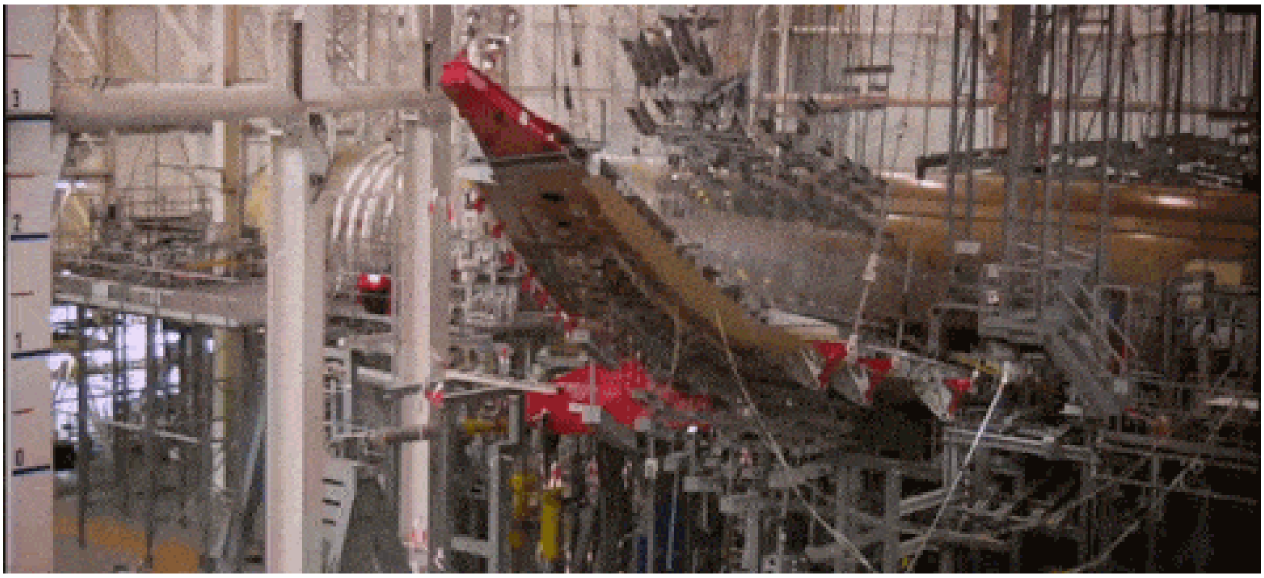
6 FATIGUE TESTS

Analysis and testing are both key aspects of fatigue design, as indicated in the flow chart of Fig. 4.1. How much time and money should be put into each is an important engineering decision. A more complete and correct analysis involving iteration and optimization can provide prototypes that are closer to the final product and thus require less testing. Insufficient or incorrect analysis may result in too much dependence upon testing and retesting, creating both time and cost inefficiencies. Analysis capabilities are largely dependent upon the computer capabilities available to the engineer. Complete computer pro-grams are available for taking a product from an input such as a strain or load spectrum, to a final calculated fatigue life. However, the engineer must realize that these calculations are for the models; the key to confidence in these results is how closely the models represent the real product and its usage. For example, environmental influence and nonproportional multiaxial loading conditions are not usually properly integrated into the calculations, along with the fact that the results have varied from excellent to fair to poor. Thus, even the best analysis should not necessarily be the final product design, particularly with safety critical products. However, analysis is a must in proper fatigue design and should lead to a very reasonable prototype design. A design based on analysis alone, without fatigue testing, requires either a large margin for uncertainty or an allowance for some probability of failure. A probability of failure of a few percent can be permitted if failures do not endanger lives and if replacement is considered a routine matter. In most other situations, analysis needs to be confirmed by tests.

Fatigue testing has involved enormous differences in complexity and expense and has ranged from the simple constant amplitude rotating beam test of a small specimen to the simulated full-scale, complex, variable amplitude thermomechanical cycling of the Concord supersonic aircraft structure in the 1970s or the Boeing 777 aircraft structure in the 1990s. The objective of fatigue testing may be to obtain the fatigue properties of materials, aid in product development, determine alterations or repairs, evaluate failed parts, establish inspection periods, or determine the fatigue durability of components, subassemblies, or the full-scale product. Durability testing requires a representative product to test and therefore occurs late in the design/development process. Parts manufactured for fatigue testing should be processed just like production parts because differences in processing (for instance, cut threads instead of rolled threads or forged parts instead of cast parts) may have a major effect on fatigue resistance. Test specimens may be considered one-dimensional, as with small cylindrical specimens used for baseline material characterization under well-controlled environmental conditions. They may be considered two-dimensional in simple component testing that may include geometrical discontinuities and surface finish such as. an engine connecting rod. Three-dimensional specimens would include subassembly structures such to full-scale structures such as the Concorde and the Boeing 777 aircraft.



Aircraft engineering fatigue design relies in the first instance on baseline coupon tests to assess the many locations identified as susceptible to cracking. The coupons may be loaded by constant amplitude or representative variable amplitude load histories, and they may try to represent some feature of a built-up structure.

The results of these coupon tests are averaged to give an indication of the structural life for a production aircraft. However, there are significant limitations to this approach:

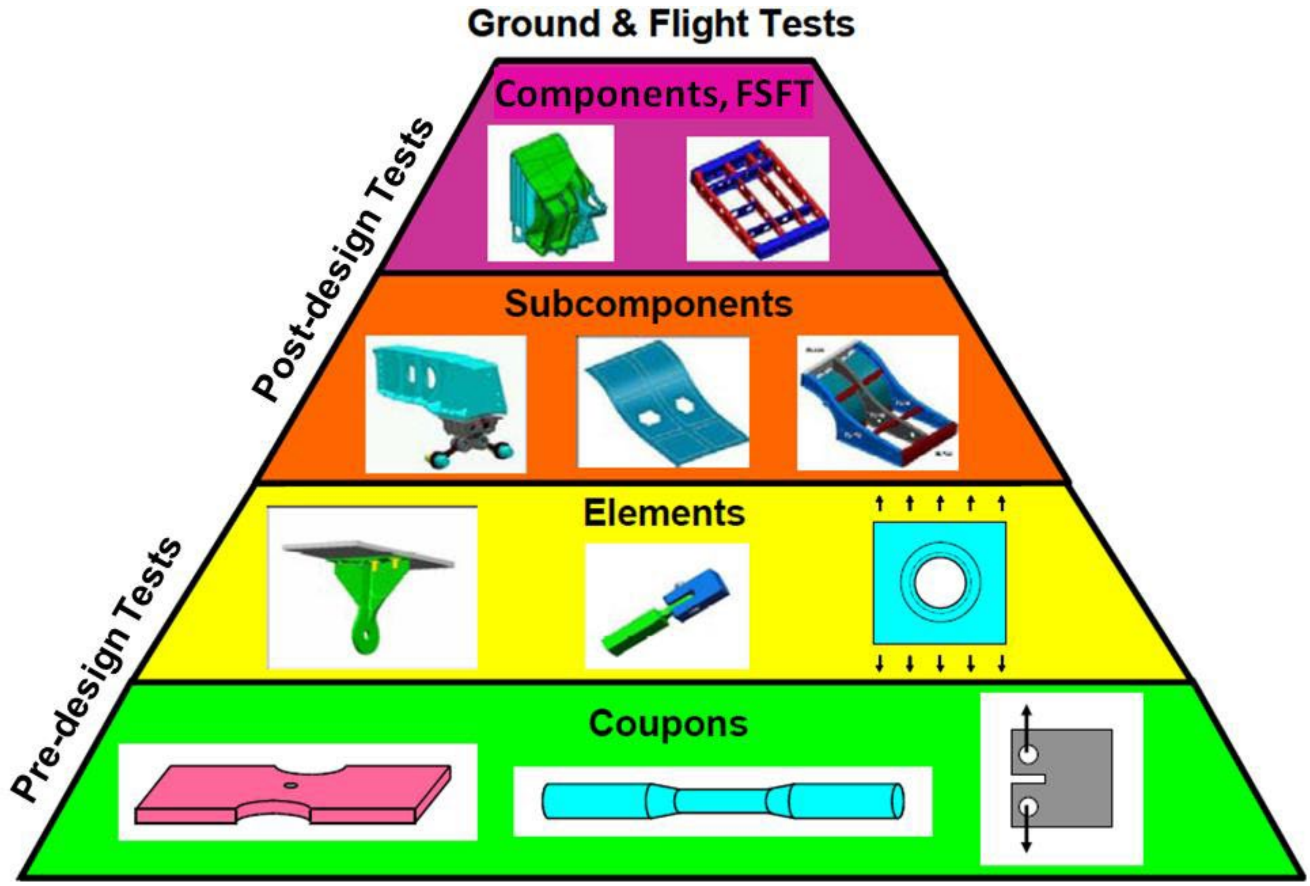
1. Experience has shown that in high performance aircraft the components have many features with the potential to crack, and that each of these features is typical of a single type of "representative" coupon. Hence a component's average indicated life is equivalent to only the shortest average life from tests on several types of coupons.

2. Even when the most critical feature of a component has been identified and assessed by coupon testing, the coupons are rarely fully representative, notably with respect to the surface treatments and finishes required for production aircraft. This is important because the commencement of fatigue cracking is primarily surface-influenced and therefore greatly dependent on small surface discontinuities inherent to component production, as well as any surface-connected discontinuities inherent to the material.

These limitations are addressed by other means. One way, which is mandatory for all modern aircraft is to test actual components, and conduct full-scale fatigue testing (FSFT) on part of the structure or even the full airframe, thereby including the effects of component geometry and production. (FSFT became mandatory for military aircraft in 1969, and civil aircraft in 1998)

Another way is to improve coupon testing by making the coupons optimally representative of the most fatigue-critical details, e.g. by applying surface treatments and finishes used in component production. This may seem obvious, but it is sometimes neglected or overlooked.

Figure shows a schematic 'Building Block' (BB) approach for testing materials, components and structures as part of an aircraft certification process. This is adapted from a schematic for the Lockheed Martin F-35 Joint Strike Fighter (JSF), but is generically valid. The BB approach may be viewed as a pyramid whose base is the initial material evaluation. Each level of the pyramid is the foundation for the next, and the structural complexity and costs increase with each level up to the FSFT(s). The final phase of certification is ground and flight testing of the aircraft.



“Building Block” fatigue test approach for materials, components and structures

There are several points to be noted about the testing approach and procedure:

1. Coupon testing level: This includes standard and non-standard tests. Examples of standard tests are stress – life (S–N); strain – life (ε–N); cyclic stress − strain (S− ε).

2. **Element to FSFT levels**: At all these levels it is advisable to add marker loads to the fatigue load histories. Sometimes a realistic load history will result in natural crack front markers, but it is better to make sure that they occur. There are comprehensive guidelines for this.

Crack front marking is especially relevant to analyses of fatigue cracks detected during FSFT teardowns. Besides being used (and required) directly for certification, the FSFT teardown results are important for possible design modifications, verifying structural analyses, and determining whether retrofits may be advisable or necessary.

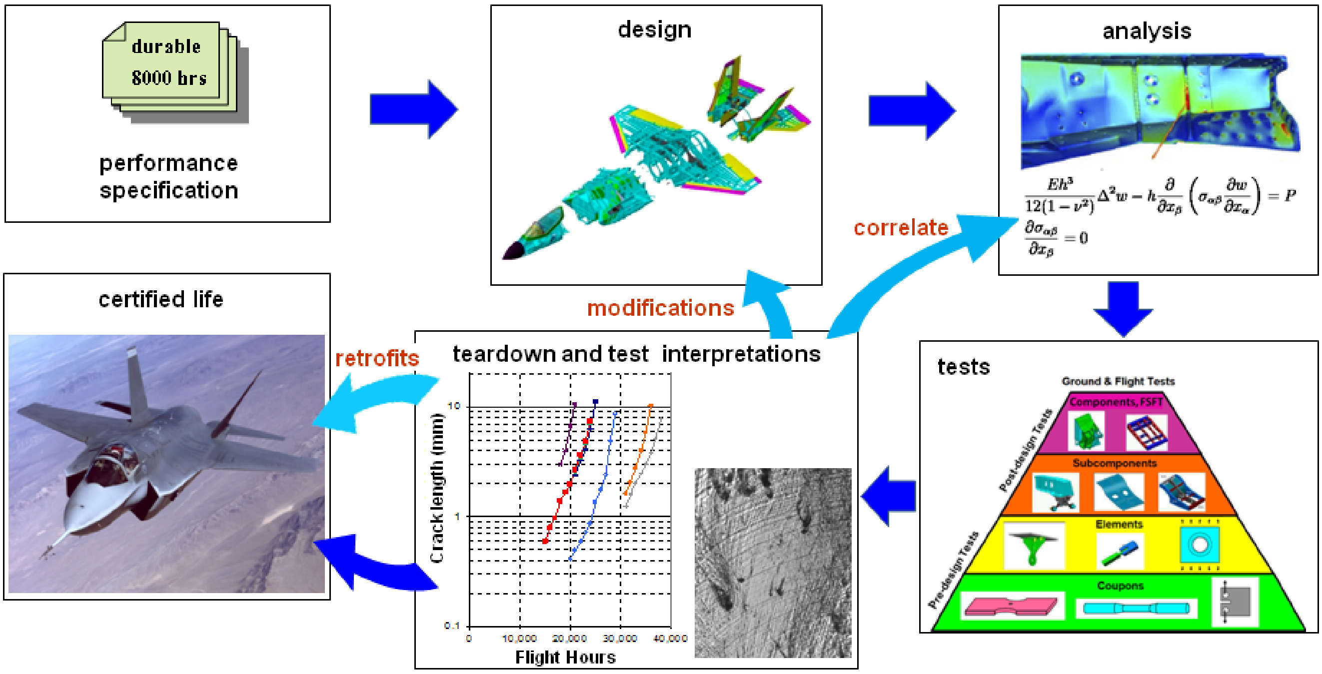


Fig. Airframe fatigue certification and the central role of fatigue testing

FSFT types: It is important to note that Full-Scale Fatigue Testing does not imply testing of the entire airframe. This may be done in some instances, but the available space and testing equipment often dictate that major parts of the airframe are tested separately.

An example of part-structure FSFT is the Airbus A380 fatigue test, in which candidate fuselage skin materials were tested. Figure shows the types of applied loads, namely fuselage pressurization (ΔP) and bending (MY, MZ) and ground loads (QZ); and the number of simulated flights applied during testing. This is slightly more than twice the nominal Design Service Goal (DSG) of 20,000 flights.

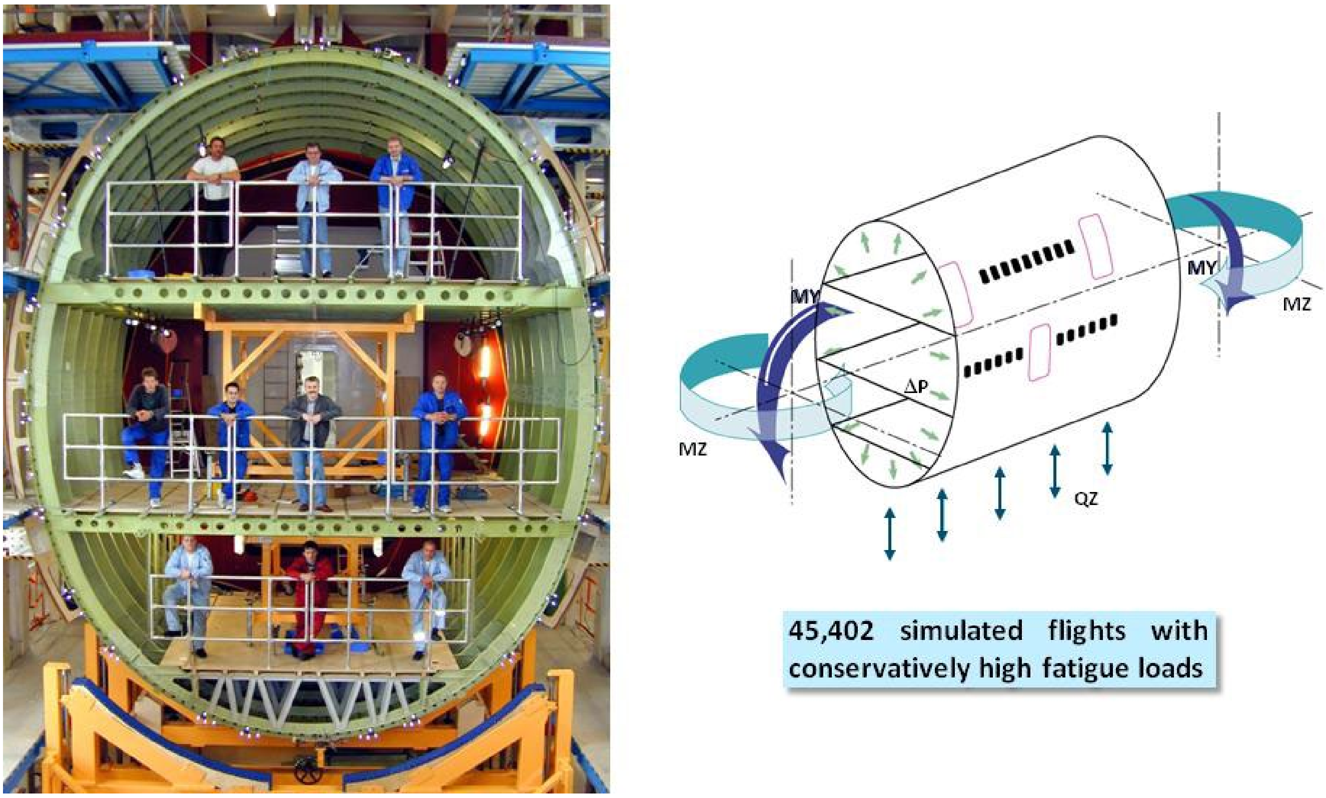


Fig. Airbus A380 full-scale fatigue test ‘specimen’, the general loading conditions, and the number of simulated flights applied during testing

FSFT requirements: As mentioned cases of Widespread Fatigue Damage (WFD) in civil transport aircraft led eventually to mandatory FSFT from 1998 onwards; and in 2011 the Limit Of Validity (LOV) concept for aircraft above 34,000 kg. The LOV concept requires FSFT to determine the onset of WFD.

These changes were reflected in the FSFT requirements, or rather expectations. From 1998 to 2011 the expectation was that an FSFT would be done to a minimum of 2 DSGs followed by specific inspections and analyses. With introduction of the LOV concept it is recommended that the FSFT is run to 3 DSGs, followed by residual strength testing.

6.1 Fatigue Test Machines

Systematic, constant amplitude fatigue testing was first initiated by Wohler on railway axles in the 1850s. Figure 3 schematically shows several common constant amplitude fatigue test machines.

Rotating bending machines are shown in Figs. 3a and 3b.

The test machine in Fig. 3b produces a uniform, pure bending moment over the entire test length of the specimen, while the cantilever test machine in Fig. 3a has a nonuniform bending moment along the specimen's length. These test machines are known as «constant load amplitude machines» because, despite changes in material properties or crack growth, the load amplitudes do not change.

A constant deflection amplitude cantilever bending test machine that produces a nonuniform bending moment along the specimen's length is shown schematically in Fig. 3c. Since the rotating eccentric crank produces constant deflection amplitude, the load amplitude changes with specimen cyclic hardening or softening and decreases as cracks in the specimen nucleate and grow. For a given initial stress amplitude, constant deflection test machines may give longer fatigue life than load-control machines because of the decrease in load amplitude. The eccentric crank test machines, however, do have an advantage over the rotating bending test machines in that the mean deflection, and hence the initial mean stress, can be varied.

Figure 3d shows a schematic of an axial loaded fatigue test machine capable of applying both mean and alternating axial loads in tension and/or compression.

A common test setup for combined in-phase torsion and bending with or without mean stress loading is shown in Fig. 3e. This test machine provides a uniform torque and a nonuniform bending moment along the specimen's length. Many additional test machines have been designed over the years, but the most important contribution to fatigue testing has been the closed-loop servohydraulic test system.

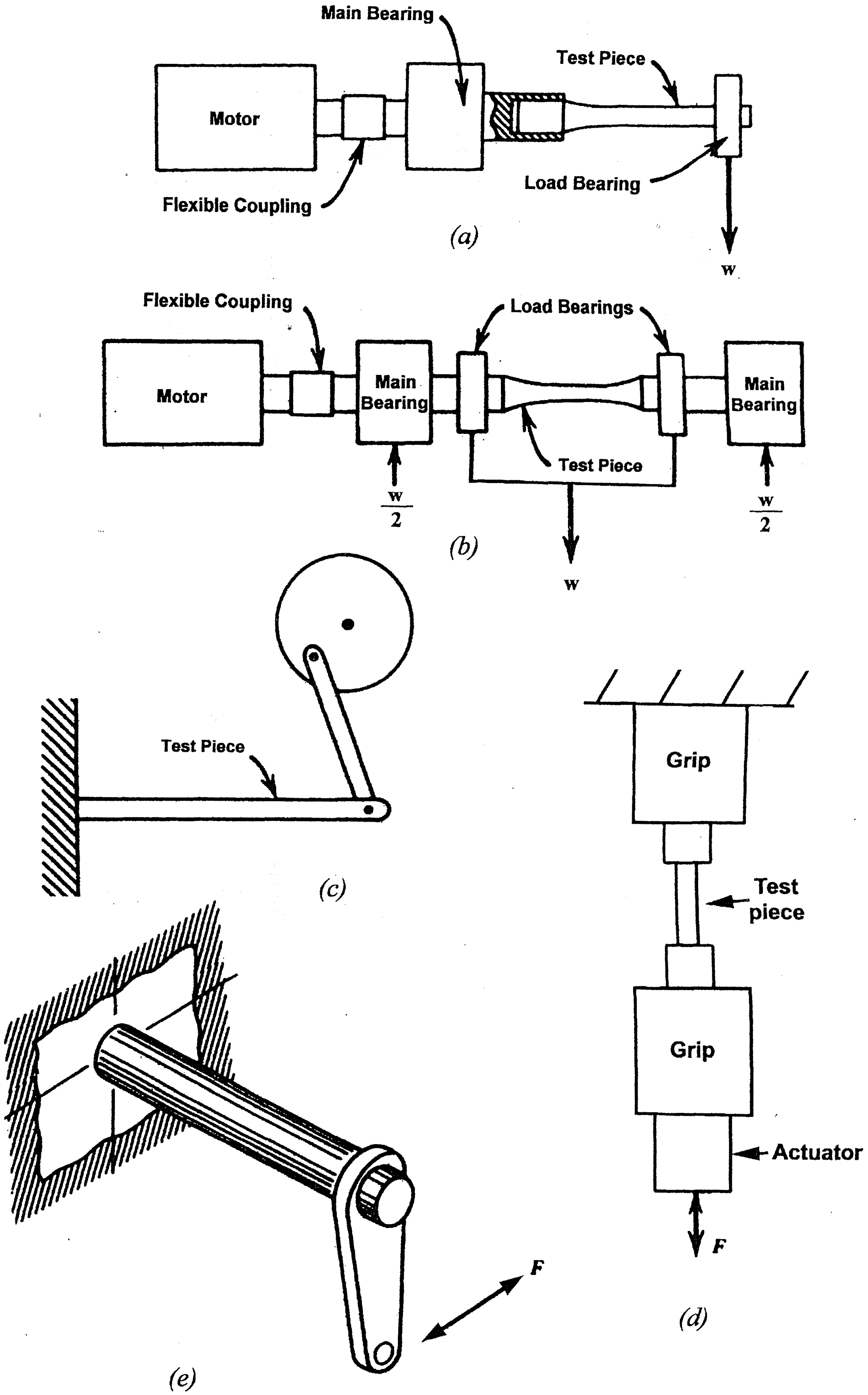


Figure 3. Fatigue testing machines, (a) Cantilever rotating bending, (b) Rotating pure bending, (c) Bending cantilever eccentric crank, (d) Axial loading, (e) Combined torsion and bending

A modern servohydraulic test system utilizing its own personal computer is shown in Fig. 4. The principle of operation includes generating an input signal of load, strain, or displacement using a function generator and applying this input through a hydraulic actuator; measuring the specimen response via a load cell, a clip gage, or a linear variable differential transducer (LVDT); and comparing this with the specific input. The difference drives the system. Control and test data outputs are usually through a personal computer and software. The test frequency can range from mHz to kHz. These test systems can perform constant or variable amplitude load, strain, displacement, or stress intensity factor controlled tests on small specimens or can be utilized with hydraulic jacks for components, subassemblies, or whole structures. Two or more control systems are used for multiaxial testing.

Fig. 4

6.2 Fatigue Test Specimens

Common test specimens for obtaining fatigue data are shown in Fig. 5. The specimens shown in Fig. 5a-f have been used to obtain total fatigue life, that includes crack nucleation life and crack growth life. These specimens usually have finely polished surfaces to minimize surface roughness effects.

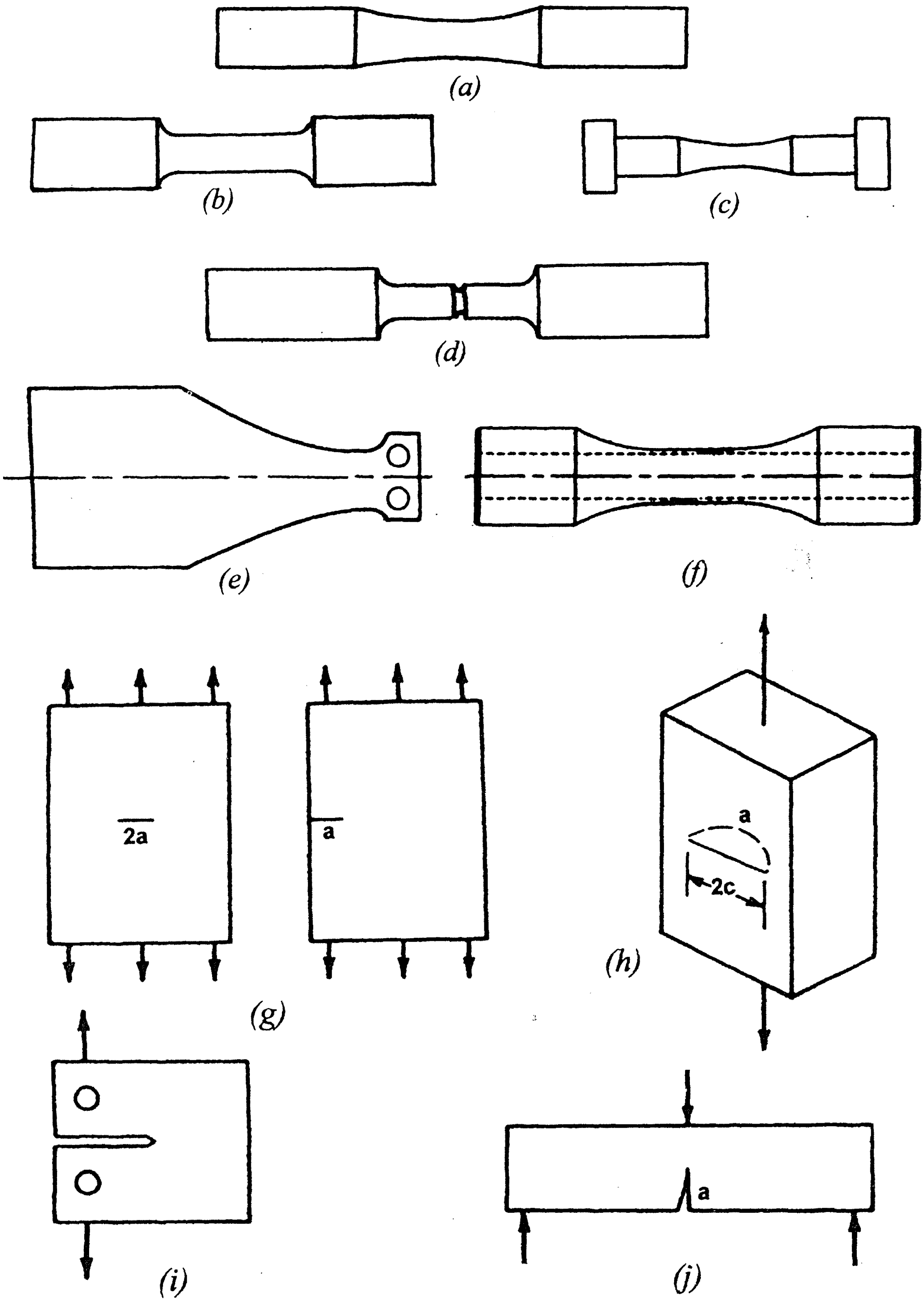


Figure 5 Fatigue test specimens. (a) Rotating bending. (b) Axial uniform. (c) Axial hourglass. (d) Axial or bending with circumferential groove. (e) Cantilever flat sheet/ plate. (f) Tubular combined axial/torsion with or without internal/external pressure, (g) Axial cracked sheet/plate. (h) part-through crack, (i) Compact tension. (j) Three- point bend.

No distinction between crack nucleation and growth is normally made with these specimens, but it can be done with special care and observation or measurement. The keyhole specimen in Fig. 5i was designed specifically to monitor both fatigue crack nucleation and fatigue crack growth lives. Bending, axial, torsion, and combined axial/torsion specimens are included in Fig. 5a-f. The specimen in Fig. 5f is a thin-walled tube designed for torsion and combined axial/torsion, with the possibility of adding internal and/or external pressure. This multiaxial loading can be performed in-phase or out-of-phase. The thin-walled tube allows for essentially uniform elastic or inelastic normal and shear stresses in the cross-sectional area, making it very advantageous for multiaxial loading. Bending and axial specimens with solid circular cross sections usually have diameters between about 3 and 10 mm. Stress concentration influence can be studied with most of these specimens by machining in notches, holes, or grooves, as shown with the specimen in Fig.5d. Careful alignment is needed for axial loaded specimens to minimize bending.

The specimens shown in Fig. 4.5g-j have been used to obtain fatigue crack growth data. In all cases a thin slit, notch, or groove with a very small root radius is machined into the specimen. A small pretest fatigue crack is then formed at this root radius by cycling at a low stress intensity factor range. After this sharp pretest fatigue crack has been formed, the real fatigue test can begin.