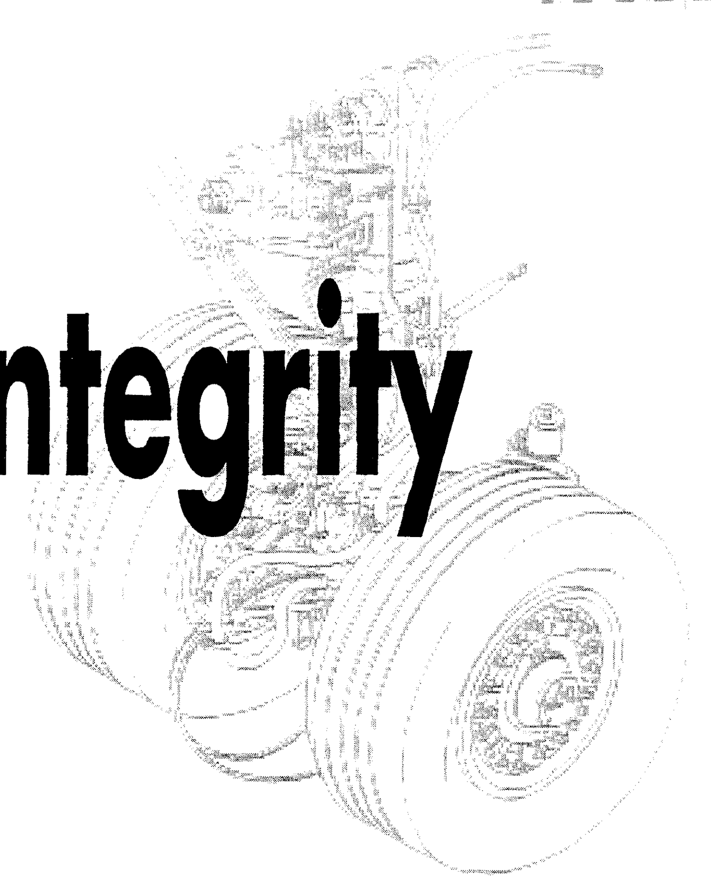
Landing gear structural integrity



Various analyses of landing gear design are presented, along with a discussion of critical loading conditions.

A landing gear features an oleo-pneumatic shock strut which, as the name suggests, is filled with oil and air. The strut has a dual function: to dissipate the kinetic energy of vertical velocity on landing, and to provide ease and stability for ground maneuvering. A schematic of an oleo-pneumatic shock strut is shown in Figure 1. When the airplane lands, the oil is forced from the lower chamber to the upper one through an orifice. Most struts have a metering pin extending through this orifice that strokes with the piston. By varying pin diameter, orifice area is varied, allowing optimization of the shock strut efficiency. Figure 2 shows typical landing gear components.

The landing gear also enables the aircraft to roll up to its takeoff position and to take off without using a launching catapult or trolley, as well as to carry its own means of braking, without resorting to external arresting equipment. Shock struts are designed to withstand a vertical sink rate of 10 ft/s for commercial airplanes, and as much as 25 ft/s for carrier-based aircraft. In service, the probability of a 10 ft/s touchdown is about one in 10,000,000 for a commercial airliner.

Typical landing gear sizes are shown in Figure 3. One company that produces landing gear is BFGoodrich Landing Gear Division. BFGoodrich produces landing gear for commercial jets; executive jets; Air Force bombers, fighters, and transports; Naval fighters and trainers; and helicopters. The gross weight of these aircraft ranges from 9700 to 878,000 lb. The firm is currently designing landing gear for a New Large Airplane that has a mass exceeding 1,000,000 lb.

The two basic types of landing gear are cantilever and articulated. The most widely used configuration is cantilever, which is also the most cost and weight efficient. With this type, the shock strut supports drag and side loads. Illustrations of single-axle and double-axle cantilever gear are shown in Figure 4.

Articulated gear are used for cases in which the ground clearance is low or stowage room is limited. They offer a maintenance advantage, since the shock strut can be removed in the field without major effort. European companies often prefer articulated gear to obtain a smoother taxi ride over uneven runways. The shock strut is pin ended and does not support drag and side loads.

Semi-articulated gear configuration is similar to fully articulated, except that the cylinder also acts as a structural member, and carries drag and side loads. This type of gear is not widely used. Fully articulated and semi-articulated gear are shown in Figure 5.

Flotation analysis determines the capability of an aircraft to operate on a specific airfield. Flotation capability is primarily a function of total shock strut load, single-wheel load, and tire pressure. On this basis, the number of tires, tire size, and tire spacing are determined. Main gear are typically of a tandem, dual-tandem, or tri-dual-tandem configuration. Nose gear consist of a single or dual arrangement.

Some gear must undergo sequenced shape change, such as retraction or planing, to fit in the wheel well when retracted. A rotating or planing mechanism is then designed into the gear. Another method consists of shrinking the shock strut during retraction to clear the gear into the wheel well. Other special features include provisions for uplocking the gear in the wheel well, bogie positioners to adjust the attitude of the truck beam for stowage, and launching mechanisms for naval applications.

Although it might be assumed that the landing gear is subjected to its highest loads during landing, in reality, landing conditions are critical for only about 20% of the landing gear structure. Ground handling conditions, especially turning and taxiing, are critical for the remainder of the structure.

Every landing gear has its own set of loads, which are critical for various components of the gear. For a given gear, landing load conditions which may be critical include maximum sink-speed landing, level landing, tail landing, lateral drift landing, spin up, and spring back. Critical ground handling load conditions include taxiing, towing, turning, jacking, braking, pivoting, and steering. Other load conditions consist of extension and retraction actuator load, brake application during retraction, brake chatter, shimmy, rebound, catapult launching, uplock/

downlock, and tie-down loads.

Landing gear loads include limit loads, which are the highest loads that the gear may be subjected to during its service life. Ultimate loads are limit loads multiplied by a safety factor of 1.5. Fatigue loads consist of a spectrum of realistic loads to which the structure will be subjected during its service life. Sustained loads are those on the gear components from carrying the weight of the airplane, 1-*g*, in static condition, or those due to shrinking the shock strut.

Structural analyses of landing gear include static, fatigue, fracture mechanics, damage tolerance, sustained stress, finite element, and weight-strength optimization analyses.

Static analysis incorporates tests for the following:

- ultimate static strength — stresses due to ultimate loads are not allowed to exceed the ultimate allowables of the component material
- yield strength — stresses due to limit loads are not allowed to exceed the yield allowables of the component material (no permanent deformation is permitted under limit loads)
- static and dynamic gear stability — especially during high-speed takeoff roll
- component stability — column checks of compression-loaded components.

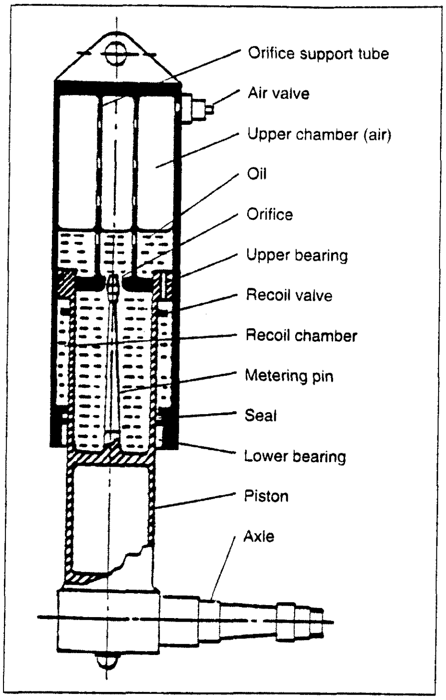


Figure 1. Oleo-pneumatic shock absorber.

In the detailed analysis, all the stresses — axial, shear, bending, and torsion — are calculated at a section, and a stress ratio is calculated for each by dividing the stress by the allowable strength of the component material. Then a utilization factor is determined by combining all the stress ratios. This factor must be maintained at less than 1.0 to have a positive margin of safety.

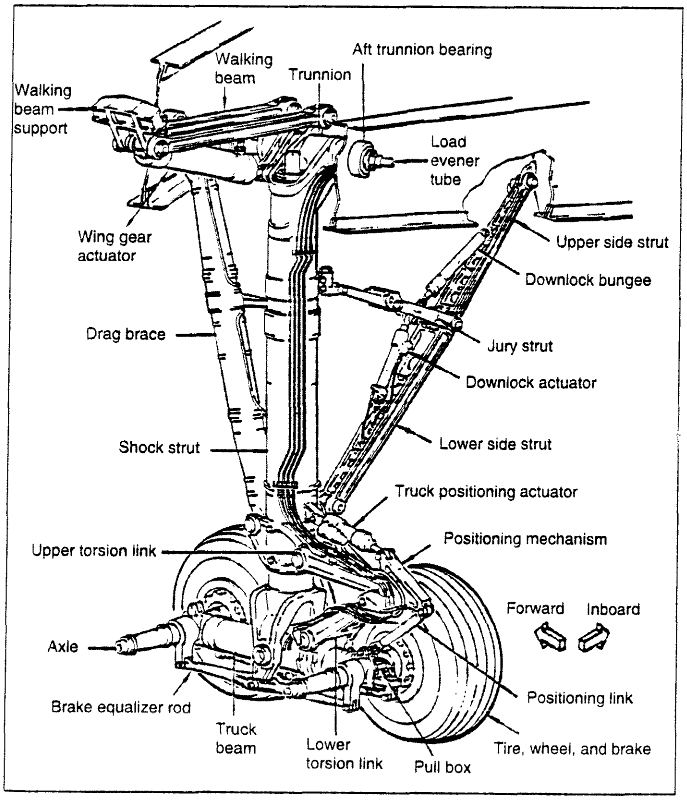


Figure 2. Component nomenclature.

Fatigue design criterion of aircraft structures are usually one of the following: infinite-life, safe-life, fail-safe, and damage-tolerant design. Because landing gear structures do not have redundancy in their means of support, the safe-life criterion is used. The calculation of the component's life may be based on stress-life or strain-life relations. The safe life includes margins for the scatter of fatigue results and for other unknown factors. The fatigue life consists of crack-initiation and crack-propagation stages.

Landing gear materials usually feature an initiation stage, consisting of 90-95% of the total life, and a propagation stage of 5-10% of the total life. Because of this safe-life criterion, landing gear must have defined inspection techniques, frequencies, and replacement times so that probability of failure due to fatigue cracking is extremely remote.

Many military programs require sufficient residual strength for a damaged structure to be able to withstand limit loads without catastrophic failure. In the detailed fatigue analysis, each load/unload cycle constitutes a fatigue pair. Stresses/strains at each end are determined. An equivalent, fully reversed stress level or strain range is calculated, and from the stress-life or strain-life relation, the life is determined. These relations are curves of test data for the material. By dividing the life read from

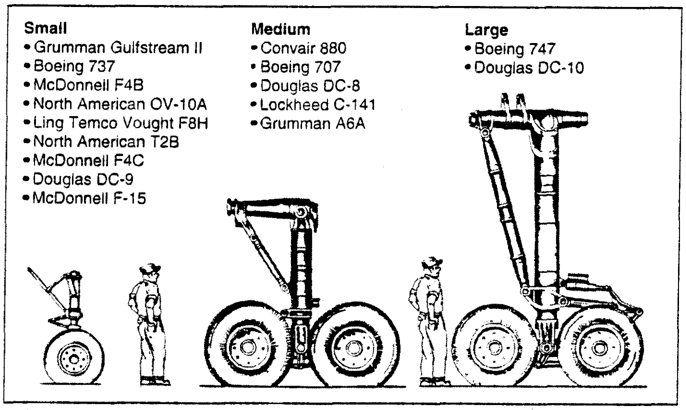


Figure 3. Typical landing gear sizes.

the curve by the required life for the subject load pair, the damage ratio for this loading condition is determined. Similarly, the damage ratio is determined for all loading conditions. The summation of all damage ratios is referred to as cumulative damage ratio — and it should not exceed 1.0.

Fracture mechanics and damage tolerance analyses are performed to predict the growth of an existing crack. Sustained stresses caused by 1-*g* static reaction are checked on components such as axles, truck beams, and trunnion pins, and must be below the allowable sustained stress threshold of the material.

The finite element method (FEM) of analysis has become widely used in areas of redundant load paths and complex geometric transitions. Weight/strength optimization is an especially important task of the structural analysis. The landing gear structure must be of sound structural integrity and at a minimum possible weight. The value of a pound of weight is worth about $200-$300 on a recurring basis.

Performance analyses must also be conducted on landing gear. Shimmy analysis is performed to determine whether the gear will shimmy during high-speed roll, and provide the necessary damping. (Shimmy is a self-induced buildup of a high-frequency oscillation of a landing gear structure.) Retraction analysis is performed to size the retract actuator to enable gear retraction into the wheel well in a required time span. Paper drop analysis is performed to size the orifice and the metering pin to meet landing energy dissipation requirements, and is later verified by actual drop testing. Rebound analysis is performed to calculate loads from the sudden extension of the shock strut during takeoff, and provide damping, if needed. Kinematics analysis checks the trajectories of components during retraction and extension to assure that there is no interference between two components or with adjacent structures along the entire path. Launch-bar dynamics and kinematics analysis is performed for naval nose gear.

Reliability and maintainability analyses are also performed. In addition, such issues as material compatibility, wear protection, and corrosion protection are considered.

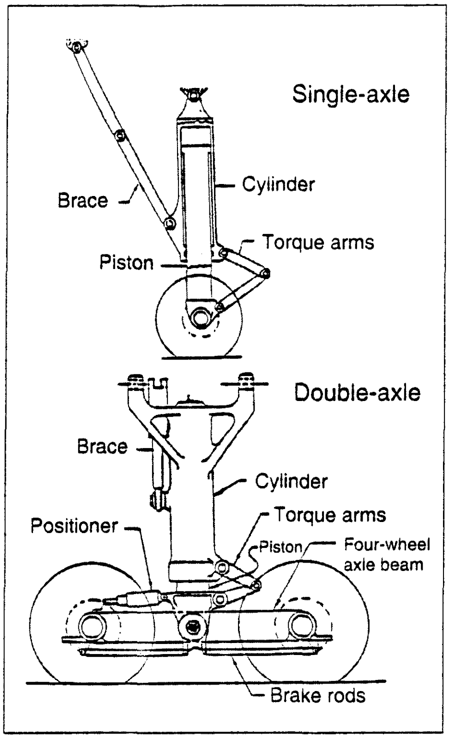


Figure 4. Cantilever gear.

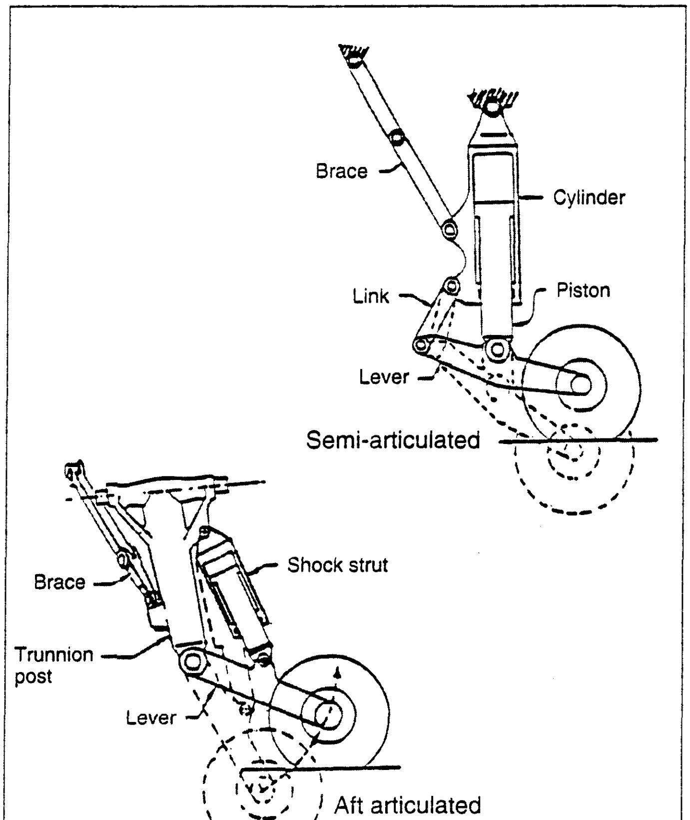


Figure 5. Articulated gear.

Another consideration in designing landing gear is material selection. Landing gear materials must be of high strength and stiffness, low cost and weight, and have good machinability, weldability, and forgeability. They also must be resistant to corrosion, stress corrosion, hydrogen embrittlement, and crack initiation and propagation. Because of the stringent requirements, landing gear components are fabricated from forgings. Castings have not been acceptable for landing gear structures due to poor fatigue-related characteristics such as grain flow and porosity.

The most widely used landing gear steel is 300M steel. It is heat treated to a 280,000-psi strength level. European equivalents to 300M are S155 and 35NCD16 steels. Recently developed Aermet 100 has the strength of 300M and substantially superior fracture toughness and stress corrosion thresholds. It is also five times the cost of 300M. When strength is not critical, but stiffness is, 180,000-psi 4340 steel is used. HP-9-4-30 and HY-TUF steel have a 220,000-psi strength, but a high fracture toughness, and have been widely used in naval gear.

Among nonferrous alloys, the most widely used are high-strength titanium alloys such as Ti-10V-2Fe-3Al and Ti-6Al-6V-1Sn, and high-strength aluminum alloys such as 7075-T73 and 7175-T74. European equivalents are IMI1551 titanium and AZ74 aluminum.

Manufacturing and processing considerations are also critical. A typical outer cylinder for a widebody jet is made from a forging. For example, the forge shop starts with an 8000-lb round billet, and using a series of dies and tremendously high loads, shapes the billet into a forging that resembles the envelope of the finished part. This process takes place at approximately 2000°F.

After thermal treatment, the forging is shipped to the gear manufacturer in a subcritical annealed condition, with a Rockwell "C" hardness around 25, and a 120,000-psi tensile strength. In this condition, the part goes through numerous rough machining operations:

- location of tooling points
- profiling
- rough boring of inside diameters
- rough turning of outside diameters
- rough drilling of lug holes
- rough milling of faces
- barbering, or metal finishing.

At this stage, the close tolerance features are not machined to the final blueprint requirements, anticipating some distortion during heat treatment. After rough machining, the part is heat treated to its final condition — Rockwell "C" hardness 53-55, and a tensile strength of 280,000-300,000 psi. Following heat treatment, all the features are machined to the blueprint requirements. Final turning, boring, and milling occur at this stage.

Further operations include:

- cutting of threads
- drilling, boring, and reaming of lug holes
- grinding, as necessary

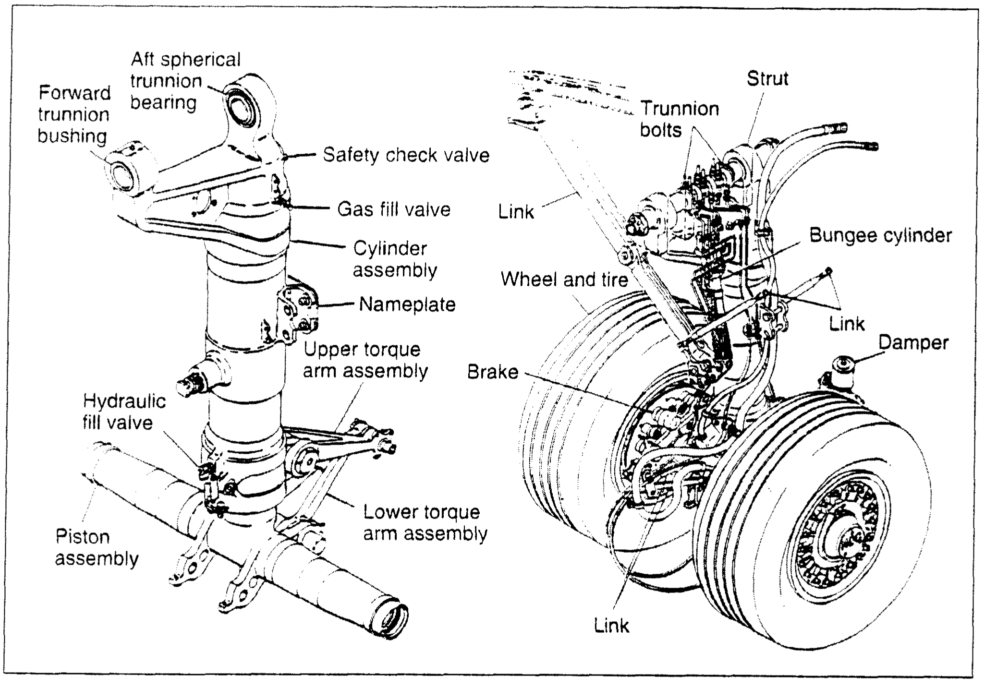


Figure 6. Bare and dressed gear.

- honing of inside diameters
- final barbering and blending corner radii.

At this stage, the part is finish machined, and weighs about 1200 lb, or 6800 lb lighter than the forging. These 6800 lb went into chips. Following machining, the part is:

- dimensionally inspected
- nital etch inspected to assure no thermal damage during machining
- stress relieved
- magnetic particle inspected to assure no cracks, indications, discontinuities
- shot peened to induce residual compressive stresses on the surface of the part, and enhance fatigue resistance
- wear surfaces are chrome plated
- cadmium plated for corrosion resistance
- embrittlement relief baked to prevent hydrogen embrittlement
- chrome is ground, if required
- final magnetic particle inspection is conducted
- bushings are installed
- primed
- painted
- strut is assembled
- leakage of the strut is tested per blueprint requirements.

To validate the design, and obtain gear qualification and certification, landing gear structures may be subjected to the following tests:

- Drop testing to verify the capability of the gear to dissipate the kinetic landing energy
- Ultimate static testing verifies the ability of the structure to support ultimate loads without failure for three seconds
- Limit load testing to verify lack of permanent deformation of the structure
- Fatigue testing to demonstrate the ability to withstand spectrum loading
- Photostress testing may be done on a plastic model to locate high stress areas before the actual parts are being produced. The test occurs during design.
- Strain gauge surveys are performed to correlate calculated stresses with the actuals
- Element tests are performed on an isolated component to eliminate larger setups
- Sudden extension testing
- Retraction/extension testing
- Environmental testing.

Engineers foresee some trends in landing gear design. One of these concerns the transfer of system integration responsibilities from airplane manufacturers to landing gear suppliers. Landing gear systems, including the gear, wheel, brake, tire, hydraulic plumbing, electric harnesses, and microswitches, are expected to become the responsibility of landing gear suppliers. Bare and dressed gear are illustrated in Figure 6.

Smart structures, carrying embedded microgauges, will become increasingly important, as more emphasis is given to health monitoring of aging airplanes. High-strength composites will find applications in landing gear structures. Oil-level monitoring devices will be produced; and steels, titaniums, and aluminums of higher strength and toughness will be developed.

Information for this article was provided by **Jack Pink**, BFGoodrich Landing Gear Division.

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