METALLURGY

APPROACH TO FAILURE ANALYSIS

FAILURE MODES

CARE AND HANDLING OF FRACTURE SURFACES

LABORATORY EQUIPMENT

METALLURGY

The science and technology of metals and alloys.

PROCESS METALLURGY is concerned with the extraction of metals from their ores and with the refining of metals.

PHYSICAL METALLURGY is concerned with the physical and mechanical properties of metals as affected by composition, processing, and environmental conditions.

MECHANICAL METALLURGY is concerned with the response of metals to applied forces.

1. APPROACHES TO FAILURE ANALYSIS

A. Common Sense Approach

A common sense approach to failure analysis works well in most cases. The goal is to ensure that all needed documentation and measurements are done prior to any destructive examinations. The following chronological list of possible steps or "recipe" to help to avoid leaving out an important step:

- <u>Collect background information, data, history, documentation and samples</u>. This should include appropriate photographic documentation, collection and protection of fractured or failed components, and collection of specimens for chemical analysis, such as corrosion products or corrosive agents. Question people at the scene who have knowledge about or witnessed the failure.
- <u>Determine primary and secondary damage</u>. This must be done by the on-site investigator, who may or may not be a failure analyst. Even in complex failures, it is usually possible to determine a primary source of the damage. Get help from those who best know and understand the hardware.
- <u>Examine failed components</u>. Use a good stereo binocular microscope to carefully examine the failed parts and fracture surfaces. Serious failures often inspire a flurry of activity during which pertinent data and observations may be missed. It may be advisable to have more than one person examine the hardware independently.
- <u>Measure and inspect failed components</u>. Where possible, make pertinent physical measurements of failed components. Use selected nondestructive inspection (NDI) techniques to look for additional cracks, secondary cracks or damage. Such techniques include fluorescent magnetic particle inspection (MPI), fluorescent penetrant inspection (FPI), X-ray radiography, ultrasonic inspection and eddy current inspection.

- <u>Examine fracture surfaces microscopically to determine modes and origins</u>. This can be either a nondestructive or a destructive step, depending on specimen size and the type of microscope used. Smaller specimens, on the order of an inch cube, will fit directly into most modern scanning electron microscopes (SEM's). Larger specimens may need to be cut down. Remember to protect fracture surfaces during cutting operations. Cutting is not required for transmission electron microscopes (TEM's), since replicas of fracture surfaces are examined.
- <u>Examine metallographic sections</u>. This is usually a destructive step, although surface spot polishing may be nondestructive. Microstructural evaluation, grain size measurement and microhardness testing should be done at this time.
- <u>Determine cause of failures</u>. Although examination of fracture surfaces will usually determine a mode of failure, such as material overstress or fatigue, the fundamental cause of the failure may not be obvious. Work with project, test, design and structural engineers as needed to determine the cause of failure.

TRANSGRANULAR DUCTILE AND BRITTLE FAILURE MODES

TENSILE

BENDING, SHEAR, TORSION

COMPRESSION

FATIGUE

INTERGRANULAR FAILURE MODES

STRESS CORROSION

HYDROGEN EMBRITTLEMENT

COMPOSITES FAILURE MODES

STRESS RISERS

CORROSION PITTING

FRETTING

MECHANICAL DAMAGE

MACROEXAMINATION

TENSILE

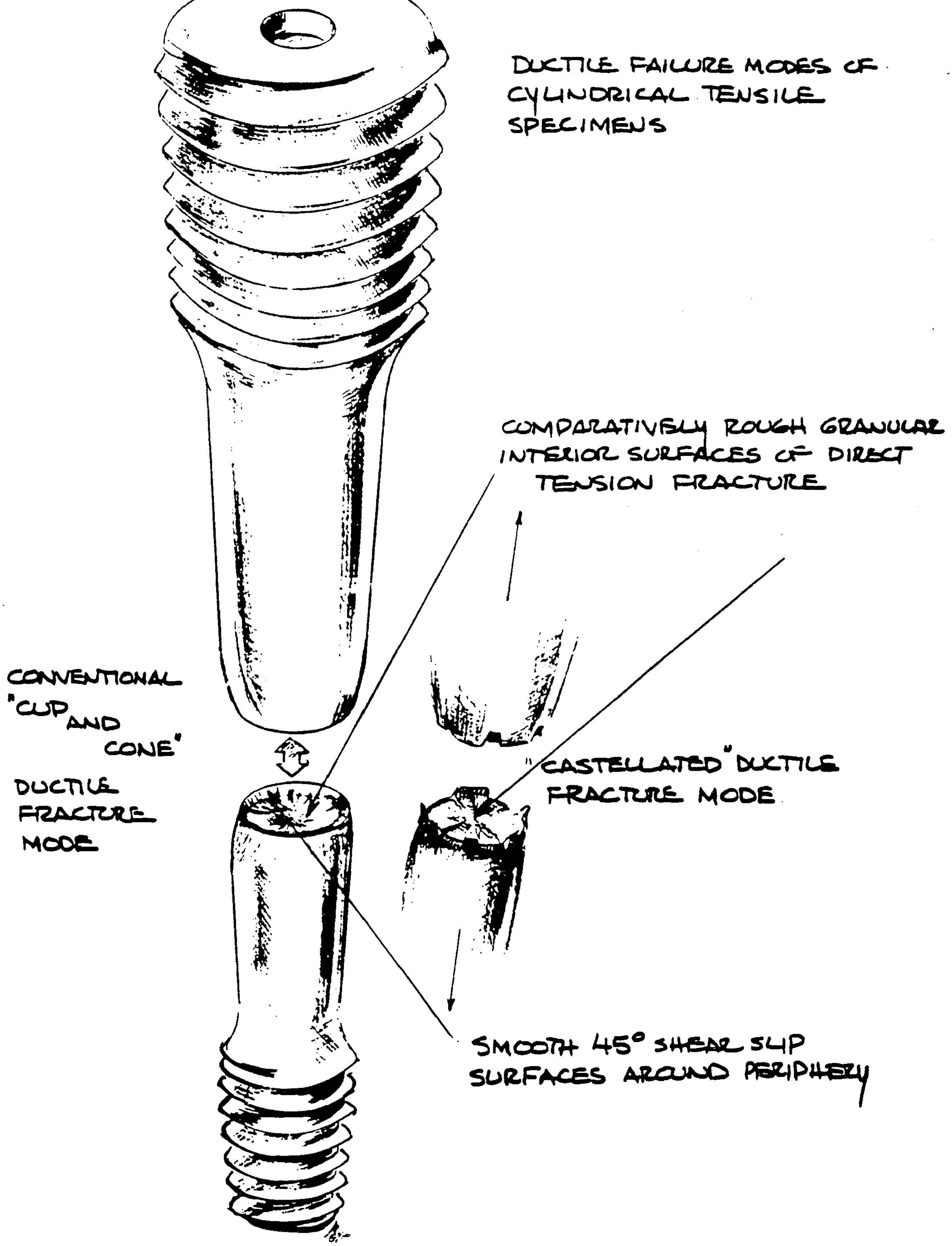
Static Failures, Ductile

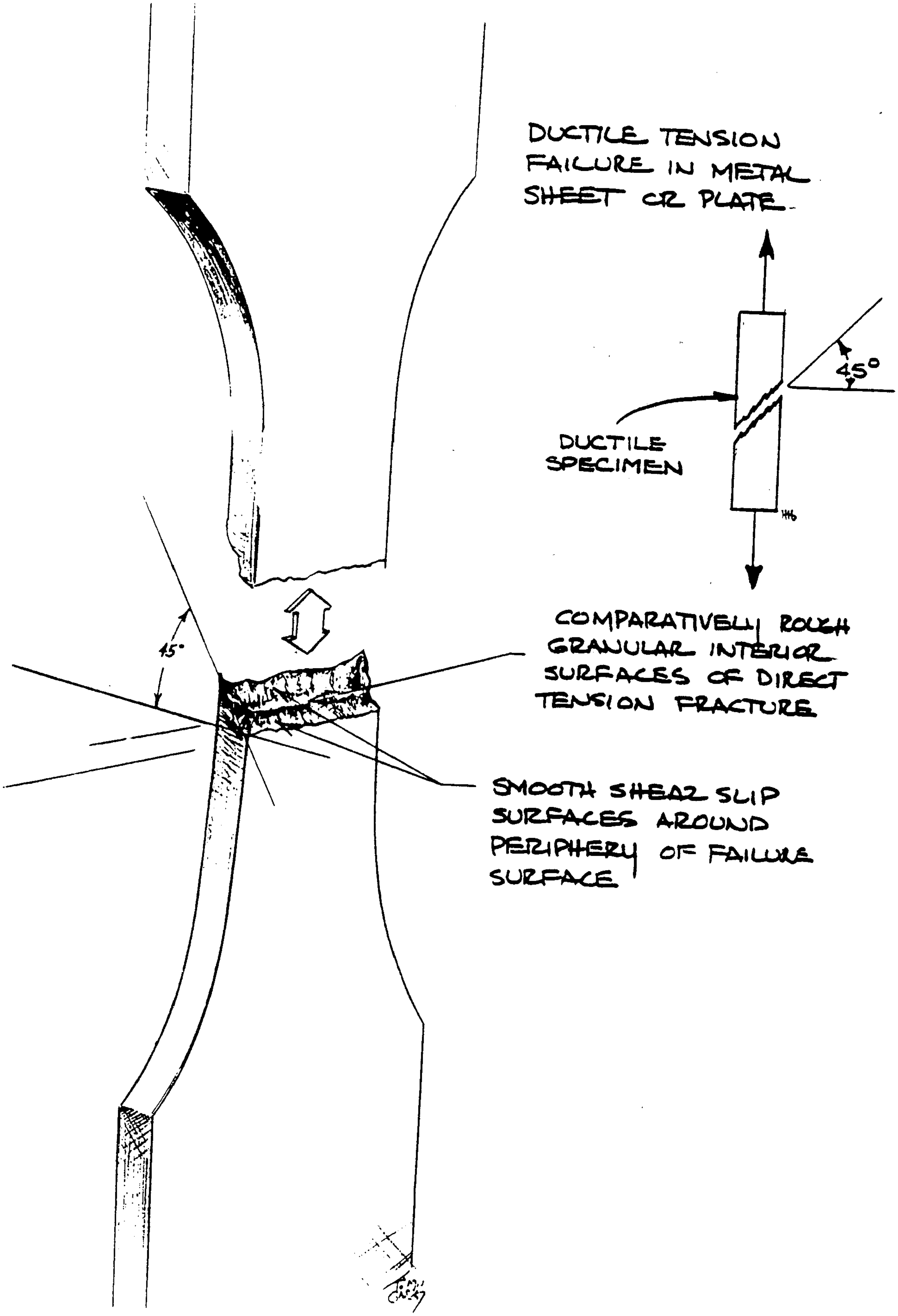
A static failure is defined as a failure resulting from a small number of load applications. The ductile static failure is characterized by permanent distortion or rupture of the member as a result of stresses in excess of the yield point of the material. This type of failure can be recognized by yielding, extending over a considerable portion of the member in the region of the failure. The phenomenon is commonly referred to as "necking" in the failure of a conventional tensile test specimen.

Static Failures, Brittle

A brittle static failure occurs when the metal breaks without appreciable distortion. Brittleness is enhanced in harder parts, rapid loading of steels, thick parts and notches. The fracture surface may be quite bright and sparkle. If the part has a long dimension, a fast running brittle crack will form chevron marks which point back toward the origin. Both ductile and brittle static fractures are types of instantaneous failures.

DUCTILE FAILURE MODES OF CYLINDRICAL TENSILE SPECIMENS



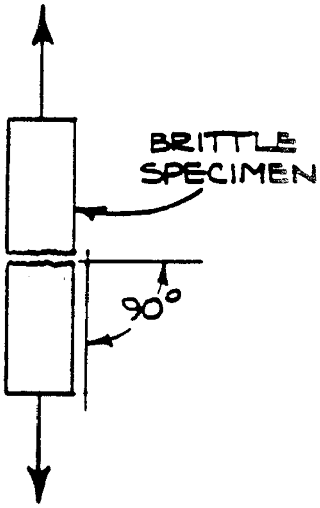


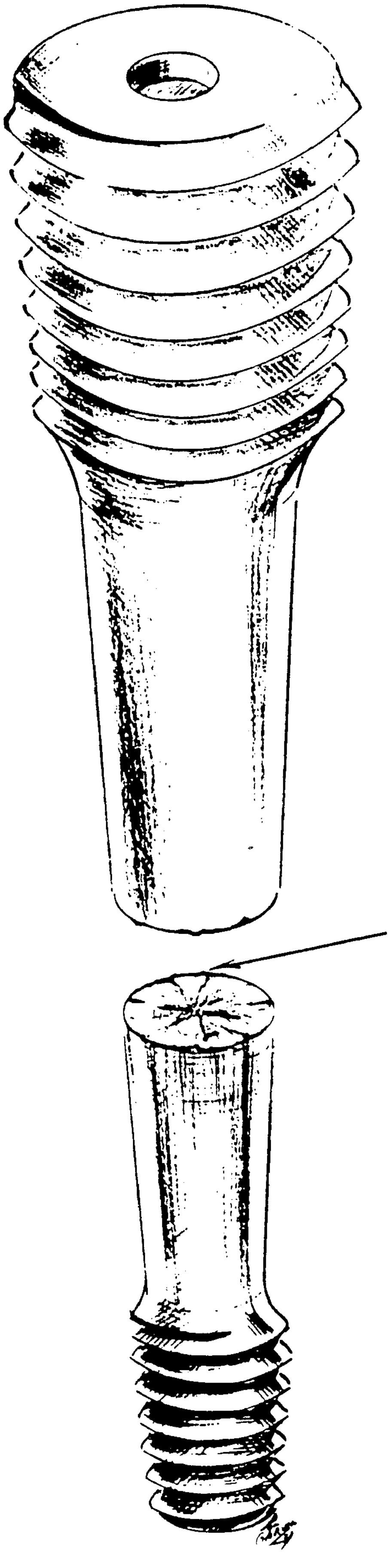
DUCTILE TENSION FAILURE IN METAL SHEET OR PLATE

COMPARATIVELY ROUGH GRANULAR INTERIOR SURFACES OF DIRECT TENSION FRACTURE

SMOOTH SHEAR SLIP SURFACES AROUND PERIPHERY OF FAILURE SURFACE

BRITTLE
TENSION
FAILURE





FRACTURE SURFACE IS PERPENDICULAR TO THE TENSILE STRESS

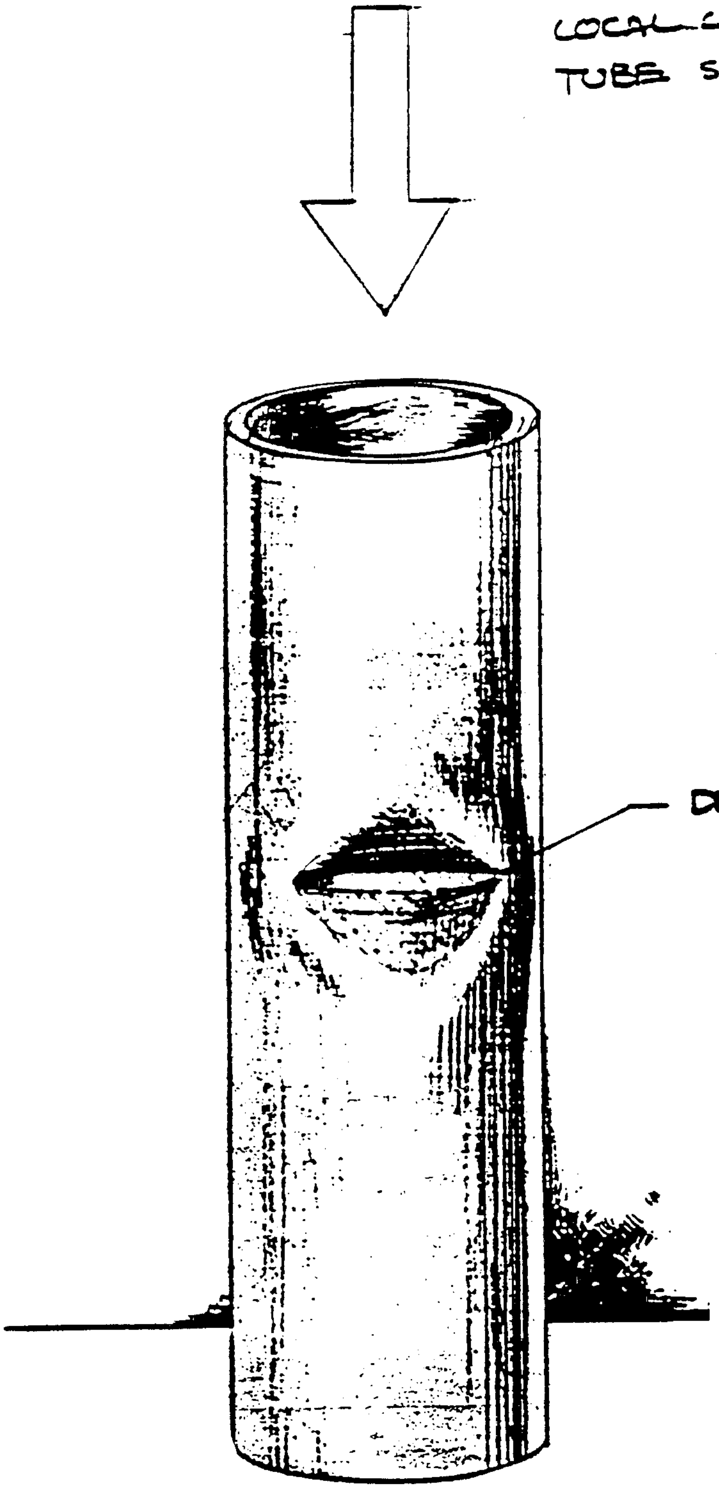
NO NECKING DOWN IS APPARENT

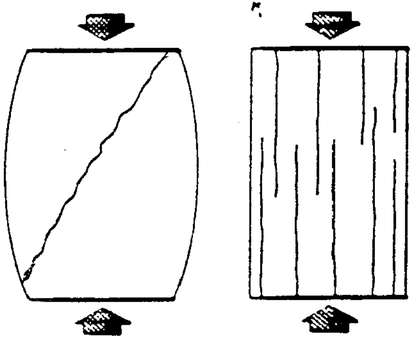
VERY SMALL 45° EDGES ARE PRESENT ALONG PERIPHERY OF FRACTURE WHEN SOME LIMITED DUCTILE BEHAVIOR EXISTS

Compression

Compression failures occur in two general forms - block compression and buckling. Block compression is generally found in heavy, short sections whereas buckling is found in long, lighter sections. When buckling occurs locally, it is referred to as crippling. When it occurs in such a way that the whole piece buckles, it is referred to as column buckling. Local buckling and column buckling are easily recognized since the part in all cases is bent from its original shape.

In block compression failures, the piece separates on oblique planes as in tension, except that there is rubbing of the two halves of the fracture during separation. In some materials there is a local increase in cross-sectional area (barreling) where the material has yielded.




Ductile Brittle

Single-overload fractures

Compression

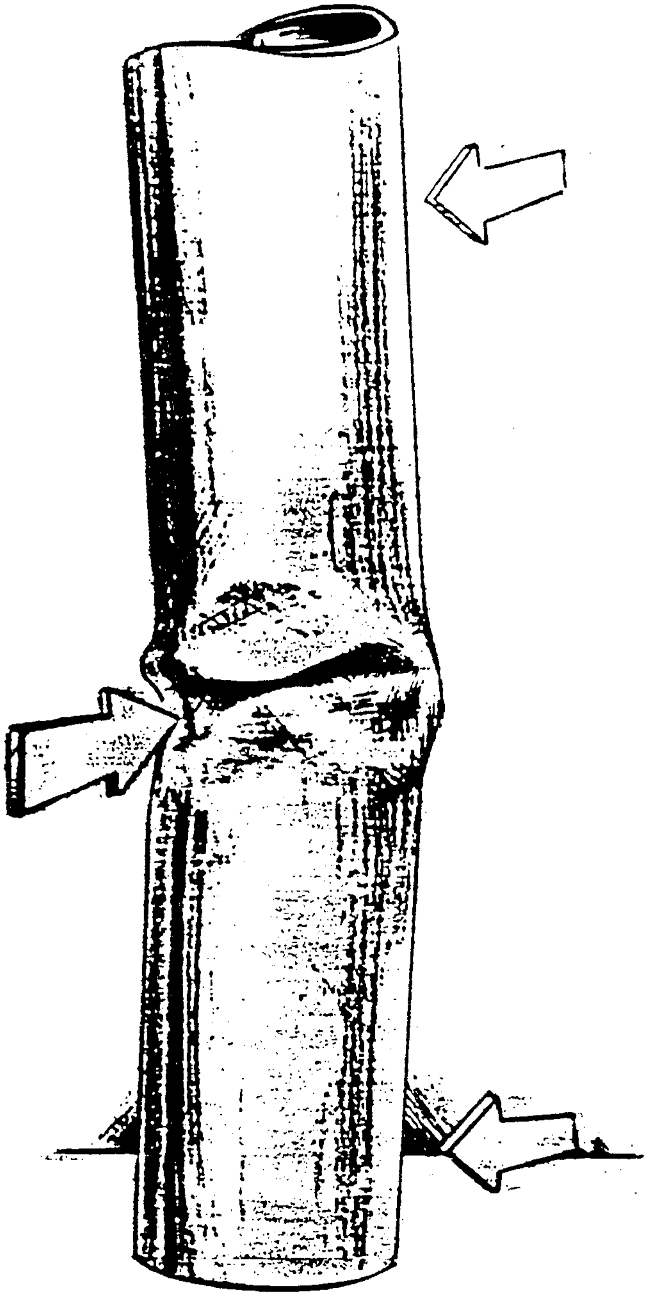
SOLID STRUCTURE

BENDING FAILURES

Identifying Characteristics

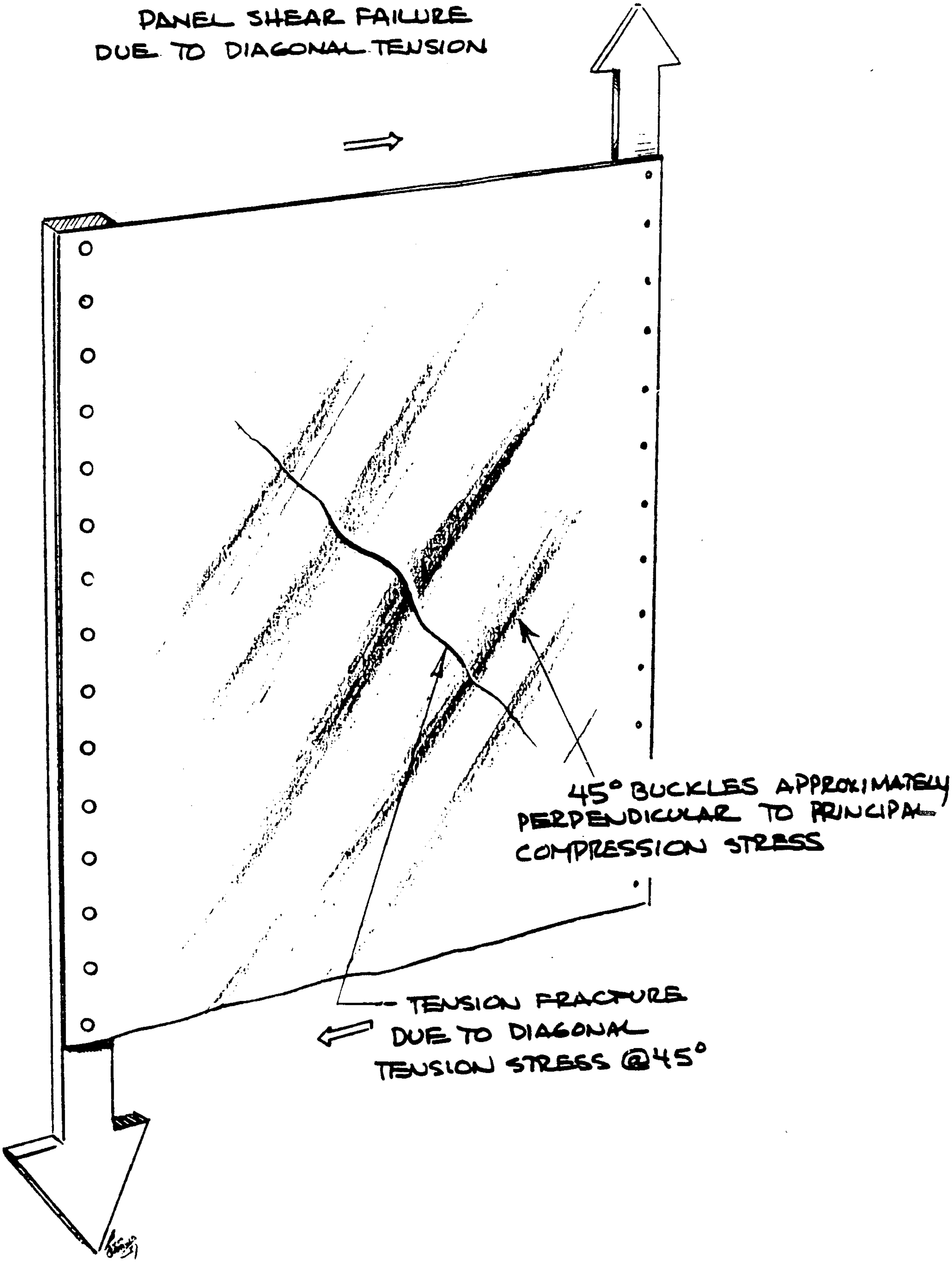
Bending failures are identified by the gross curvature of the part consistent with the direction of the applied forces. The curvature causes the outside of the bend to develop tensile stress, whereas the inside radius of the bend is put into compression. The tensile side usually stretches, the compressive side may cripple. If the part has a shear web, the web panel usually develops diagonal buckling which follows the lines of induced diagonal tension at 45° to the axis of the part. The surfaces of the separation will exhibit instantaneous fracture types.

BENDING FAILURE BY BUCKLING ON COMPRESSION SIDE



Shear buckling generally occurs in thin sheet metal such as wing skin or spar webs. The shear induces tension at 45° to the applied shear loadings. The sheet will buckle in a diagonal fashion and the direction of force application can be told from the appearance of the buckle.

PANEL SHEAR FAILURE DUE TO DIAGONAL TENSION



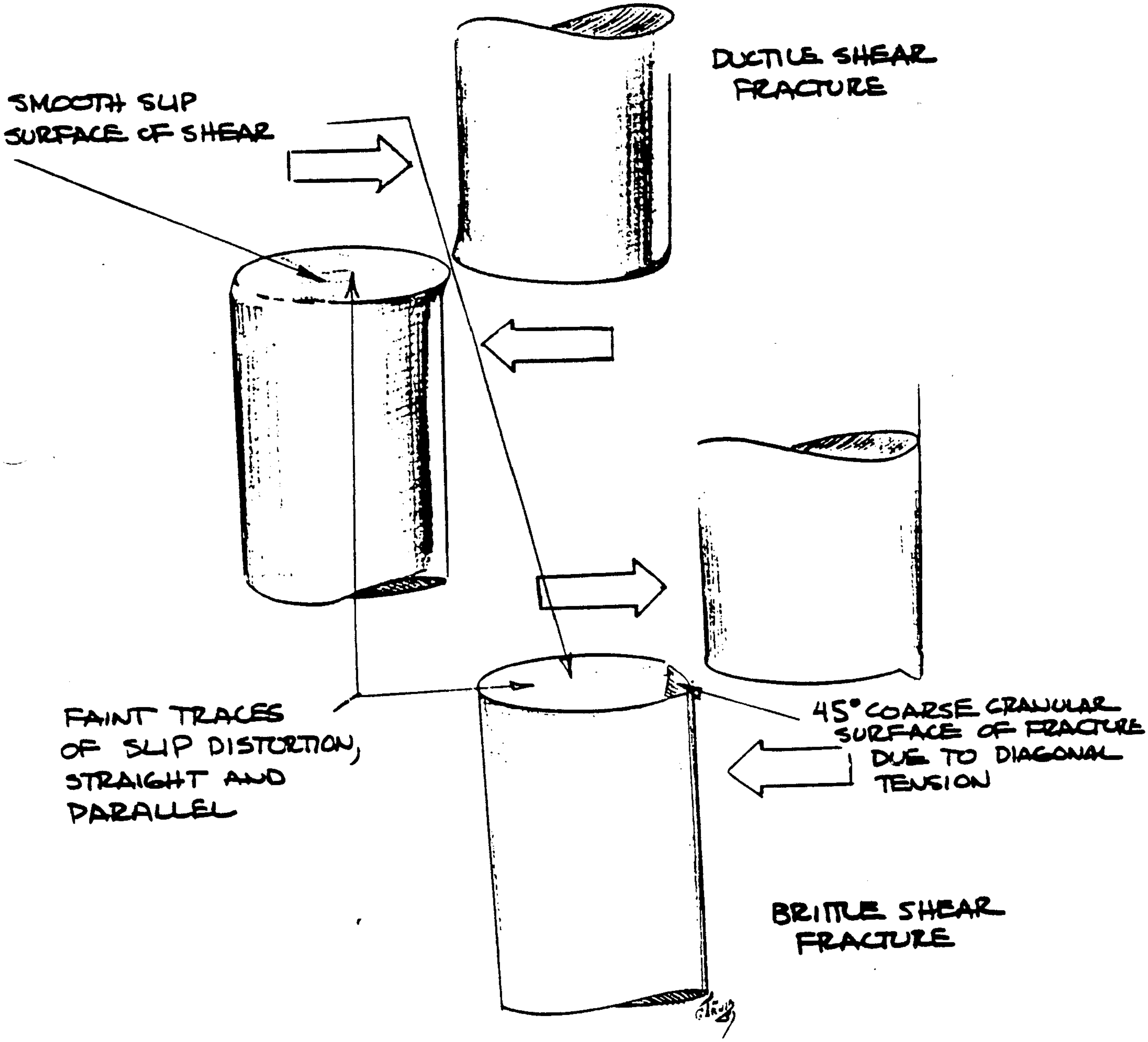
45° BUCKLES APPROXIMATELY PERPENDICULAR TO PRINCIPAL COMPRESSION STRESS

TENSION FRACTURE DUE TO DIAGONAL TENSION STRESS @45°

2.3d Shear

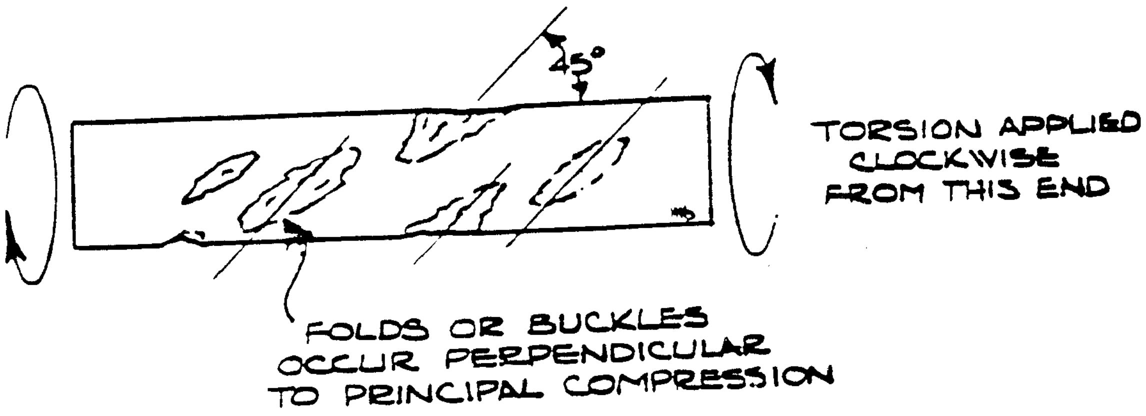
As in compression failures, shear failures can occur in two distinct ways - block shear and shear buckling. In the former type of failure, the two halves of the fracture will slide across each other, and the fracture will appear rubbed, polished, or scored. The direction of scoring will give a clue to the direction of the applied shearing force.

MODES OF SHEAR FRACTURE

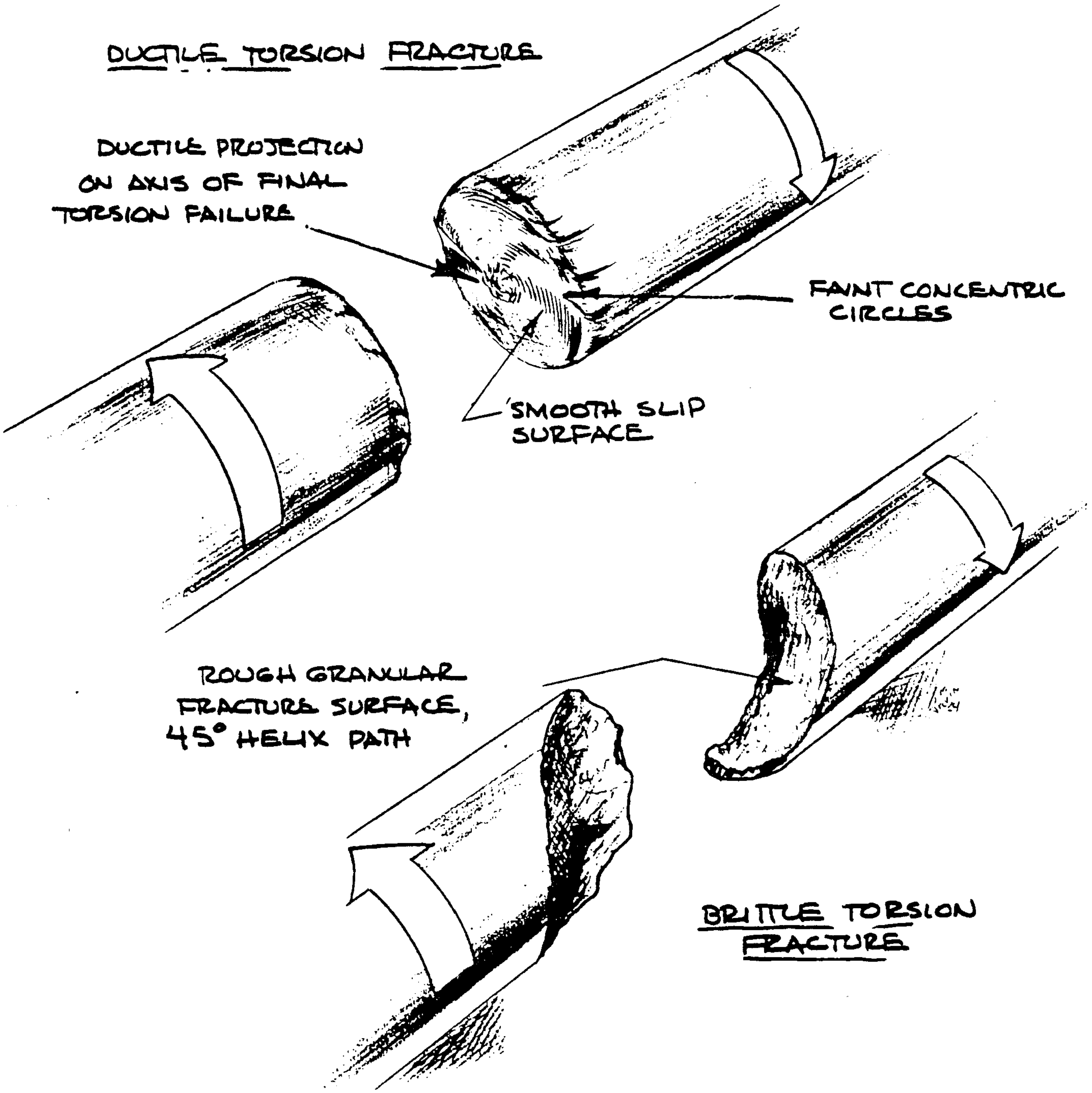


Torsion

Since torsion is a form of shear, the failure from torsion overload will be somewhat similar to the shear failure. Evidence of the direction of torque can be seen on the fractured surface by observing the scoring marks. Most parts retain a permanent twist and this can be used as an indication. In tubing members or a large open section, like the wing, torsion failures often occur as instability failures in a buckling manner. Again the direction of twist can be determined by close examination of the buckle.


45°
TORSION APPLIED CLOCKWISE FROM THIS END
FOLDS OR BUCKLES OCCUR PERPENDICULAR TO PRINCIPAL COMPRESSION

MODES OF TORSION FRACTURE



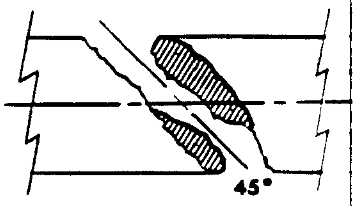
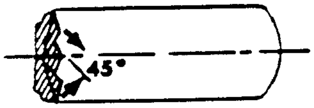
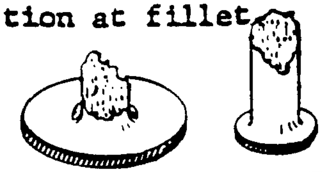
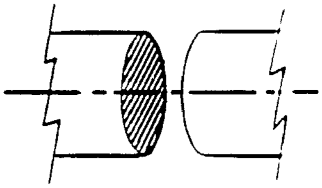
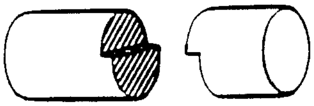
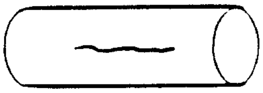
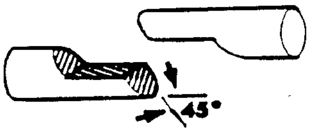
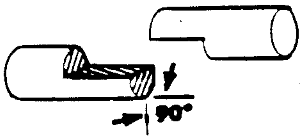
Type of Failure	Basic Pattern	Variations of Basic Pattern	
		(a)	(b)
Tensile 1		Star Pattern 	Saw tooth due to stress concentration at fillet 
Transverse Shear 2		 Small step	 Large step
Longitudinal Shear 3			

Figure 73. Typical appearance of torsional fractures.

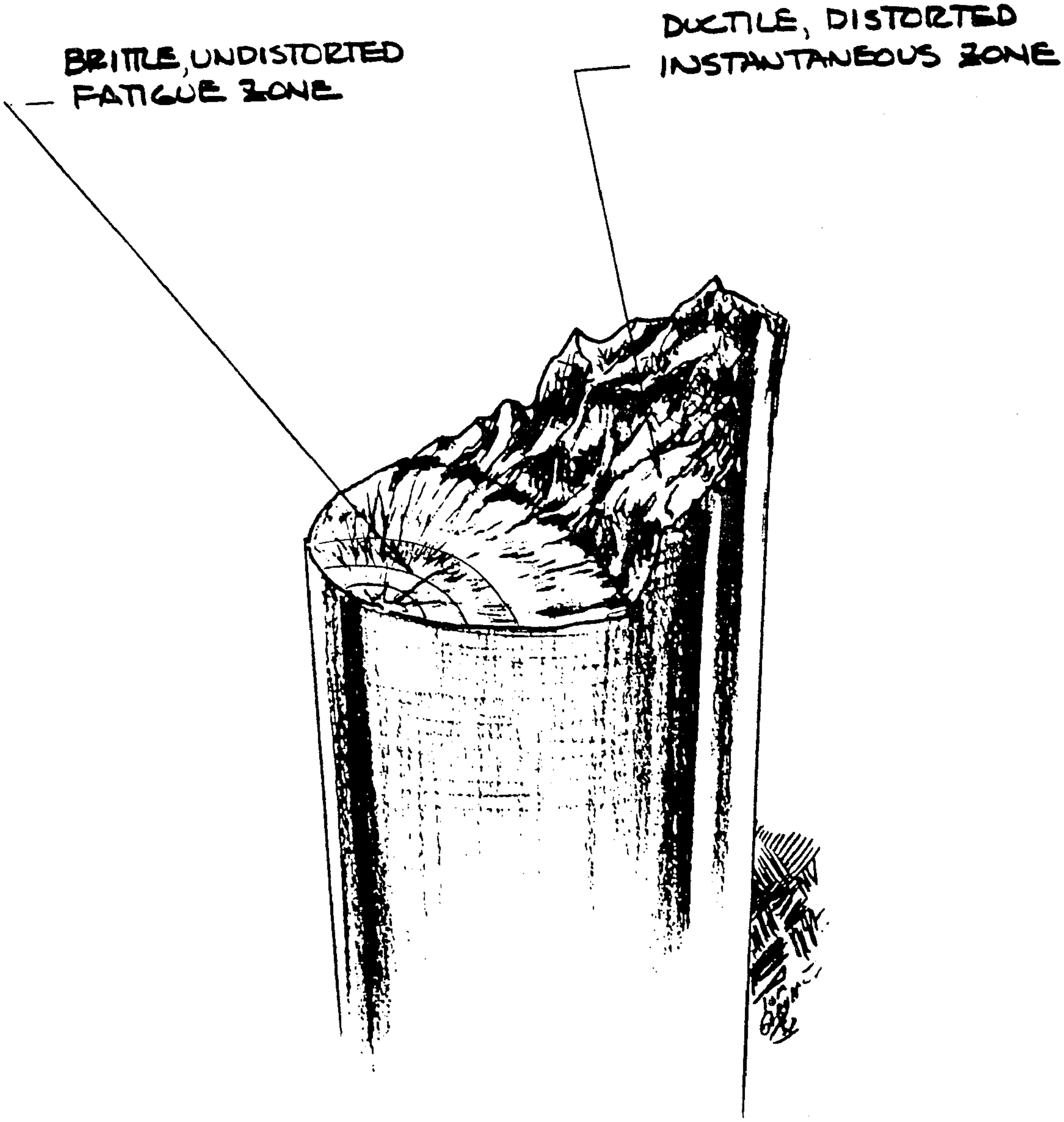
FATIGUE FAILURES

Identifying Characteristics

Fatigue failures may be identified by a two zone fracture surface. The fatigue zone will exhibit a smoother appearance and arrest marks (beachmarks) showing the progression of the crack as it enlarged. The remainder of the fracture will be more coarse consistent with the instantaneous fracture mode operating at final separation.

The fatigue zone origin is found by tracing the beachmarks back to their point of focus. The fatigue crack may have started at a notch, flaw or other feature which acted as a stress concentration. Fatigue can also start on a smooth surface if the applied cyclic stresses are high enough.

TYPICAL FATIGUE APPEARANCE



INTERGRANULAR FAILURE MODES

Stress corrosion

The cracking of a metal caused by the combined effect of corrosion and a constant tension load.

Aluminum and brass crack along grain boundaries, while some stainless steels crack across the grains. In high strength steels stress corrosion cracking seems to follow the old grain boundaries that occurred prior to heat treatment.

Those alloys (usually aluminum) that crack along grain boundaries are strongly influenced by the orientation of the grain pattern.

Stress corrosion cracking is a function of calendar time rather than flight time.

STRESS CORROSION CRACKING

Identifying Characteristics

Stress corrosion cracking may be identified by the presence of multiple, brittle appearing cracks in high strength alloys. Under magnification, the crack path is

often found to have followed the grain boundaries and to be branched (secondary cracks spreading sideways from the main crack). The cracks will form perpendicular to the major tensile stress axis which may be from either applied or residual stresses in the part. A great amount of external corrosion damage is not a necessary condition for stress corrosion cracking to form.

Hydrogen Embrittlement

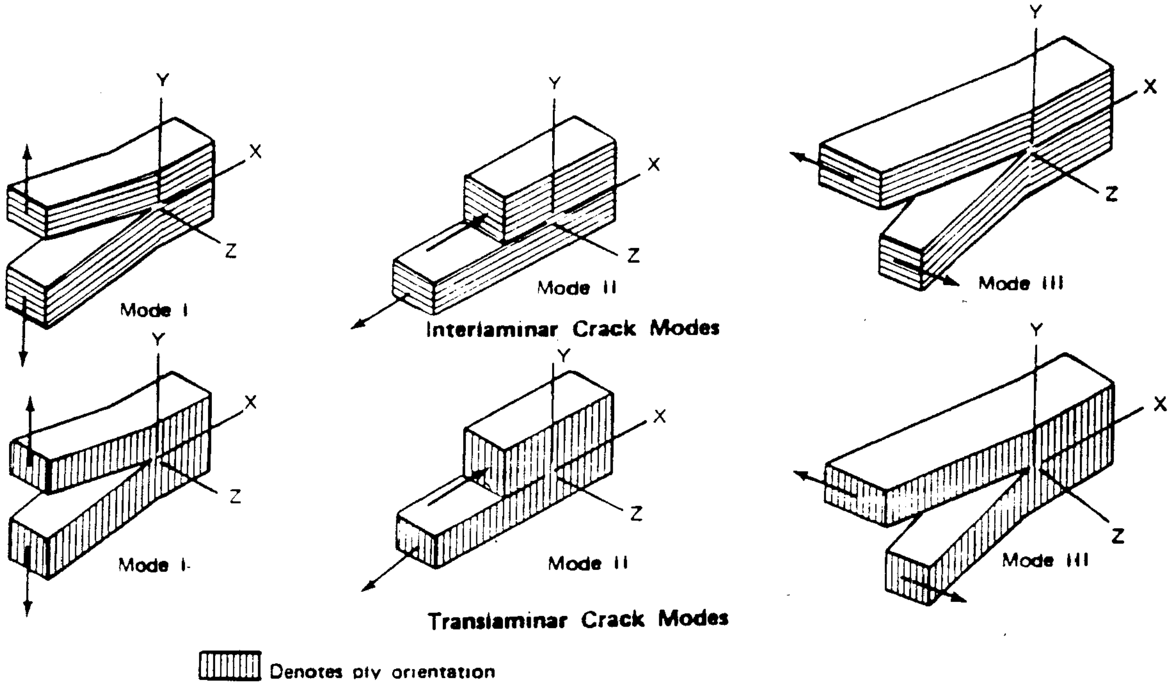
High strength steels are susceptible to cracking when hydrogen enters the metal. The hydrogen may come from the corrosion reaction with water or may be electrochemically introduced during electroplating. Many steel aircraft parts are cadmium plated. If high strength parts are plated, they must be heated to about 400°F for several hours to bake out the hydrogen. If not baked, once the part is loaded, the hydrogen moves through the metal and allows cracks to form after a period of time.

If the hydrogen is absorbed during corrosion in service, it could be considered a special case of stress corrosion cracking. Obviously, the source of the hydrogen must be determined if future cases are to be avoided. If the hydrogen is because of a missed baking operation, an entire lot of parts are at risk. A laboratory metallurgical examination should be conducted for such parts.

Hydrogen embrittlement cracks will normally be intergranular (between the grains) and will be highly branched. Once formed, hydrogen embrittlement cracks may serve to initiate fatigue or instantaneous fractures, depending upon the circumstances of the loads applied.

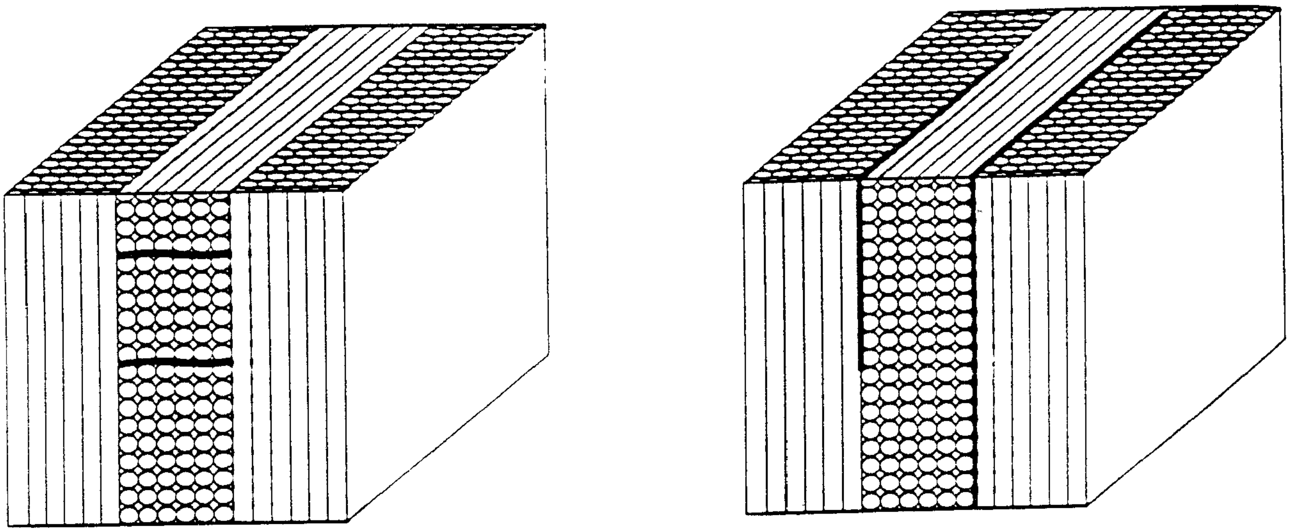
COMPOSITES

COMPOSITES - BASIC LOADING MODES AND FAILURES PRODUCED ON COMPOSITES



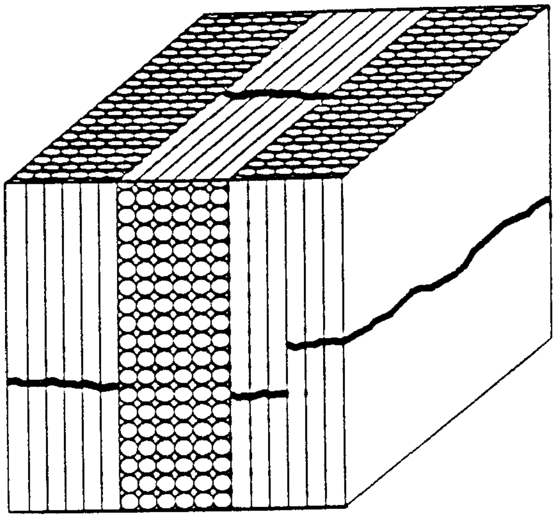
Mode I	Opening or tensile mode, where the crack surfaces move directly apart.
Mode II	Sliding or in-plane shear mode, where the crack surfaces slide over one another in a direction perpendicular to the leading edge of the crack.
Mode III	Tearing or antiplane shear mode, where the crack surfaces move relative to one another and parallel to the leading edge of the crack.

Basic Modes of Loading Involving Different Crack Types and Surface Displacements (Interlaminar and Translaminar)



(a) Intralaminar Fracture

(b) Interlaminar Fracture



(c) Translaminar Fracture

The Basic Fracture Modes

COMPOSITE FRACTURE MODE DETERMINATION (Tension, Shear, and Compression)

For interlaminar fractures, the mode can be determined as follows:

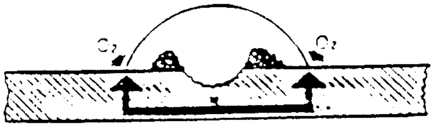
- Mode I tension dominated fractures exhibit flat resin fracture between each fiber, with river marks and resin microflow as the dominant features.
- Mode II shear dominated fractures exhibit rough resign fracture between each fiber, with hackles and scallops as the dominant features.

For translaminar fractures, the mode can be determined as follows:

- Tension dominated fractures exhibit a rough morphology, with fibers protruding at various heights from the surface. Close inspection of the individual fiber ends reveal radial lines indicative of tensile failure.
- Compression dominated fractures exhibit a smooth morphology, with most of the fibers broken at a common plane. Extensive damage is common due to rubbing between the mating fracture surfaces. Close inspection of the individual fiber ends reveal a neutral axis line with tensile radials on one side of the line and compression fracture on the other side.

Corrosion Pitting or Pitting Corrosion

Corrosion is a chemical reaction between the metal and oxygen in air, moisture, or water. In shallow depressions, the oxygen is quickly lowered, producing a low oxygen level at the bottom of the depression and a high oxygen level at the high points. The changes in oxygen level cause an electric current to flow and the corrosion rate is increased in the depression. The corrosion rate increases as the hole or pit increases in depth.



A potential difference is established between an oxygen-starved surface and a surface where oxygen is plentiful. Rusting, for example, begins at the anode formed in the center of a droplet or a stagnant puddle of water where oxygen is scarce. Cathodic reaction takes place at the outer edges where oxygen is available.

Fretting and Fretting Corrosion - A form of damage which occurs between two mating surfaces which are subjected to relative, oscillatory motions. As the two surfaces rub together, pieces of each surface are broken off and subsequently oxidized by the atmosphere. Because the oscillatory motion is small in amplitude, the debris collects between the two surfaces and acts as an abrasive, causing further damage. Fretting products from iron are reddish-brown while those from aluminum are generally black. It is generally accepted that fretting reduces fatigue life greatly.

Grinding Burns

An undesirable condition resulting from overheating the surface of a metal during the grinding process. This overheating can change the crystalline microstructure of a shallow surface layer and result in the formation of a "built-in" tension field within this layer. Stresses resulting from service loads combined with this built-in tension field can cause surface cracking. These cracks can continue to grow by the action of metal fatigue even though they extend into the less highly stresses base metal below the grinding burned layer.

CARE AND HANDLING OF FRACTURE SURFACES

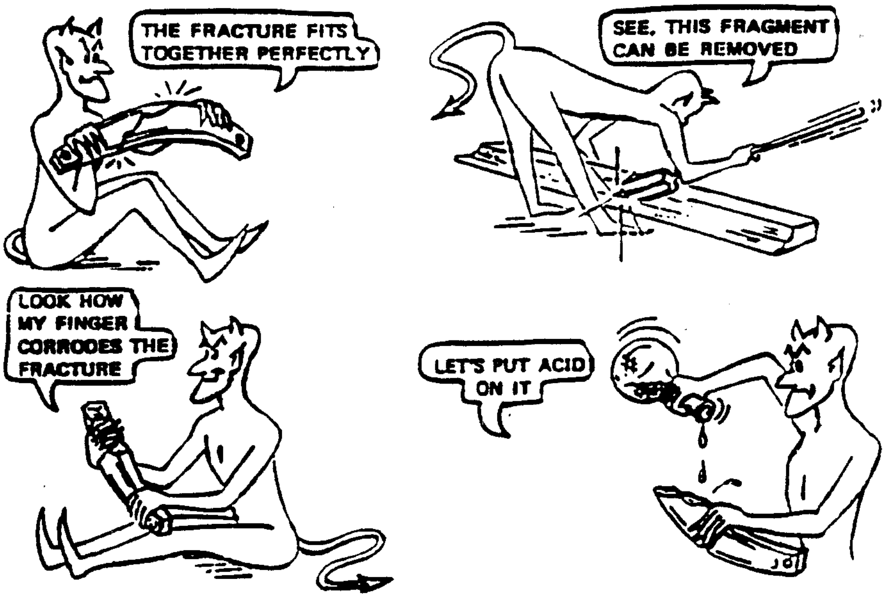
All fractures should be visually examined for any evidence of progressive or precrash failure modes. The parts will be handled during the recovery and reconstruction phases of the investigation. Due care must be exercised to avoid damage to fracture surfaces.

Inadvertent contact between fractures will permanently destroy fracture details which may be important in determining the sequence of failure. Rubbing or touching the fracture surfaces may add or subtract chemical impurities which may also be important.

Place soft padding over the fractures (cotton, clean cloth, paper towels) and securely tape the padding in place. Fracture surfaces on larger parts may be covered with cloth or cardboard. Tag the parts including information as to how the fractures have been treated. Each fracture should be placed in a separate paper envelope or plastic bag, preferably with a desiccant.

You should also consider sending the lab a separate sample of any suspected corrodent so the lab can analyze it and determine whether it may have masked part of the evidence.

HANDLE FRACTURES WITH CARE



Examples of things not to do.

Resist the temptation to fit the two halves of the fracture back together, as this could damage microscopic features. Do not pick at the fracture surface with tweezers or other instruments. Any unnecessary contact with the fracture surface should be avoided because acids or other contaminants on the hands could damage fine features.

CLEANING FRACTURE SURFACES

When possible, cleaning of fracture surfaces should be avoided, especially where analysis of contaminant elements or corrosion products may be required. The fracture appearance should be documented by photographing or the taking of notes before any cleaning is attempted. Also, it must be ascertained whether identification of foreign products on the fracture will aid in the failure analysis. Identification of these products can be quite useful in pin pointing adverse environmental conditions that contributed to the fracture. Hasty cleaning can remove important evidence. The problem of cleaning the fracture surface should be approached with caution and common sense.

Fracture surfaces should only be cleaned when you are certain that the material on the surface was introduced in the crash and leaving the potential corrodent on the fracture would cause certain harm before it could be examined in the laboratory. Fresh water rinsing followed by drying with anhydrous alcohol or acetone should be enough.

If a fracture surface is covered by loosely adherent dust or dirt, a soft natural fiber brush may be used. Dry compressed air is also useful for removing loose contamination. Do not use stiff plastic brushes or any kind of metal brush because plastic can be imbedded in the fracture and metal can mechanically damage the features. If dried mud is present on the fracture, warm soapy water and a stiffer natural fiber brush may be used. Parts should be immediately rinsed followed by drying with anhydrous alcohol or acetone and reprotected.

Oils and greases may be removed by organic solvents, such as mineral spirits or a vapor degreasing agent such as trichloroethane.

A general rule is to use the gentlest and mildest cleaning procedures possible. Any corrosion or attack of the base metal by a cleaning agent, even on a microscopic scale, will probably damage the fracture surface. If the fracture surface is severely corroded or oxidized, the chances are good that any fracture features have already been destroyed, and cleaning will not restore them; however, overall or general features, such as chevron markings or fatigue thumbnails, may remain.

INFORMATION FORWARDED WITH THE PARTS

Laboratory testing is a valuable tool which can be employed to good advantage in many accident investigations. To take full advantage of the technique, it is required that the investigator forward complete information relative to the circumstances surrounding the failure. Unless this is done, a positive determination of the cause may not be possible.

As complete a history on the part as can be developed should be forwarded with the failed part. This history should include information such as:

a. When the part was installed in the aircraft.
b. Total number of hours on the part.
c. Time since overhaul or inspection.
d. Whether any previous difficulties had been reported.
e. Other pertinent data which might help in determining how or why the part failed.

LABORATORY EXAMINATION OF FAILED PARTS

During the course of a particular investigation, the investigator may decide that additional study or testing of a specific part or item may be necessary or desirable. A wide range of laboratory facilities is available.

At the present time, three government agencies are available to perform test work on failed aircraft parts. Wood parts are tested by the Forest Products Laboratory. Metallic parts are tested by the NTSB Metallurgical Laboratory or National Bureau of Standards. Most of the chemical analyses are performed by the Federal Bureau of Investigation Laboratory, although the N.B.S. also does some of this type of testing. On certain occasions, tests are conducted at the manufacturer's plant or independent laboratory under the investigator's supervision and control. All of the test work performed by other government agencies is paid for by a transfer of funds to the particular agency. For this reason, the investigator should evaluate the importance of the information to be gained from testing and the relationship of this information to the determination of the probable cause of the failure.

The various types of tests that can be conducted are too numerous to be listed in detail. Some of the more frequently conducted tests are:

a. Tests on metallic parts for evidence of fatigue cracking, poor welding, substandard material properties, poor heat treatment, stress corrosion cracking, inadequate dimensional properties, etc.;

b. Tests on wooden parts for evidence of inadequate glue bond, substandard material properties, moisture content, improper grain slope in splice connectors, etc.;

c. Tests on smears, scores, cuts, etc. to determine the nature of the substance and direction of applied force, etc.;

d. Tests on fuel and oil to detect presence of foreign substance or nonconformity with standard specifications.

FAILURE ANALYSIS EQUIPMENT

PHOTOGRAPHIC:	35 mm 120 mm Polaroid
MICROSCOPIC:	Magnifying Glass - 5X, 10X Stereo Zoom Microscopes 7X - 30X Scanning Electron Microscope Transmission Electron Microscope
NONDESTRUCTIVE:	Fluorescent Magnetic Particle Fluorescent Liquid Penetrant Electromagnetic (Elect. Conductive Mat.) Ultrasonic Radiography (X-Ray, Gamma Ray)
MECHANICAL:	Hardness Tensile
PHYSICAL:	Micrometers, Gages, etc.
METALLOGRAPHIC:	Sanding Polishing Etchants Metallograph (50-800X)

CLEANING AND STRIPPING