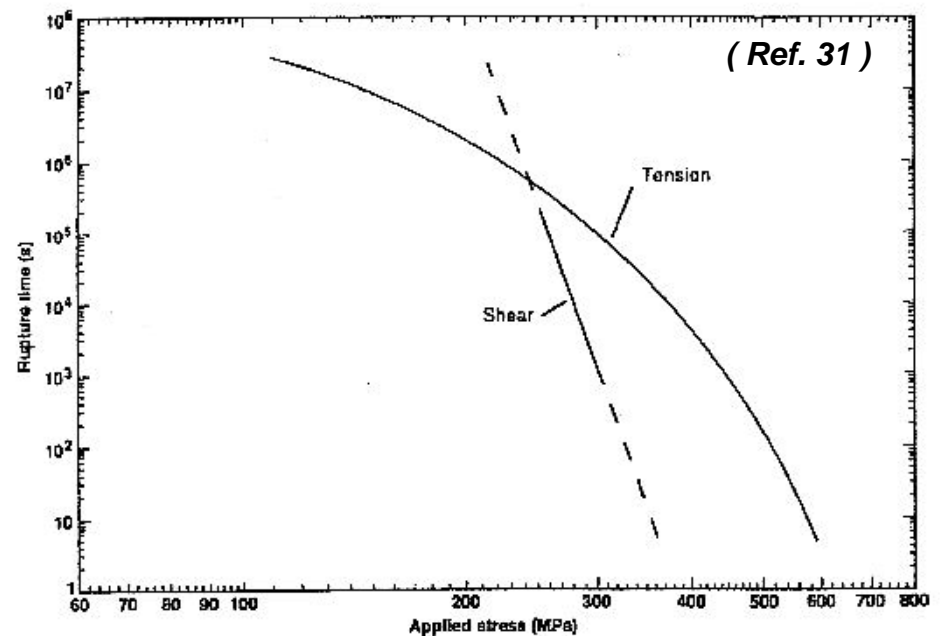
## □ DELAYED FAILURES

□ THERE IS PRELIMINARY EXPERIMENTAL EVIDENCE ( *Ref. 31* ) THAT UNDER MULTIAXIAL LOADING, THE DELAYED FAILURES IN BRAZED JOINTS OCCUR AT MUCH LOWER STRESS LEVELS.

□ IT IS IMPERATIVE TO DETERMINE WHETHER THE BASE / DUCTILE FILLER METAL COMBINATION ( Cu – BASED FM COULD ALSO BE VULNERABLE) THAT REPRESENTS YOUR CRITICAL BRAZED STRUCTURE IS SUSCEPTIBLE TO A DELAYED FAILURE.

□ A RUPTURE TEST CAN BE PERFORMED DURING THE DESIGN PHASE OF THE PROJECT TO SEE WHETHER YOUR BRAZED ASSEMBLY IS SENSITIVE TO DELAYED FAILURE. A DOUBLE LAP SHEAR AND TENSILE TEST SPECIMENS (AWS C3.2 OR SIMILAR) CAN BE TESTED UNDER CONSTANT LOAD AT VARIOUS STRESS / TEMPERATURE COMBINATIONS.

□ PLOT ON THE RIGHT INDICATES THAT SHEAR TEST IS PRONE TO DELAYED FAILURE AT LOWER STRESSES THAN BUTT TENSILE SPECIMENS. HOWEVER (CROSS OVER ON THE PLOT) FOR VERY LONG EXPOSURE TIMES, TENSILE SPECIMENS MAY FAIL EARLIER THAN SHEAR ONES.



### **□ FINAL COMMENTS**

- SELECTION OF TENSILE AND SHEAR ALLOWABLES MUST ACCOUNT FOR ALL DESIGN AND MANUFACTURING CONCERNS, SUCH AS RESIDUAL STRESSES, INTERNAL QUALITY OF THE BRAZED JOINTS, MISALIGNMENT, DELAYED FAILURE SUSCEPTIBILITY, SERVICE ENVIRONMENTS, DYNAMIC LOADS, SENSITIVITY TO IMPACT LOADING AND NOTCHES (STRESS CONCENTRATION).**
- TENSILE AND SHEAR TEST DATA OBTAINED FROM OTHER SOURCES HAVE TO BE CAREFULLY EXAMINED BEFORE USING IT FOR DESIGN OF CRITICAL STRUCTURES. FOR EXAMPLE, ASPECT RATIOS OF THE TEST SPECIMENS, QUALITY OF THE BRAZED JOINTS TESTED, AMOUNT OF RESIDUAL STRESSES PRESENT, ETC. A LACK OF INFORMATION ON THESE VARIABLES COULD RENDER THE DATA PUBLISHED IN PAPERS LESS THAN ADEQUATE FOR DESIGN PURPOSE.**
- IF THE CRITICAL BRAZED STRUCTURE IS GOING TO BE ASSEMBLED INTO A LARGER STRUCTURE USING MECHANICAL FASTENERS, THE ASSEMBLY STRESSES MUST BE ACCOUNTED FOR WHEN PREDICTING THE MARGINS OF SAFETY OF THE BRAZED JOINTS. IF ASSEMBLY STRESSES ARE A BIG CONCERN, A CERTAIN NUMBER OF STRAIN GAGES SHOULD BE BONDED AROUND THE MOST VULNERABLE BRAZED JOINTS PRIOR TO FINAL ASSEMBLY. IF AFTER ASSEMBLY, THE STRAIN GAGES READ STRAINS THAT ARE GREATER THAN PREDICTED, THE SAFETY MARGINS OF THE BRAZED JOINTS MUST BE RE- ASSESSED.**
- IF RADIOGRAPHIC INSPECTION OF THE BRAZED STRUCTURE IS REQUIRED, THE ABILITY TO DETECT INTERNAL DISCONTINUITIES BY THE SAME RADIOGRAPHIC TECHNIQUE MUST BE DEMONSTRATED ON GEOMETRY SPECIFIC SPECIMENS REPRESENTING THE ACTUAL BRAZED JOINTS.**
- THE EXISTING BRAZED JOINT TEST STANDARDS MUST BE UPGRADED TO REFLECT THE NEED FOR DEVELOPING A FAILURE CRITERIA OF THE BRAZED JOINTS FOR DESIGN OF CRITICAL BRAZED STRUCTURES.**
- THE COST OF DEVELOPING BRAZED JOINT ALLOWABLES MUST BE INCLUDED IN THE MANUFACTURING COST ESTIMATE PRESENTED TO THE CUSTOMER WHEN BIDDING ON FABRICATION OF THE CRITICAL BRAZED STRUCTURE.**

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