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Superseding AIR4566

Crashworthy Landing Gear Design

RATIONALE

AIR4566A has been reaffirmed to comply with the SAE five-year review policy.

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1. SCOPE

The intent of this SAE Aerospace Information Report (AIR) is to document the design requirements and approaches for the crashworthy design of aircraft landing gear.

This document covers the field of commercial and military airplanes and helicopters. This summary of crashworthy landing gear design requirements and approaches may be used as a reference for future aircraft.

2. REFERENCES

The following publications for a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of the other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1 FAA Publications

Available from Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, www.faa.gov.

14 CFR 23.561, 23.721, 25.561, 25.721, 27.561, 29.561

2.2 EASA Publications

Available from European Aviation Safety Agency, Postfach 10 12 53, D-50452 Koeln, Germany, Tel: +49-221-8999-000, www.easa.eu.int

CS 23.561, 23.721, 25.561, 25.721, 27.561, 29.561

2.3 U.S. Government Publications

Available from the Document Automation and Production Service (DAPS), Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, <http://assist.daps.dla.mil/quicksearch/>

AFSC DH 2-1 – Design Note 2A2, paragraph 4

SD-24L, Volume 1, paragraph 3.8.3

MIL-STD-1290 (AV)

JSSG-2009, Joint Services Specification Guide, Air Vehicle Subsystems, 30 October 1998, Appendix A, A.3.4.1.3.1.3

2.4 Other Publications

Light Fixed-and Rotary-Wing Aircraft Crash Resistance, MIL-STD-1290A (AV) (March 1986), Dept. of Defense, Washington, DC

Army Helicopter Crashworthiness - Carper, C. H., Burrows, L. T. and Smith, K. F., Applied Technology Laboratory, US Army Research and Technology Laboratories, Fort Eustis, Virginia 23604. Presented in May 1983

Helicopter Crashworthiness - Fox, R. G., Bell Helicopter Textron Inc. Presented at Flight Safety Foundation Corporate Aviation Safety Seminar (April 1989)

Tilt Rotor Crashworthiness - Cronkhite, J. D., Bell Helicopter Textron Inc. and Tanner, A. E., Boeing Vertol Co. Presented at 41st Annual Forum of the American Helicopter Society, Fort Worth (May 1985)

Structural Design of a Crashworthy Landing Gear for the AH-64 Attack Helicopter - McDermott, J. M., Hughes Helicopters Inc. Presented at 38th Annual Forum of the American Helicopter Society (May 1982)

Crashworthiness Versus Cost Based on a Study of Severe Army Helicopter Accidents During 1970 and 1971, Haley, J. L. and Hicks, J. E., U.S. Army. Published in April 1980 issue of Journal of American Helicopter Society

Advanced Technology Helicopter Landing Gear Preliminary Design Investigation - Sen, J. K. Votaw, M. W., Weber, D. C., Hughes Helicopters, Inc. (July 1985), AD-A158 816; USAAVSCOM TR-84-D-20

Helicopter Landing Gear Design and Test Criteria Investigation - David Crist, L. H. Symes, Bell Helicopter Textron Inc. (Aug. '81) USAAVRADCOM-TR-81-D-15

KRASH Analysis Correlation with Full Scale YAH-63 Helicopter Crash Test - Berry, V. L. & Cronkhite, J. D., Bell Helicopter Textron Inc. Presented at National Specialists Meeting of the American Helicopter Society, Atlanta, Georgia (April 1986)

3. REQUIREMENTS

The regulatory requirements for crashworthy design features of landing gear are contained in the following documents. Certification outside the USA may require conformance with other documents for both commercial and military applications.

a. Commercial

Fixed Wing USA: 14 CFR 23.561, 23.721, 25.561, 25.721

Fixed Wing European: CS 23.561, 23.721, 25.561, 25.721

Rotary Wing USA: 14 CFR 27.561, 29.561

Rotary Wing European: CS 27.561, 29.561

b. Military

Fixed Wing USA:USAF- AFSC DH 2-1 - Design Note 2A2, paragraph 4

USN - SD-24L, paragraph 3.8.3

Rotary Wing USA:MIL-STD-1290 (AV)

3.1 14 CFR 25.721 (a)

a. The main landing gear system must be designed so that if it fails due to overloads during takeoff and landing (assuming the overloads to act in the upward and aft directions), the failure mode is not likely to cause--

1. For airplanes that have a passenger seating configuration, excluding pilots seats, of nine seats or less, the spillage of enough fuel from any fuel system in the fuselage to constitute a fire hazard; and
2. For airplanes that have a passenger seating configuration, excluding pilots seats, of 10 seats or more, the spillage of enough fuel from any part of the fuel system to constitute a fire hazard.

3.2 CS 25.721 (a)

a. The landing gear system must be designed so that when it fails due to overloads during takeoff and landing, the failure mode is not likely to cause spillage of enough fuel to constitute a fire hazard. The overloads must be assumed to act in the upward and aft directions in combination with side loads acting inboard and outboard. In the absence of a more rational analysis, the side loads must be assumed to be up to 20% of the vertical load or 20% of the drag load, whichever is greater.

4. REASONS FOR CRASHWORTHY LANDING GEAR DESIGN

The reason for crashworthy landing gear design is to contribute to the overall aircraft design goals in the event of a crash. These goals are to prevent occupant fatalities and injuries, damage to the aircraft, and damage or injury to adjacent equipment or persons. On fixed wing commercial and navy aircraft it is a requirement that the landing gear enables the failure modes to be such as to prevent damage, which can cause spillage of fuel sufficient to cause a fire hazard. In cases where centerline gears are used, consideration is given to the amount of damage that can be caused should the centerline gear fail so as to penetrate the fuselage, causing injury to persons, damage to structure and in the case of body fuel tanks spillage of fuel.

For helicopters the landing gear is part of a crash energy attenuation system to limit loads to the occupants and to minimize aircraft damage. The most stringent requirements are for helicopters designed to MIL-STD-1290 (AV) which requires maintenance of the occupied area and transmittal of noninjurious accelerative loadings to occupants for up to a combined high angle impact of a vertical velocity of 42 ft/s and a longitudinal velocity of 27 ft/s onto a rigid surface at specified roll and/or pitch angle attitudes. The other components of the energy absorption system are a crushable subfloor structure, a stroking seat, which is primarily a load limiter, and other structural yielding and strain during the crash.

The most significant difference in fixed wing and rotary wing crashes is in the forward velocity at impact. The primary concern for fixed wing is to have the landing gear break away from the aircraft without rupturing the fuel tanks. For a rotary wing at near zero forward speed, the "crash" is excessive vertical velocity and the landing gear should function in its crash mode to absorb energy and limit the "g" level of the occupants.

5. APPROACHES TO CRASHWORTHY LANDING GEAR

The design approaches applied to crashworthy landing gear design include:

- a. Control of energy absorbed and dissipated by the landing gear so as to limit the loads applied to the airframe and its occupants
- b. Inclusion of structural fuses and fuse pins to control the mode of failure of the landing gear when excessive loads are applied

For commercial and some military fixed wing aircraft, these requirements apply during a crash or emergency situation involving the landing gear during landing, takeoff, taxiing, or ground maneuvering.

Also, for military helicopters, to reduce damage, MIL-STD-1290 (AV) states that as a minimum the landing gear shall be capable of decelerating the aircraft with 1 DGW rotor wing lift and from a vertical impact velocity of 20 ft/s onto a level, rigid surface without allowing the fuselage to contact the ground. Plastic deformation and damage of the landing gear is acceptable; however, the remainder of the aircraft structure should be flightworthy after the impact. The aircraft shall be capable of meeting these criteria in accidents including a simultaneous fuselage angular alignment of ± 10 degree roll and $+15$ to -5 degree pitch. The landing gear shall be designed so that gear failure does not increase danger to occupants, either by gear penetration of the occupied areas or by rupturing flammable fluid containers or by damaging onboard stores such as missiles, rockets, and ammunition. It is desirable that the landing gear continue to absorb energy even after fuselage contact has been made, to maximize the protection afforded by the gear.

5.1 Fuse Pin Design and Analysis

The analysis of fuse pins is very complex and must be verified through test as discussed below. Typically, as shown in the following sketches (Figure 6, 8, 10 and 13), fuse pins are notched at the inside diameter at the shear face of the pin to assure a clean failure at the desired location. While the maximum shear stress will drive the failure, the state of stress is complex and is oftentimes analyzed using finite element analysis (FEA) to best resolve the state of stress.

Even using FEA techniques this is not a simple solution due to the plasticity of high strength steels. The analyses may need to be iterative by varying the inside diameter of the pin and the configuration of the notch until the FEA analysis will no longer converge. This approach will assure a relatively constant state of stress through the wall at the notch around the circumference of the pin.

In order to minimize the weight impact and to protect the back-up structure, the tolerance on the static shear strength due to material and manufacturing variability of each heat treat lot of fuse pins should be held to a narrow range. It is suggested that this range be between 5% and 10%. The backup structure must then be strength checked to some load factor above the maximum fuse pin strength to ensure that the fuse pin is the weak point and not the backup structure. The value of the backup load factor used depends on the accuracy to predict the actual load of the fuse pins and the accuracy of the structural analysis. On some older models, this load factor has been as high as 25% but with current advanced modeling and analytical techniques, 10% is a more reasonable number.

In addition to the static stress, the fatigue strength of the pin is normally considered. The notch created to assure static failure could reduce the fuse pin fatigue life depending on the geometric configuration of the notch, resulting in a reduced life limit on the pin. Care should be taken to minimize the fatigue notch effects.

While the most care and thought may be put into the analysis, the analysis does not account for variation in tensile strength of the pins from various heat treat lots. Therefore, each heat treat lot is normally tested after heat treat and the final inside diameter of the pin determined by test. For example, it may be required to test three (3) pins after heat treat to determine the required inside diameter for final machining. After final machining, a number of pins from each heat treat batch should be tested in the final configuration to ensure the proper inside diameter. The number of pins tested should be determined based upon the backup load factor and the designed variation of the heat treat lot. The regulation is not met if the backup structure fails prior to the fuse pin.

Under abnormal conditions, the landing gear may be subjected to the following:

- a. Excessive drag load from the wheels hitting a ditch or similar obstruction
- b. Excessive vertical load from crash landing onto a hard runway
- c. Combinations of excessive drag and vertical loads from rolling onto a soft surface
- d. Excessive side load from off runway excursions or during landing at high roll or yawed attitudes

In such cases of landing gear failure, the fuel tank is to remain intact to minimize the danger of fire.

The failure sequence is established by first examining all combinations of vertical load and aft acting drag load to identify the location of initial fuse failure. In addition, combinations of side/vertical and side/drag loads are considered. The probable motion of the landing gear and landing gear beam, when applicable, is then estimated and secondary failure locations identified. This procedure is continued until a complete sequence of failure is determined, demonstrating that the landing gear and the gear support structure can fail due to local overloading without rupturing the fuel tank.

6. GENERAL DESCRIPTIONS

The following is a description of applications of crashworthy landing gear designs. Some specific aircraft applications are shown to illustrate the design solutions employed.

6.1 Boeing 757 Main Landing Gear

The 757 Main Landing Gear is shown in Figure 1. The emergency breakaway structural fuses are shown in Figures 2 and 3.

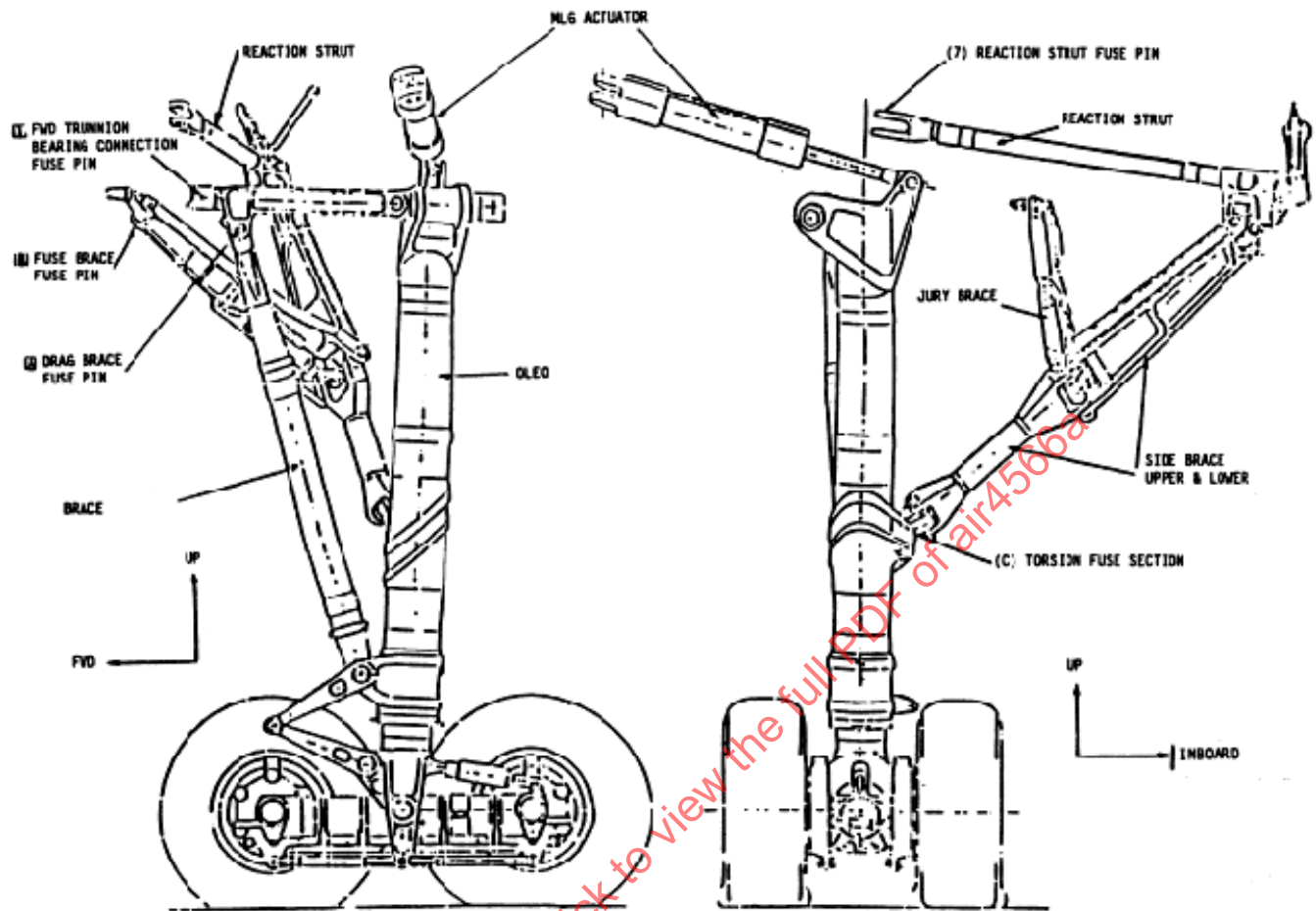
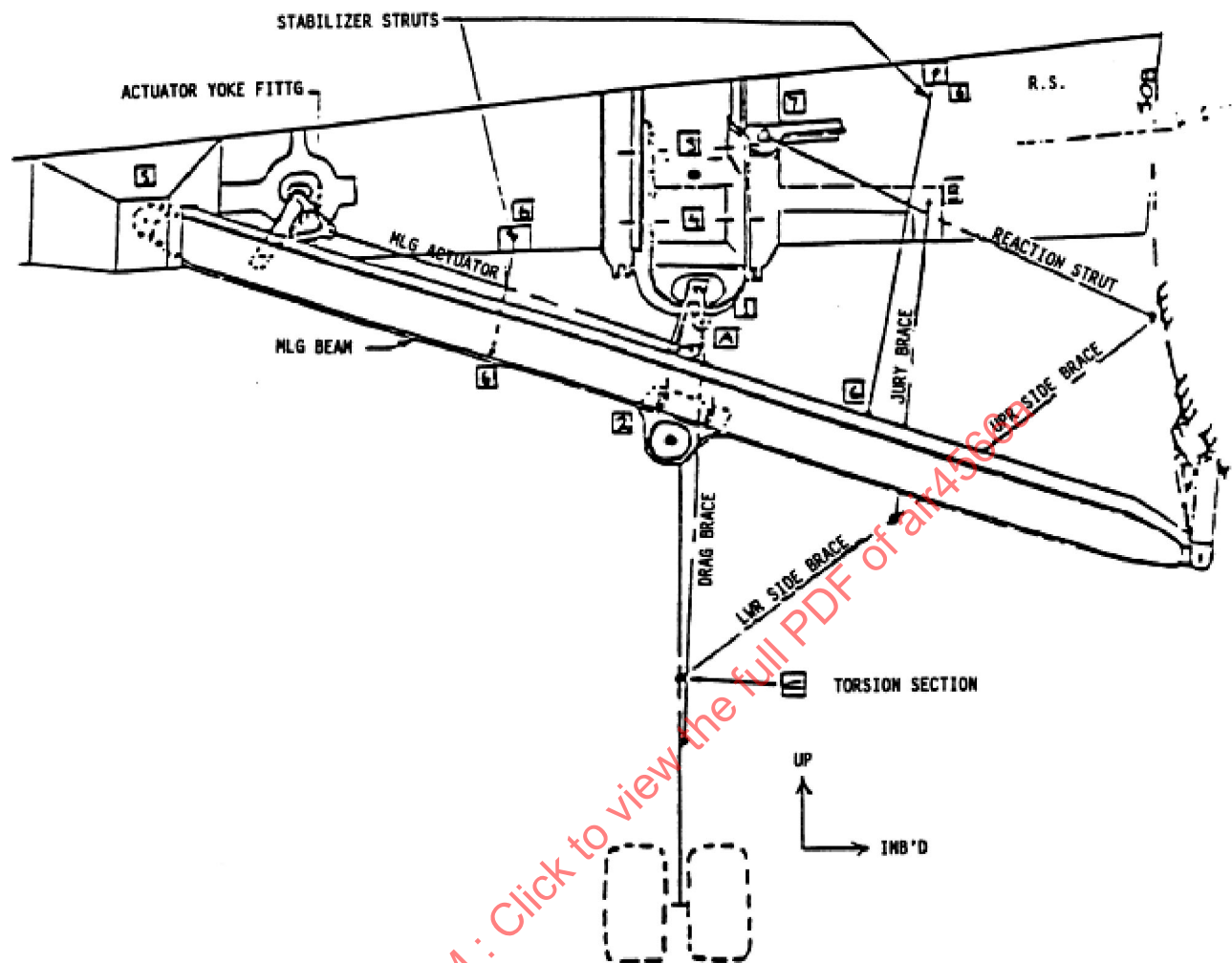


FIGURE 1 - BOEING 757 MAIN LANDING GEAR

WING FUSE PINS

- 1 Forward Trunnion
- 2 Aft Trunnion
- 3 Forward Trunnion Hanger-upper
- 4 Forward Trunnion Hanger-lower
- 5 MLG Beam-outboard Support
- 6 Stabilizer Strut
- 7 Reaction Strut

GEAR FUSES

- A Drag Brace Pin
- B Jury Brace Pin
- C Torsion Section

FIGURE 2 – BOEING 757 MAIN LANDING GEAR STRUCTURAL FUSES

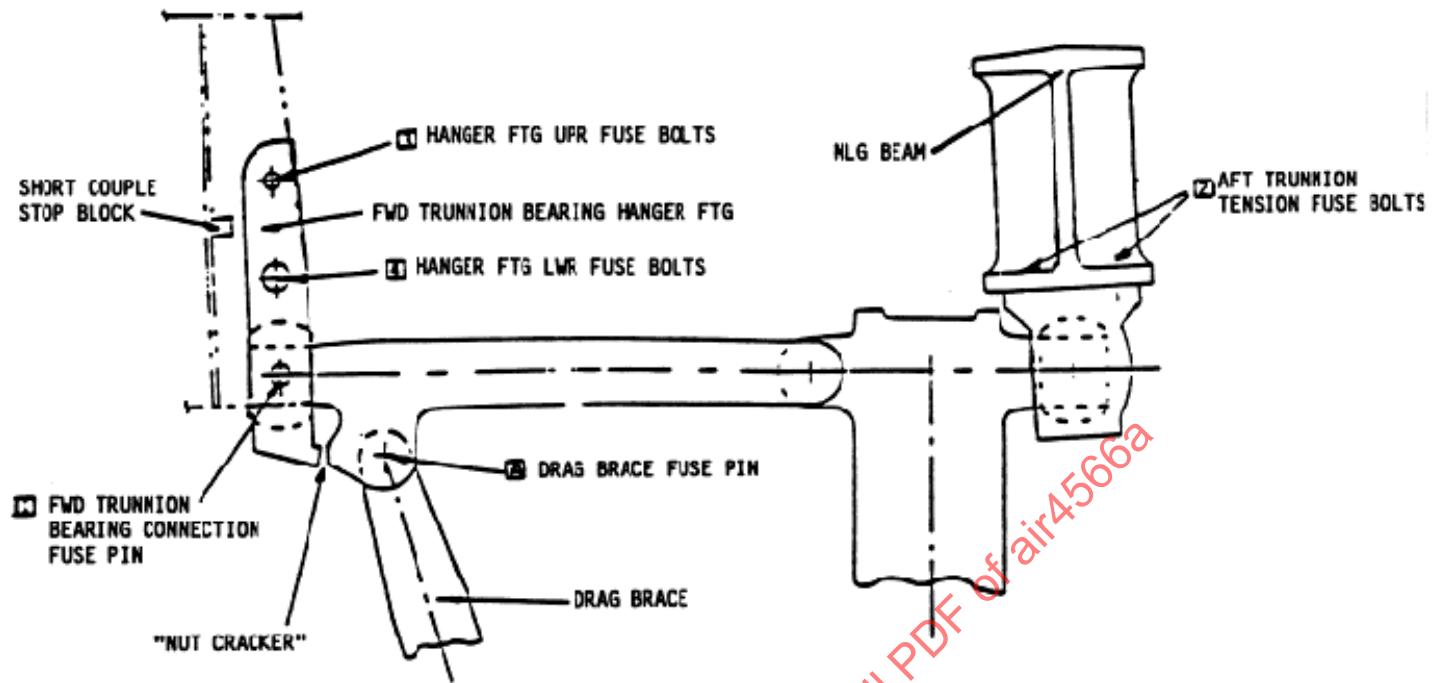


FIGURE 3 – BOEING 757 MAIN LANDING GEAR STATIC POSITION

6.2 Boeing 737 Classic Main Landing Gear

The 737 main gear trunnion forward bearing bolt is designed to fail if the landing gear receives a severe impact, thus minimizing damage to the structure. A special shear bolt is used for the upper attachment of the upper drag brace to minimize damage to the structure should the landing gear receive a severe drag impact (see Figure 4).

6.3 Boeing 767 Main Landing Gear

6.3.1 Fuse Pins

- a. The main gear and gear support beam are attached to the airplane wing structure at critical points by fuse pins. These fuse pins shear under extreme loads and provide a release of the gear to prevent major damage to wing structure and prevent rupturing of the fuel tanks.
- b. Five fuse pins attach the main gear to the rear wing spar. Four of these attach the shock strut trunnion into the forward trunnion bearing housing. The other attaches the upper end of the drag strut to a fitting on the rear spar. Two more fuse pins attach the outboard end of the main landing gear support beam to wing structure (see Figure 5).

6.4 Boeing 747 Wing Landing Gear

The wing landing gear and gear support beam are attached to the airplane wing structure at critical points by fuse pins. These fuse pins shear under extreme loads and provide a release of the gear to prevent major damage to wing structure and prevent rupturing of the fuel tanks.

6.4.1 Fuse Pins

Landing gear structural fuse pins are located at the following locations (see Figures 6 and 7).

- a. Landing gear support
- b. Beam to rear spar
- c. Rear spar, landing gear
- d. Trunnion bearing retaining nut
- e. Rear spar, landing gear forward
- f. Trunnion support pin
- g. Wing landing gear trunnion
- h. Rear bearing outer sleeve
- i. Wing gear outboard door
- j. Forward hinge support rod
- k. Wing landing gear walking beam

The wing landing gear is designed to break free of the airplane under extreme loads. The rear spar, to which the gear attaches, serves as the closing bulkhead for the integral wing fuel tanks. To maintain integrity of the fuel tanks under excessive shock loads, structural fuses are incorporated between the rear spar and gear components. These fuses provide points between gear and spar sufficiently strong to handle normal operating loads. However, these points will give way under excessive loads before damage to the spar can occur, which would cause fuel tank rupture.

Under severe impact loads, it is not desirable for the body gear or nose gear to break free of the airplane. Therefore, no structural fuses are incorporated in attaching these gears to the structure.

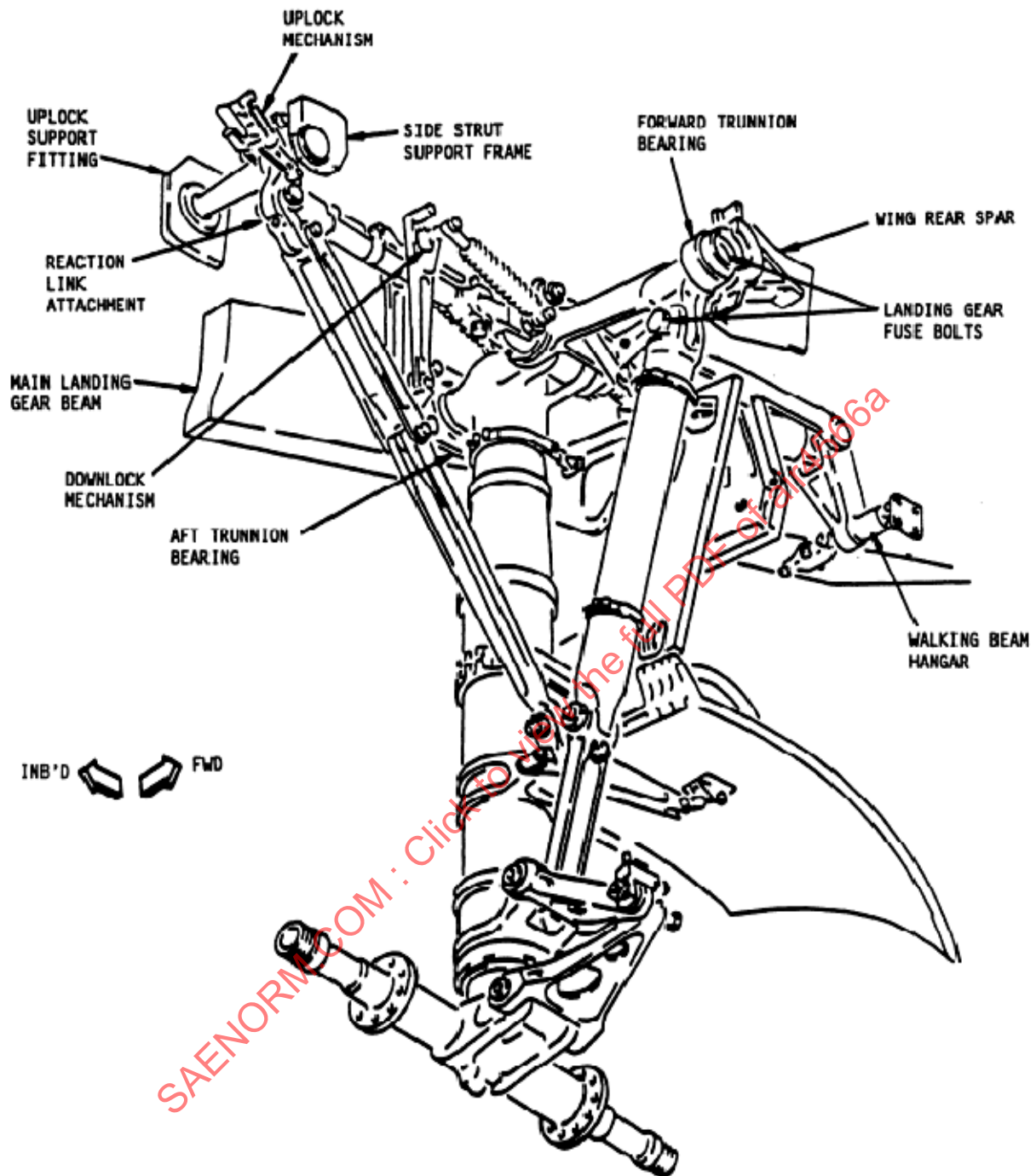


FIGURE 4 - BOEING 737 CLASSIC MAIN LANDING GEAR

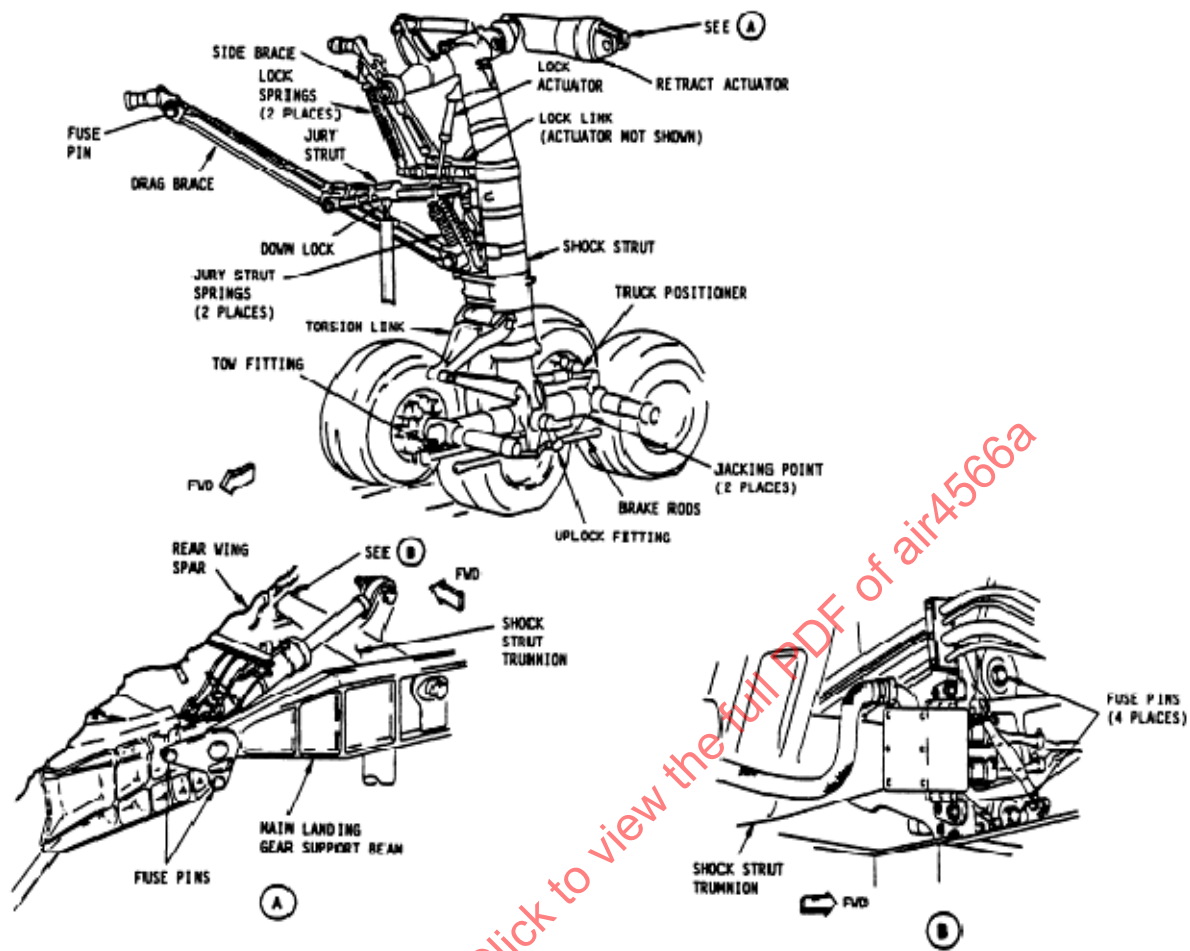


FIGURE 5- BOEING 767 MAIN LANDING GEAR

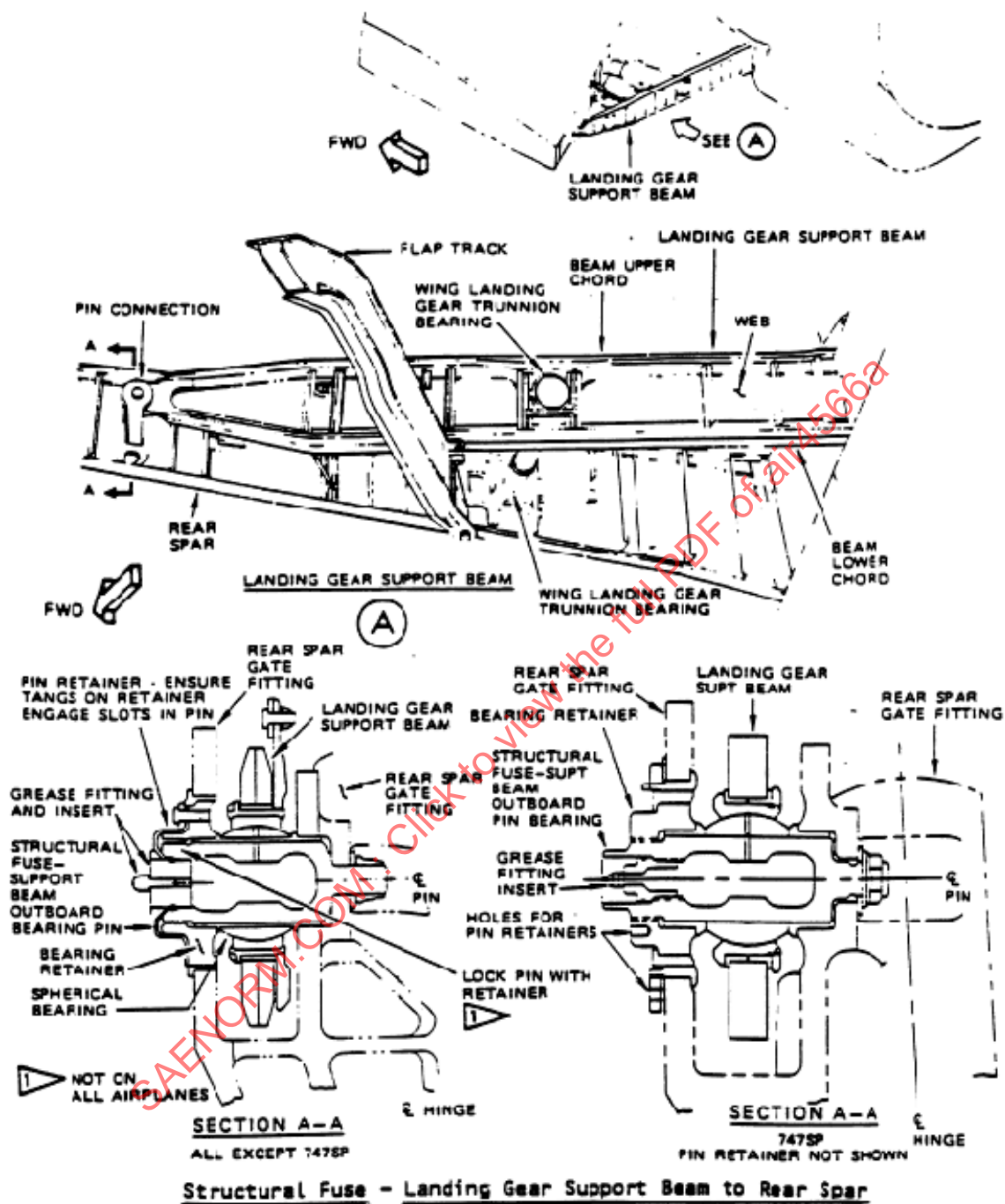


FIGURE 6 - BOEING 747 WING LANDING GEAR

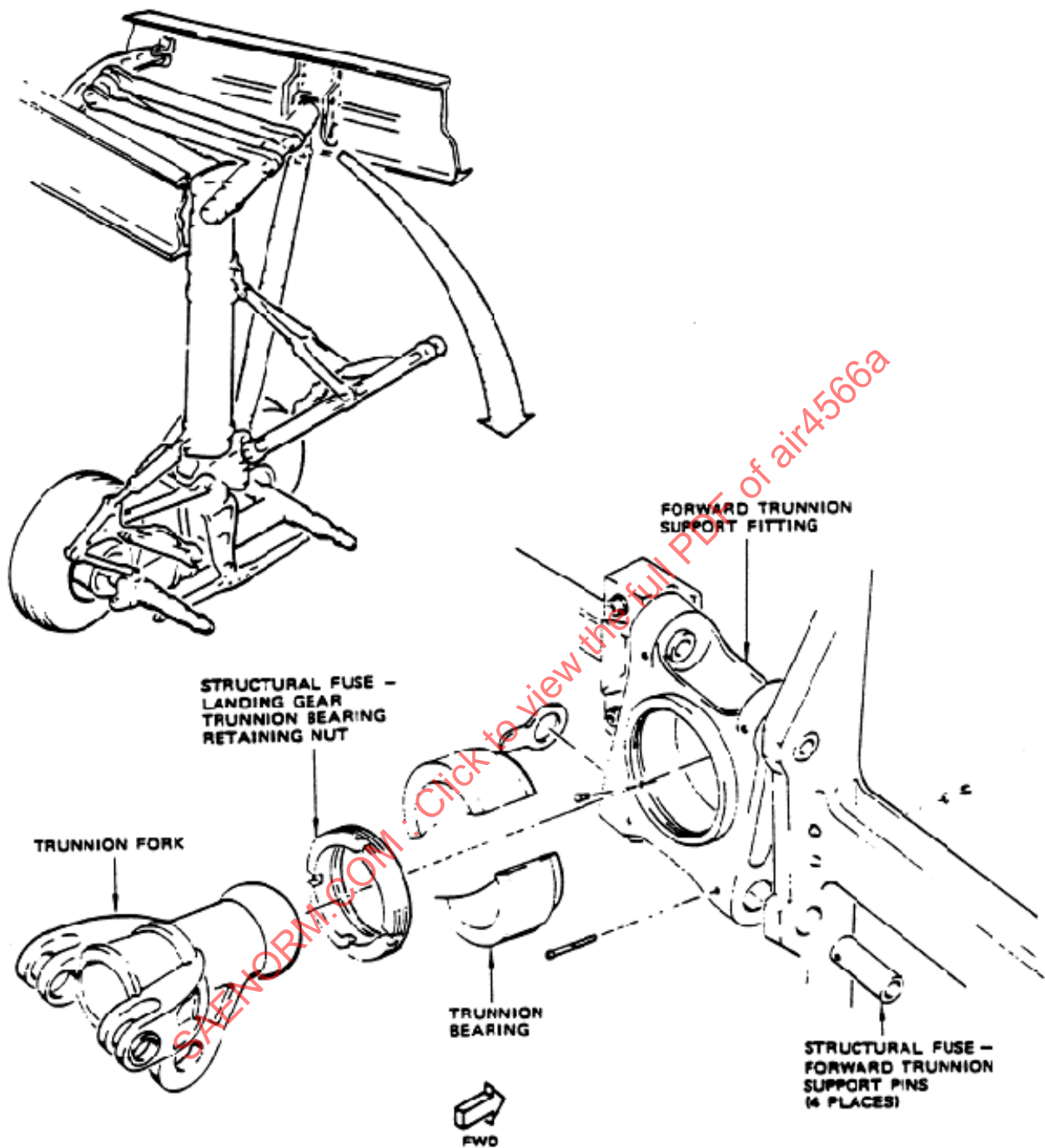


FIGURE 7 - STRUCTURAL FUSE - 747 WING LANDING GEAR

6.5 Airbus A330/340 Wing Landing Gear

Figure 8 shows the main landing gear configuration of the Airbus A330/340 wing landing gear.

In order to assess the effect on the aircraft primary structure of landing gear collapse due to overload, the landing gear vendor determines the rupture strength of the main load-bearing members of the landing gear under specific combinations of vertical, drag, and side load. The aircraft designer specifies the loading conditions to be considered and the critical regions of the landing gear units for which strength values are required.

The applicable airworthiness requirements, with which demonstrated compliance is necessary, are given in CS 25.721 (a) and Interpretative Material requiring the effects of sideways-applied overload to be considered.

6.5.1 Loading Conditions

The required load cases are:

- a. High drag with or without vertical load
- b. High vertical load with or without drag
- c. Side load - inward or outward - with or without vertical load

In each case the load in the "secondary" direction should be taken as:

- a. Zero
- b. Design limit load

The load in the "primary" direction, which will cause rupture of the specified item, should then be calculated. In instances where the relationship between "primary" and "secondary" loading is nonlinear, it might be necessary to consider values of "secondary" load intermediate between (a) and (b) in order to establish the most critical combined loading.

It is essential that, in the event of sideways-applied overload, the side stay does not fail at, or near to, its upper end when in compression (inboard-acting side load), to obviate any danger of its puncturing the fuel tank (spar box) when the gear folds inwards. It is equally essential that no failure of the side stay/rear-spar attachment fitting or its bolting to the rear spar should occur because of the obvious danger of fuel leakage which this would cause. Therefore, it is required that the hinge pin at the attachment of the side stay to the lower Cardan pin (side stay/gear main fitting swivel joint) should act as a structural fuse.

6.6 Lockheed L-1011 Main Landing Gear

Figure 9 indicates the expected failure sequence for an L-1011 main landing gear.

6.7 Bombardier Dash-8 Main Landing Gear Structural Fuse Design

The fuse pin is located in the yoke to shock strut cylinder joint (see Figure 10). It is designed to fail when subjected to an overload in the upward and aft direction, which is the spin up case for this landing gear.

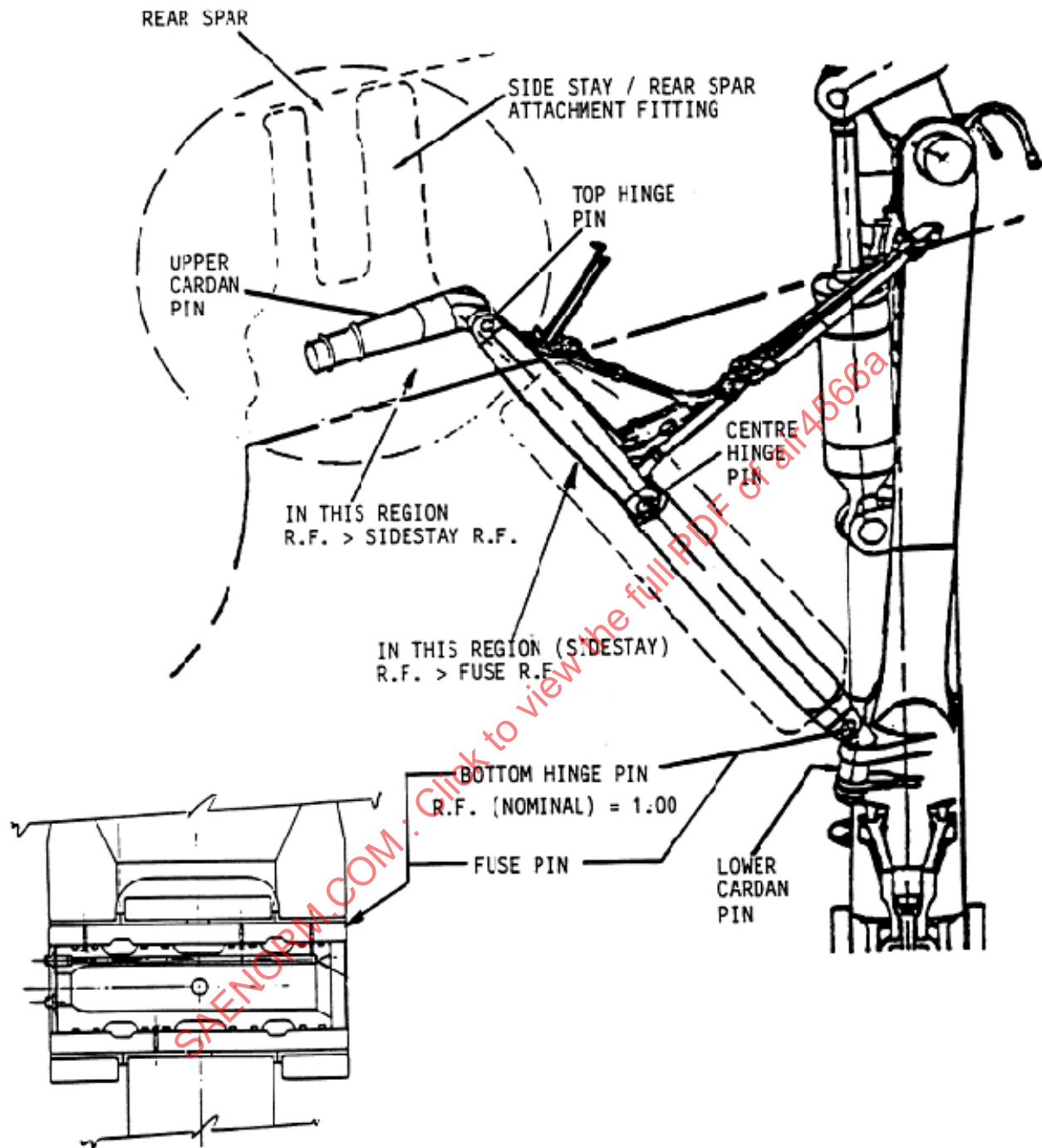


FIGURE 8 – AIRBUS A330/340 WING LANDING GEAR

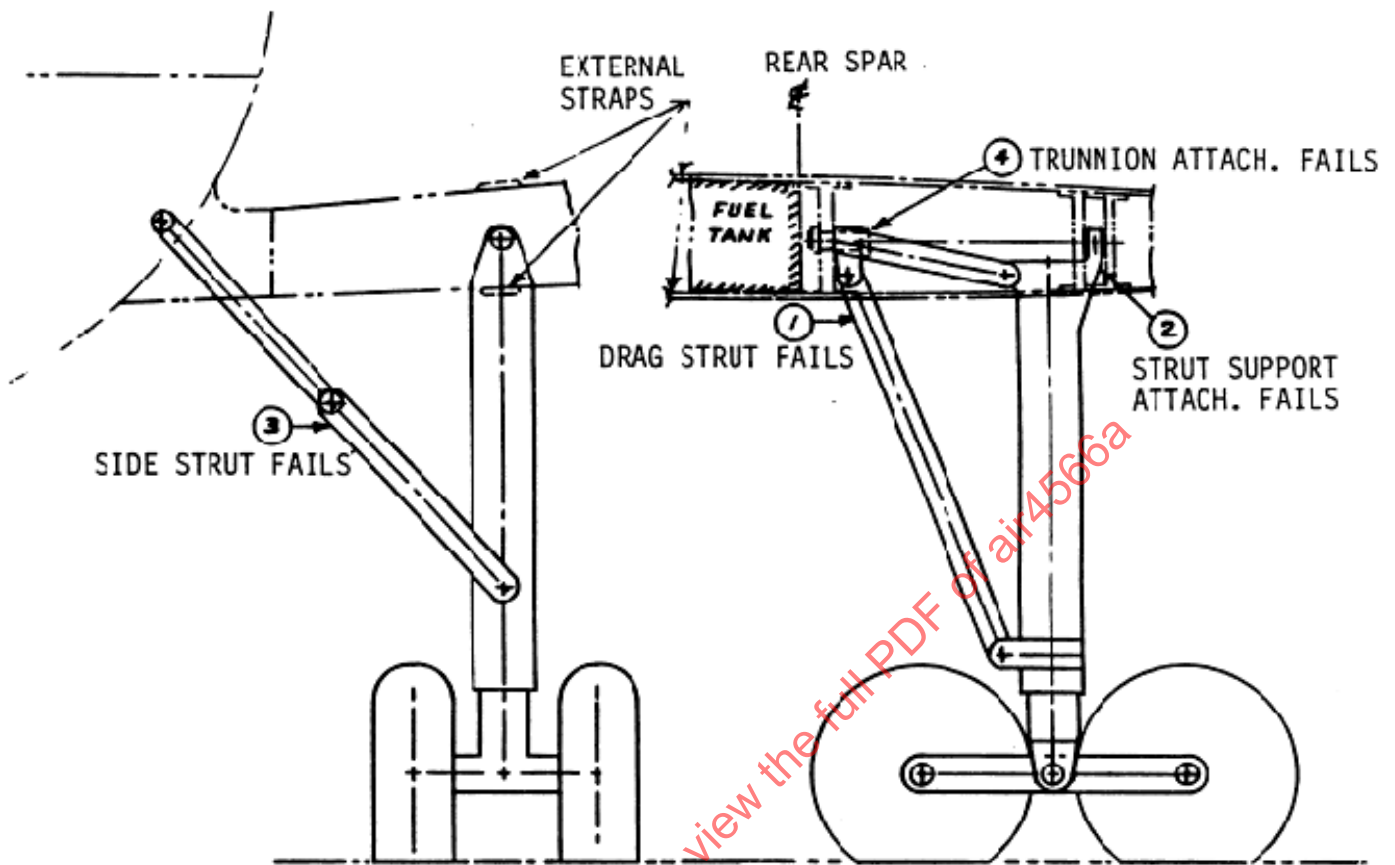


FIGURE 9 – LOCKHEED L-1011 BREAKAWAY MAIN LANDING GEAR FAILURE SEQUENCE

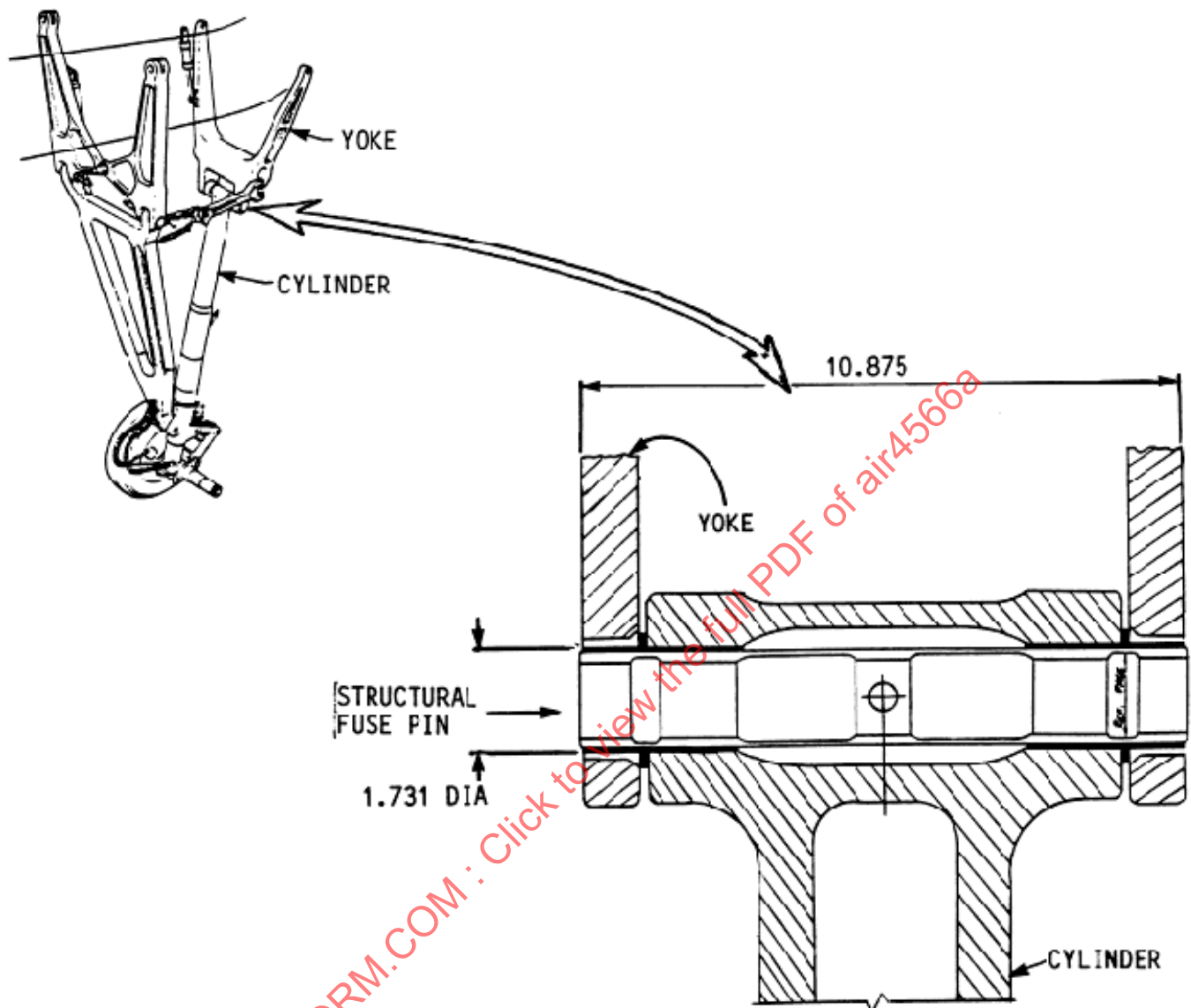


FIGURE 10 – BOMBARDIER DASH 8-100, -200, -300 SERIES STRUCTURAL FUSE DESIGN

6.7.1 Fuse Pin Design

The fuse pin shown in Figure 10 illustrates the Dash 8-100, -200 and -300 series fuse pin design. Frequently an undercut on the internal diameter is used to control the fuse load and location. Fuse pins also successfully use a straight bore. Fuse pin material can be the basic landing gear material such as 300M.

As it is usually advantageous to have the minimum spread on the fuse load, the pin wall thickness can be refined by element testing and the use of close tolerances on the fuse section and by material heat treatment. The properties are monitored during production by material hardness and wall thickness checks.

6.8 Saab 340 Main Landing Gear

The main landing gear drag brace support fitting and trunnion fitting are attached to wing structure by fusible bolts which are sized to fail before any gear element (see Figures 11 and 12). This same design philosophy was successfully used on the A-10A aircraft, designed and manufactured by Fairchild Republic Company.

6.8.1 Landing Gear Overload

The main landing gear attachment has been designed to break cleanly away without inducing enough deformation in the wing box to release any fuel. This has been achieved by attaching the drag brace support fitting and the trunnion fitting to the machined wing ribs by "fusible bolts" which are sized to fail before any gear element and before appreciably distorting the fuel tank. No fuel is carried in the wing between the landing gear ribs.

In addition to the above, an analysis was performed at a vertical descent velocity of 18 ft/s which showed the structure capable of resisting the ground loads generated without failure.

If the main gear fails by collapsing in an inboard direction, penetration of the fuel tank will be prevented by the tire.

With the landing gear retracted in any combination, the fuel tank will always be prevented from striking the ground by protecting structure.

6.8.2 Landing Gear Separation

If the main landing gear tears away from the wing structure, then some hydraulic fluid will be spilt. The maximum quantity of fluid in the system for landing gear operation is slightly more than 2 U.S. gallons, but the postcrash procedure detailed in the aircraft flight manual should generally assure that less than this is released by the action of switching off the hydraulic pump. Some sort of ignition would, of course, be necessary in order to start a fire and the most likely source would be sparking from an electrical short-circuit associated with the microswitches. It is considered that the probability of a fire starting is very low.

A similar argument is made for the nose landing gear.

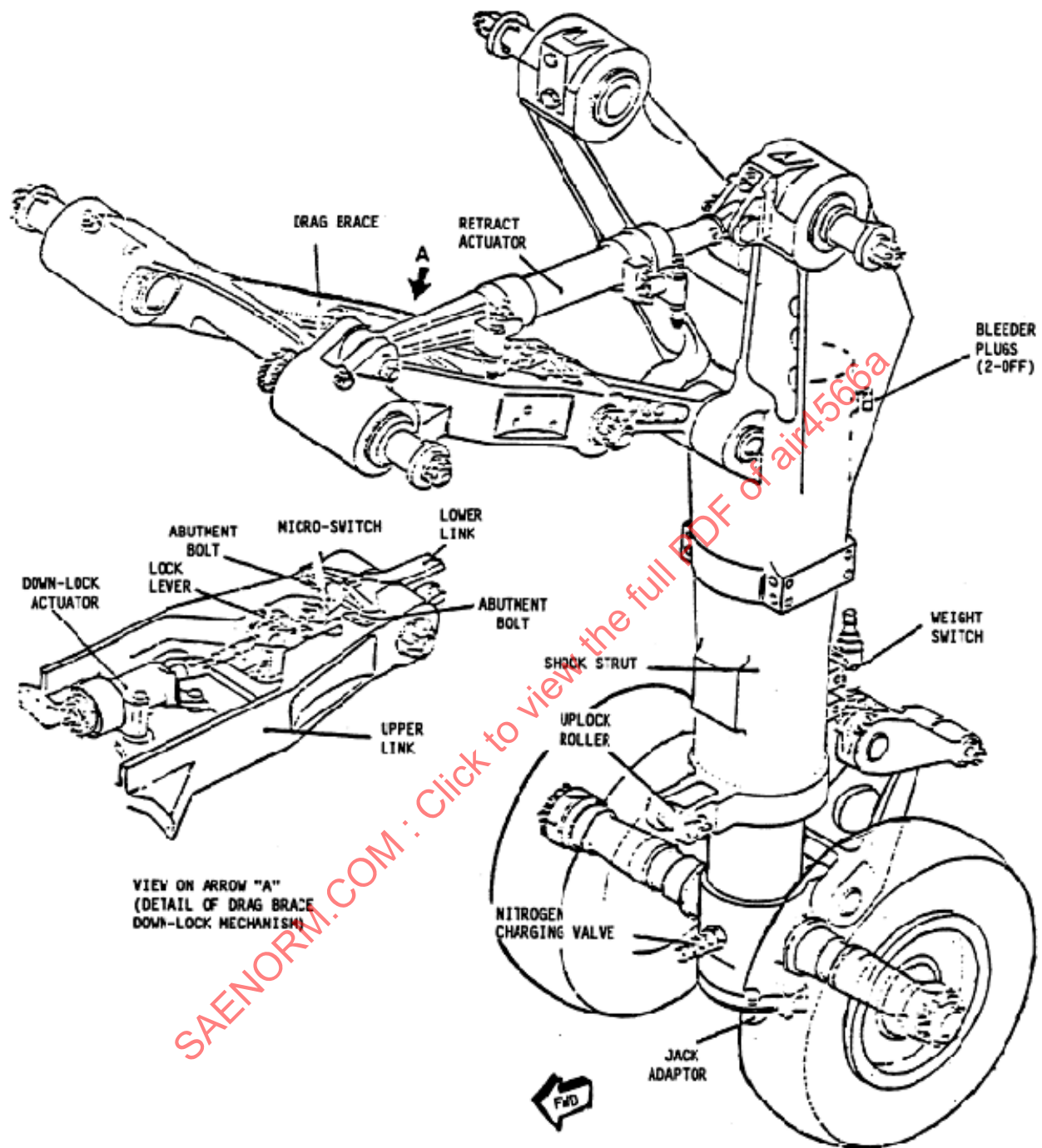


FIGURE 11 – SAAB 340 MAIN LANDING GEAR ASSEMBLY

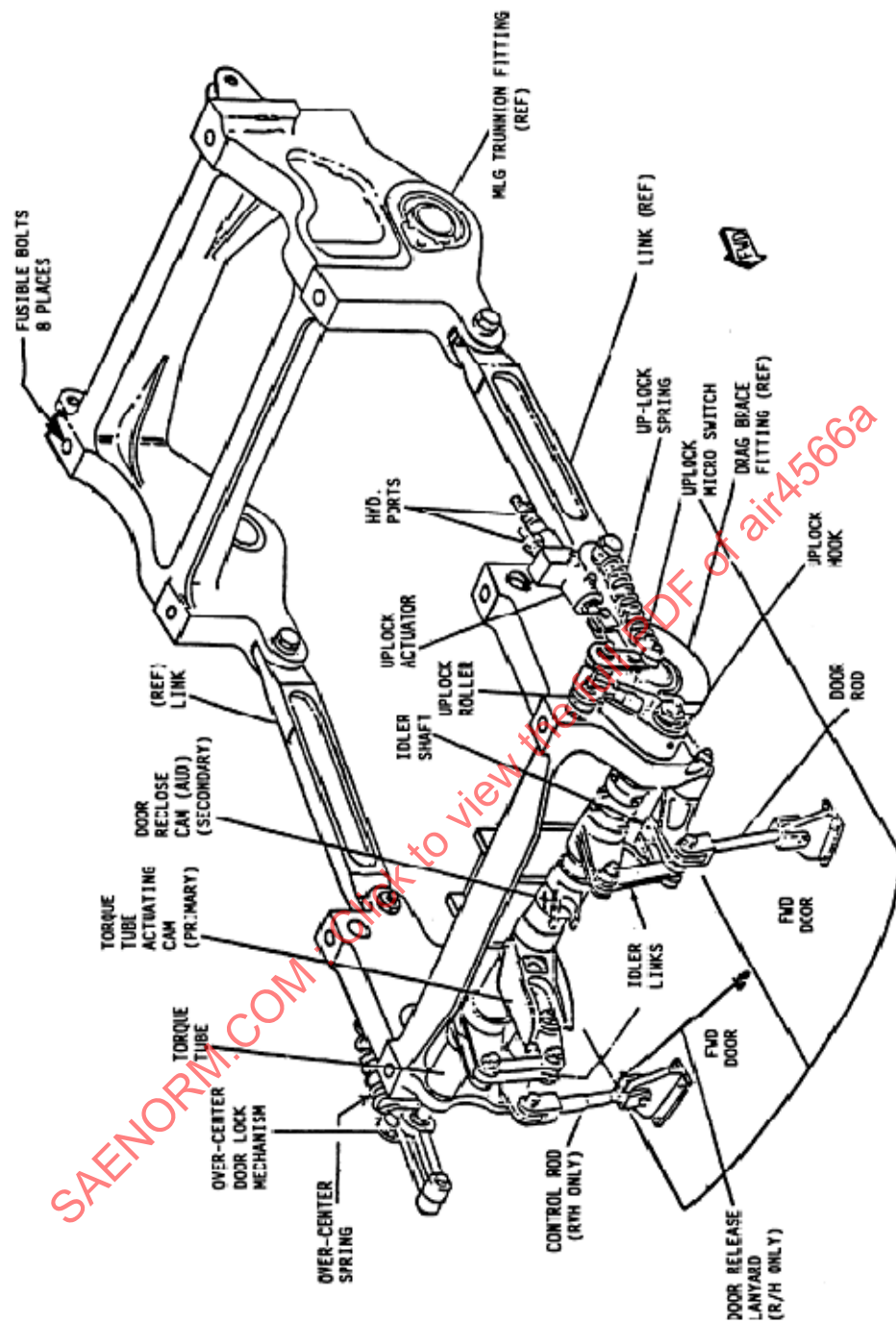


FIGURE 12 – SAAB 340 MLG DOOR MECHANISM AND UPLOCK INSTALLATION (SHOWN IN "UP" POSITION)

6.9 Bell-Boeing V-22 Main Gear Structural Fuse Design

The main landing gear drag brace to shock cylinder attachment pin is designed to fail in the high aft drag case, which was the braking case for this landing gear (see Figure 13).

The V-22 aircraft landing gear was designed for a hard landing descent velocity of 14.7 ft/s with no yielding allowed and a crash capability of 24 ft/s with no structural failure. A two-stage shock strut is used on the MLG.

6.10 McDonnell Douglas AV-8B Structural Fuse Design Data

The design criteria for the fusible link on the AV-8B wing landing gear is as follows:

6.10.1 Construction

Landing gear shall meet the structural strength requirements specified. Landing gear links or struts shall not pierce fuel tanks or lines, should collapse of the gear be caused from an extremely severe landing. The wing landing gear shall be designed to assure the gear shall collapse in an aft or lateral load application direction only.

6.10.2 Drag Failure Strength

The actuator to shock strut attach rod end shall be capable of resisting all the required loadings without damage or failure. The rod end shall be designed to fail at an actuator load of 25,600 lb; that is 44% above the actuator design load of 17 600 lb. The purpose of this feature is to allow the strut to collapse under high drag loads without damaging the wing tanks. The maximum breaking strength shall be demonstrated by test.

6.10.3 Side Load Failure

The outer cylinder of the wing gear has integral flanges which react the side load in a conventional manner. In the event an excessive inboard or outboard side load is applied, the flange will fail on the compressive side in a crippling mode.

6.11 Sikorsky Design

6.11.1 Crashworthy Landing Gear History

Sikorsky has built, tested, and flown the following crashworthy landing gears:

- a. The Army H-34 (Sikorsky S-58) uses a honeycomb energy-absorption system applied to a production helicopter. The S-61 and S-62 models also have similar honeycomb systems. They consisted of a strut filled with pre-crushed metal honeycomb in series with the oleo. This device is activated at high sink speeds, when hydraulic lockup of the shock strut is encountered. It activates when the load reaches a predetermined value and shears specially calibrated pins. When the pins are sheared, the strut compresses the honeycomb in a plastic manner, efficiently absorbing the kinetic energy of impact. The manufacturer judges this device as being successful in service. This design is illustrated in Figure 14.
- b. The CH-54A Army Flying Crane uses a pressure-relief valve for its energy-absorption system. It requires servicing after use (see Figure 14).

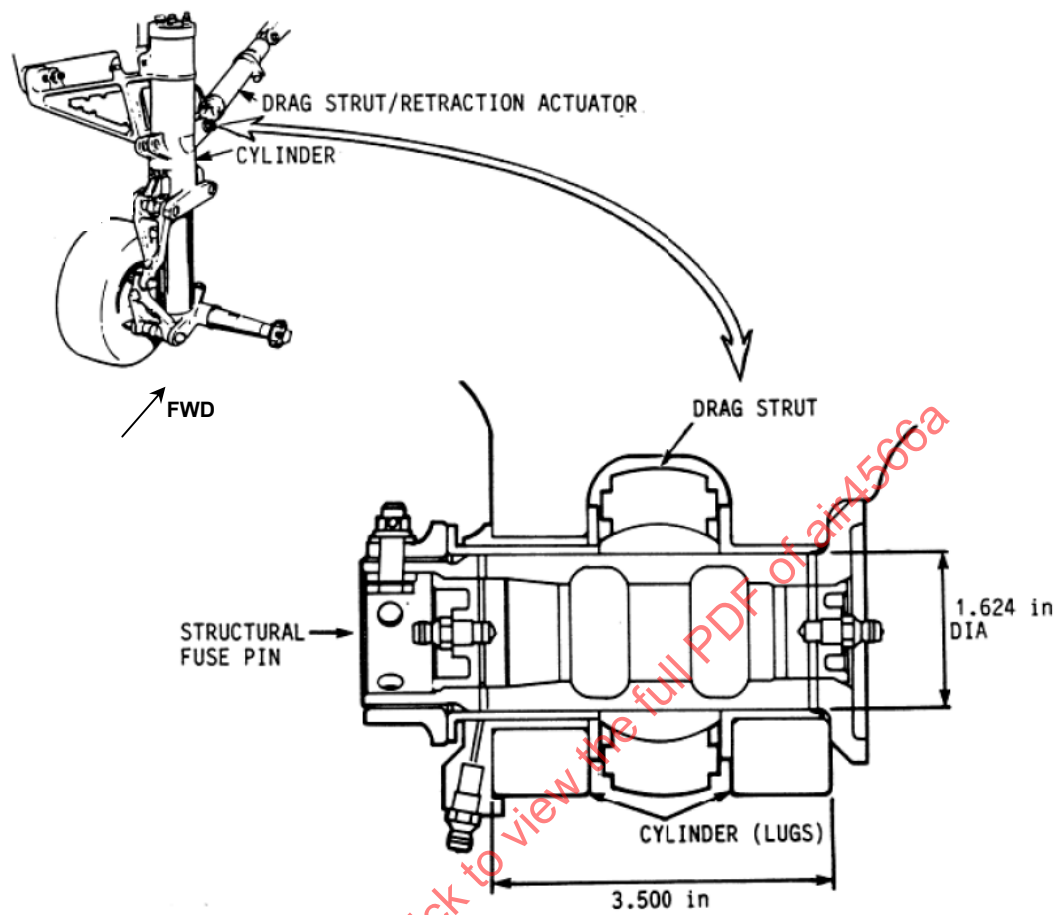


FIGURE 13 – BELL-BOEING V-22 MAIN LANDING GEAR STRUCTURAL FUSE

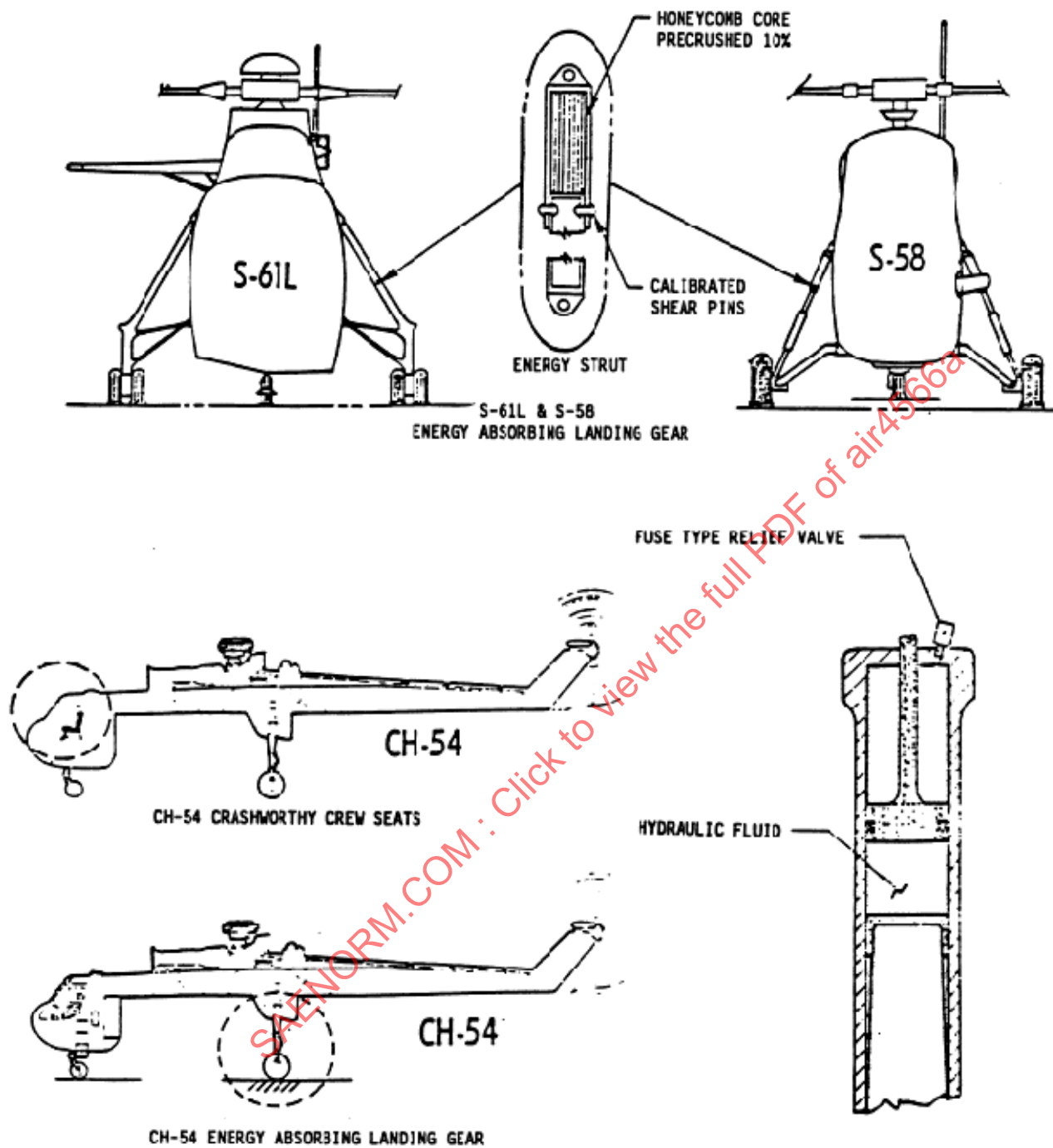


FIGURE 14 - SIKORSKY AIRCRAFT CRASHWORTHY GEAR DESIGNS

- c. The UH-60A energy absorption system uses a pressure relief valve that is self-contained and resets automatically (see Figure 15).
- d. The ACAP requires the nose gear as well as the main to absorb energy during a crash landing. The ACAP utilizes a variable orifice in the first stage of the oleo combined with a honeycomb frangible structure to satisfy the energy dissipation requirements (see Figure 16).

The ACAP is a fixed tricycle landing gear configuration. The gear is designed for a reserve energy sink speed of 12.25 ft/s for normal landings and is also designed for crash conditions. The gear absorbs approximately 63% of the energy resulting from a 42 ft/s sink speed level crash condition and approximately 75% of the energy generated by a 36 ft/s crash with 20 degree roll and 5 degree nose down pitch. The remaining energy is absorbed by a fuselage crushing. The gear is structurally adequate for any crash attitude up to 42 ft/s sink speed with 10 degree roll and pitch angle, applied simultaneously.

The main landing gear is designed so that the primary stage strokes before the secondary stage for any crash condition. In a crash, the tire first flattens then the wheel collapses and the primary stage of the shock strut bottoms. Pins then shear, allowing the secondary stage to begin to stroke and crush the honeycomb. As the honeycomb crushes, the gear swings up and outboard along an arc defined by the side brace. This sequence of events is desirable to prevent the buildup of large bearing friction forces in the primary stage caused by the secondary stage stroking first and swinging the gear outward.

TABLE 1 - SIKORSKY CRASHWORTHY LANDING GEARS

Model	Other Designation	Normal Sink Speed	High Energy Sink Speed (FPS)	Type of Energy System
S-58	CH-34	8	15	Honeycomb Core
S-61	VH-3A	8	15	Honeycomb Core
S-62	HH-52	8	15	Honeycomb Core
S-64	Crane CH-54	8	12	Fluid Metering
S-70	Black Hawk UH-60A	10	38	Two Stage Oleo
S-75	ACAP	10	42 /1/	Honeycomb Core

/1/ For every attitude up to 10 degree roll and pitch angle, applied simultaneously

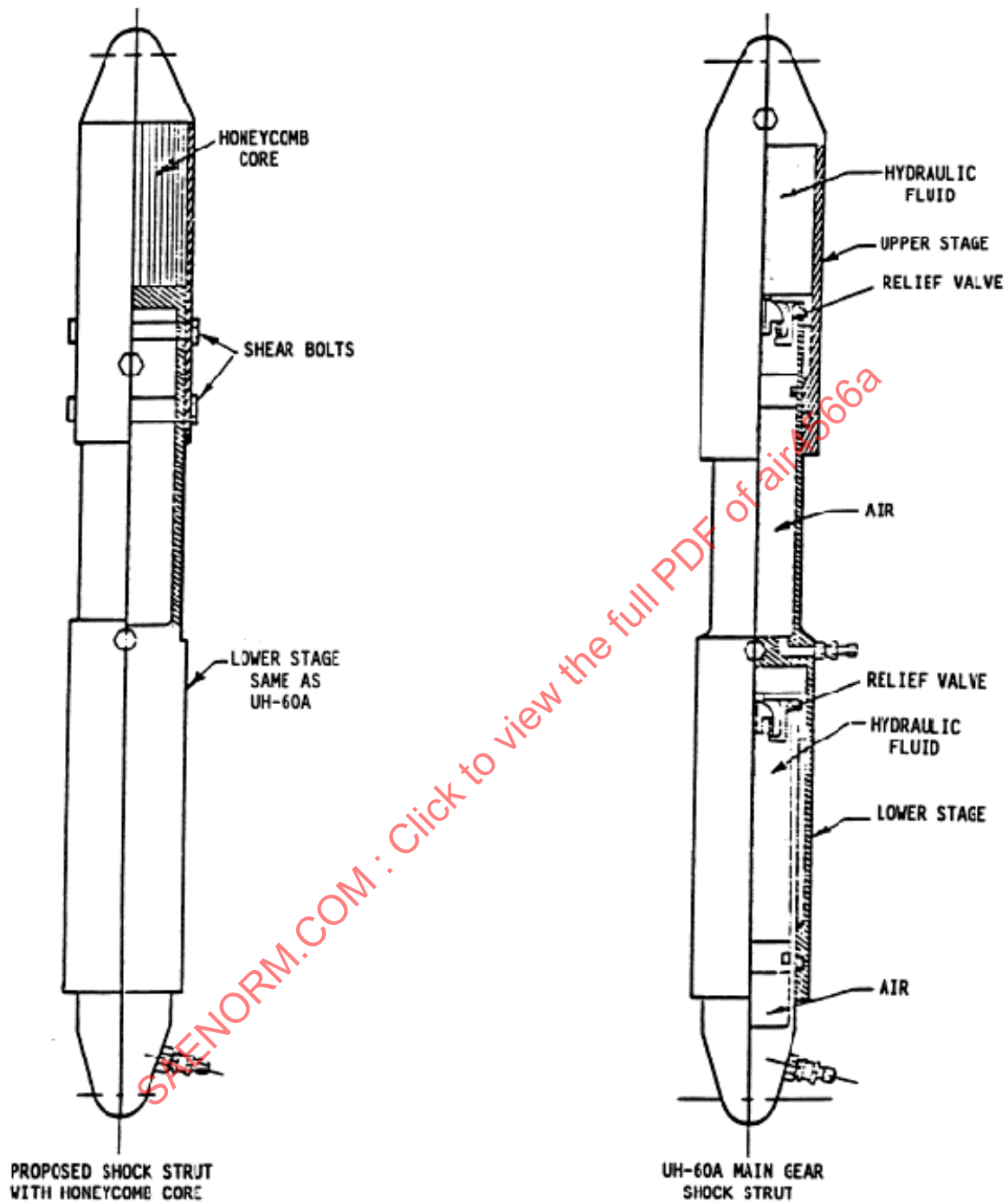


FIGURE 15 – SIKORSKY UH-60A ENERGY ABSORPTION SYSTEM

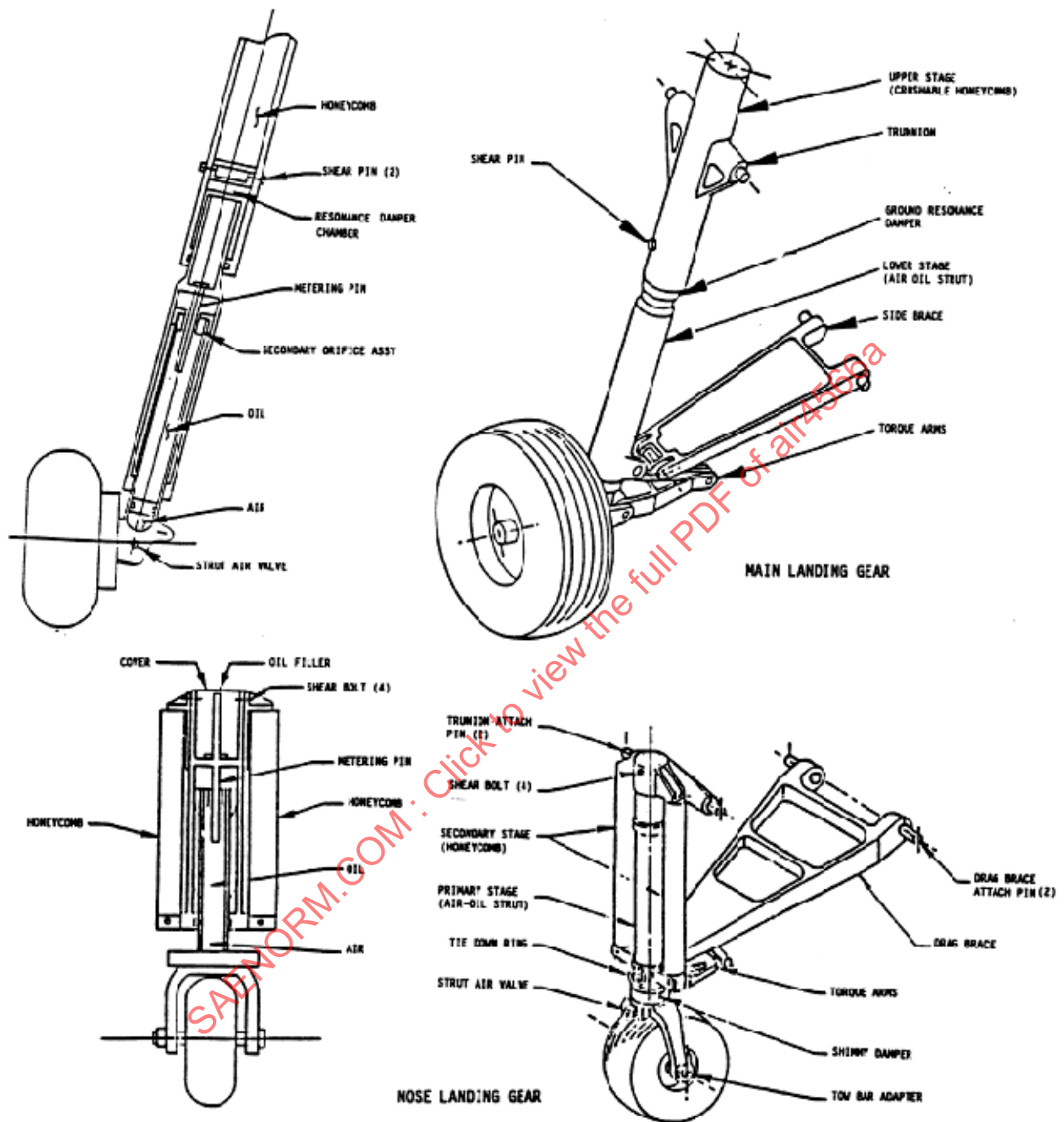


FIGURE 16 – SIKORSKY ACAP S-75 LANDING GEAR

6.11.2 Energy Absorption Devices

There are several types of energy absorption devices which may be considered. They are as follows:

- a. Air-Oil Strut: Required for meeting normal landing requirements. It is repeatable and can be compressed for retraction and air transportability. It can be designed for high efficiency for normal operation, but is not as efficient when used for crash conditions.

This device is velocity sensitive and requires modifications to prevent "hydraulic lock". Because oil damping force is a function of closure velocity squared, at high stroking rate the hydraulic loads rapidly reach strut failure or mount failure. Possible modifications are:

1. Hydraulic Relief Valve: This would reduce load so the strut can stroke without failure
 2. Energy Absorber: In series with the shock strut to reduce closure velocity so the strut can stroke at a load below the failing load
- b. Honeycomb Structure: Although not the lightest non-replaceable structure, it is easy to install and requires a minimum of testing to develop a high efficiency. It is considered repeatable and highly reliable. In addition to the various crush load magnitudes which may be obtained by selection of material, foil thickness and cell size, pre-crushing can be applied to eliminate the peak load and provide a controlled load over the entire stroke.
 - c. Tube Cutter Device: This device consists of a metal tube with a cutting die located at one end. Energy is dissipated when the die is forced into the metal tube, cutting it lengthwise.
 - d. Invertube: Absorption of energy by the invertube process involves the controlled inversion of a soft metal tube during application of an axial load. One end of the tube is clamped to a plunger which inverts the tube causing energy to be absorbed by plastic bending, compression, and shearing plus friction. It is difficult to obtain consistent load during stroking.
 - e. Buckling of Metal Shells: This energy absorption method utilizes a metal shell of cylindrical, spherical, or conical shape. Impacting at one end initiates a local buckling condition which progresses in regular stages during which the folds form a geometrical pattern from one end to the other until a completely collapsed condition is obtained. Stroke lengths reaching 90% of initial length are not uncommon for the thinner shells. Rebound force is usually negligible since a buckled shell has substantial resistance to being expanded axially.
 - f. Energy Strap: This method utilizes a metal tension strap deforming in the plastic range as a means for absorbing landing impact energy.
 - g. Bearing Failure: Bearing failure mode is a method used to provide controlled energy dissipation at predictable load levels. The ACAP landing gear lateral strut attachment uses a joint design where lateral impacts result in non-catastrophic bearing failure of the attachment frame. Energy can be absorbed in a similar manner at other mechanical joints throughout the structure.
 - h. Foamed Plastics: These materials indicate no prominent peak stress at the start of crushing action and very little difference in stress-strain characteristics with variations in velocities over the range of interest, but static tests generally show a decrease in available energy absorption capacity. As expected, there is a rapid increase in energy absorption with increased density but usable strokes are limited and rebound energies are significantly increased when large stroke values are used.