AN INVESTIGATION OF ADD-ON DAMPING TREATMENT FOR LIFE EXTENSION OF THE F-15 UPPER OUTER WING SKIN

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ABSTRACT

The purpose of this investigation was to design, fabricate, and verify candidate add-on damping treatments for the F-15 upper-outer wing skin. The F-15 upper-outer wing skin has experienced high cycle fatigue cracks caused by separated flow on the upper wing surface. The separated flow results during high load factor maneuvers and in turn induces large vibratory loads on the upper wing skin and associated substructure. The capability of the F-15 to sustain these maneuvers allows the excitation to occur for sufficiently long periods of time to result in damage. Damage accumulates due to the resonant vibration of local skin/stiffener modes. The cracks initiate at the fastener holes adjacent to the integrally machined "T" stiffeners and tend to propagate parallel to the stiffeners. Two damping treatments resulted from the investigation and were recommended for F-15 fleet retrofit. One was an external constrained-layer treatment and the other was an internal "stand-off" treatment. Laboratory vibration, corrosion, and thermal aging tests were conducted as part of the development of the add-on damping treatments. Life extension factors were estimated for both damping treatments.

INTRODUCTION

The requirement for high performance fighter aircraft places tremendous demands on the components and materials from which these aircraft are constructed. Inherent with high performance are high vibration levels. One possible cause of large vibratory loads is separated flow. Separated flow presents an unpredictable and complex environment. Within this environment it is often impossible to estimate the precise dynamic flow characteristics or loading conditions aircraft components may experience during flight. If not properly accounted for in the design phase, large vibratory loads can result in high cycle fatigue and a substantial reduction of the useful service life of the component. Skin type components, in particular outboard wing skins, are relatively light weight structures which are extremely susceptible to vibration response induced by separated flow.

The F-15 upper-outer wing skin (UOWS) panel has experienced cracks resulting from high cycle fatigue. The F-15 aircraft, shown in Figure 1, has sufficient thrust to perform sustained, high load factor maneuvers. Consequent separated flow over the wing panel contains high-level broad band random pressure fluctuations and induces large vibratory response in the UOWS panel and associated wing substructure. The resulting elevated stresses over time cause high cycle fatigue cracks to form in the wing skin. Historically, UOWS cracking dates to the late 1970's and early 1980's. At that time, the cracks were considered to occur only over a small portion of the skin closest to the wing tip. Subsequent finding show that the entire UOWS is prone to cracking.

The UOWS was originally designed for a service life of 8000 hours. Unfortunately the initial service life realized was only 250 hours. Several modifications were incorporated to improve the fatigue life of the skin, including fortifying critical locations on the wing skin. The modifications were initially thought to have resolved the fatigue cracking problem. In reality these changes only increased the life of the skin to approximately 1250 hours. The need still remained to increase the service life to the original design value of 8000 hours.

The purpose of this investigation was to design, fabricate, and verify candidate add-on damping treatments for the F-15 UOWS which would alleviate the occurrence of fatigue cracks caused by separated flow on the upper wing surface and increase the UOWS service life to the desired 8000 hours. Two candidate damping treatments resulted from the investigation and were recommended for F-15 fleet retrofit. One treatment was a field installable external system and the other an internal depot installable system. Neither system required modifications to the existing wing structure.

BACKGROUND

The F-15 UOWS is machined from a single block of 2024 Aluminum (Al) and consist of the skin, integrally machined "T" stiffeners, and chemically milled pockets between the stiffeners. The thickness varies from location to location on the panel, however assuming a constant thickness of 0.080" is sufficient for understanding the problem. Figure 2 shows the major substructure for the left wing. The UOWS extends from rib 155 to rib 224, and from the front spar to the rear spar. There are intermediate ribs at locations 172, 188, and 206. At rib 188, the front, main, and rear spars are at 10%, 45%, and 65% chord, respectively. Collectively, the above mentioned members constitute the outer wing torque box. The wing skin measures approximately 5 feet wide by 7 feet long measuring along rib 188 and the main spar, respectively. Inboard of rib 155 the wing is "wet", that is, the volume is used for fuel storage. The outer torque box is "dry". Blind threaded, flush fasteners are used to attach the skin to the rib and spar substructure. A scrapped right hand UOWS is shown in Figure 3. Visible in Figure 3 are the integral stiffeners, their runouts, spar and rib fastener holes, and various panel access holes. Stiffeners are numbered consecutively starting at the UOWS leading edge. The stiffeners are not clipped to the ribs but are allowed to move freely within the rib notch. The cracks develop in the rib fastener holes adjacent to the stiffeners. Predominately, the cracks initiate either perpendicular to the ribs or parallel to the stiffeners. A damaged UOWS, showing the crack pattern, is presented in Figure 4. Figure 5 shows close-ups of the cracks. Based on the crack patterns and the unclipped stiffener design, it was concluded that the UOWS cracks were most likely induced by stiffener rotation. Figure 6 gives a convenient shorthand designation for the spar-rib bays which will be used throughout the remainder of this paper to aid the reader in locating specific portions of the UOWS.

The UOWS cracks are caused by high cycle fatigue. Damage accumulates due to resonant vibration of local skin/stiffener modes, excited by external oscillatory pressure resulting from separated flow. The excitation occurs during high load factor maneuvers. The capability of the F-15 to sustain these maneuvers causes the excitation to occur for sufficiently long periods of time to result in damage. Other investigations concerning the aerodynamic characteristics of the F-15 suggest that 12° angle-of-attack provides the most severe disturbances and consequently the most damage.

The location of UOWS fatigue cracks evolved during the course of this investigation. Initially, the concern was for the web of stiffener 4 in bay L1 (see Figure 6) and over rib 206 between bays L1 and L2. Next, it was observed that cracks also occurred over rib 188 between bays L2 and L3. Finally, it was learned that cracks occur over ribs 188 and 206 between the main and rear spars. Ribs 188 and 206 themselves crack, but were not specifically addressed in this study. The numerous access holes in bays L4 and R4 result in a significantly heavier structure and made this area less susceptible to fatigue cracking. Thus, with the exception of bays L4 and R4, high cycle fatigue cracks were observed over the entire UOWS panel.

FLIGHT DATA

Flight data were gathered to obtain UOWS response information during high load factor maneuvers and to assess the effectiveness of the damping system. These test were conducted by McDonnell Aircraft Corporation, St. Louis MO (MCAIR), at the request and sponsorship of Warner-Robins Air Logistics Center. Numerous other investigations have provided some flight data along with data reduction and analysis. These investigations showed that obtaining accurate UOWS panel response data was highly dependent on whether the panel had been installed properly and the instrumentation used effectively. Inconsistencies in these two areas, among others, can easily lead the investigator to erroneous results. The flight test data collected for this investigation included the baseline response of the F-15 UOWS as well as the UOWS response with various candidate damping treatment configurations. Strain gages placed on internal and external surfaces of the panel were used to record the bulk of the response data. In some cases internal accelerometers were also used. Figure 7 shows the location of some of the strain gages used to obtain flight data. The strain gages were mounted adjacent to stiffener #4 at rib 188. One was positioned between the two rows of rib 188 fastener holes and the other was located just inboard of the fastener holes. The location and orientation of these strain gages were such that the strains inducing the fatigue cracks should be measured. Historically, many cracks have been discovered along stringer #4. Based on past analyses, it was observed that the response data obtained at the intersection of stiffener #4 and rib 188 could be used to represent the response over the remaining panel. Thus, the analyses performed centered on the UOWS response measurements taken at this location.

A plot of angle-of-attack (AOA) versus dynamic pressure (q) is given in Figure 8 for typical flight conditions for which high load factor maneuver data was gathered. The range of dynamic pressure, 350 psf to 500 psf, for the 12° AOA shown in this plot illustrates the difficulty, if not impossibility, of duplicating the service conditions for which damage is induced. The power spectral density (PSD), shown in Figure 9, is typical of the UOWS response at the strain gage locations shown in Figure 7 for an undamped panel. The flight conditions for this PSD were: 11° AOA, 5.9g load factor, 0.80 Mach, 20,000 feet altitude, and 424 psf dynamic pressure. Figure 9 shows high strain levels occur in the 300 to 400 Hertz (Hz) band. It is obvious that this peak makes the most significant contribution to cumulative high cycle fatigue crack damage.

Several damping treatment configurations were flight tested. The external and internal treatments which were recommended for F-15 retrofit were included in the flight tested damping treatments. Unfortunately detailed data is not yet available and will not be available before printing of this report; thus no specific flight test results can be presented. The preliminary flight test results received from MCAIR are very promising and appear to significantly improve the UOWS fatigue life. MCAIR will release the final report near the end of calendar year 1991. The above mentioned damping treatments will be discussed in detail in the next section.

DAMPING TREATMENTS

This study investigated the performance of 13 different candidate add-on damping treatment configurations under laboratory conditions. For brevity only the "1980 Damping Treatment" and the two new damping treatments which were recommended to Warner-Robins Air Logistics Center are discussed in this section. Past damping experience suggested that a constrained-layer type damping treatment would offer the most viable, cost effective solution. A constrained-layer damping system consists of a layer of viscoelastic material (VEM) which is constrained by a metal layer. The layers of viscoelastic material and metal taken together are called a constrained-layer. Often these types of damping system will be constructed of multiple constrained-layers to achieve the desired level of damping. Whenever the structure undergoes bending, the metal layer will constrain the viscoelastic material, resulting in shear deformation of the VEM. Energy is dissipated due to this shear deformation.

An important part of designing a damping treatment is determining the environmental condition to which the treatment will be exposed and insuring the selected treatment will withstand and perform properly under these conditions. Critical environmental considerations include the operational temperature range for which damping is desired, the effects of the damping treatment on corrosion of the structure, and the effects of thermal aging on the performance of the damping treatment. Recent laboratory corrosion testing shows no degradation in corrosion resistance caused by the application of the recommended damping treatments. The corrosion test panels were exposed to a standard 30 day humidity corrosion environment in the laboratory consisting of 120° F, 98% relative humidity (RH), and salt spray. The addition of the damping treatments had no affect on corrosion, primarily because the paint was not disturbed during installation. Extensive service experience with similar damping treatments has not revealed any corrosion problems. For example, the "1980 Damping Treatment" has flown externally on approximately 300 aircraft for 10 years with no adverse affects on corrosion. Although the requirements used to develop the thermal aging tests were judged to be excessive, satisfactory thermal aging characteristics have been demonstrated in the laboratory for all materials used in the new damping treatments.

The temperature exposure of 8 hours at 340° F plus 48 hours at 270° F was intended to be a conservative design condition for the 8000 hour life; however, these exposure levels are believed to be more severe than necessary. Thousands of hours of F-111 service data establish that total outside air temperature (TOAT) exceeds 125° F less than 1% of the time. Laboratory tests confirmed that thermal aging caused the damping material to slightly stiffen which tended to increase damping treatment effectiveness. An additional issue of practicality includes being able to inspect the UOWS for structural integrity while the damping treatment is installed. The damping treatment configurations used in no instance covered up fasteners or locations where the cracks initiate. Therefore, the damping treatments will not hinder inspection of the UOWS either visually or radiographically and the treatments also will not impact removal or installation of the UOWS or other maintenance functions. A discussion on the selection of the damping treatment design temperature follows.

A plot of Mach number versus altitude is presented in Figure 10 for the F-15 aircraft. Included on the plot are standard day constant value curves for the following parameters: dynamic pressure (q), total outside air temperature (TOAT), and maneuver load factor. The load factor is for an F-15 with a gross weight of 42,000 pounds flying at a 12° AOA. The equilibrium temperature for the wing skin and the installed damping treatment will fall between the TOAT and the ambient temperature. The large dash marks in Figure 10 indicate planned data gathering flight conditions. Because the ratio of oscillatory pressure to dynamic pressure tends to be a constant in the subsonic flight regime, the oscillatory pressure (thus the cumulative damage) increases as Mach 1.0 at sea level is approached from the upper left on the graph. The structural limit of the F-15 is 8g's. Based on this, a temperature range from 50° F to 75° F was selected for the damping design. No cumulative damage was expected below 0° F or above 125° F.

A previous attempt by MCAIR to correct the UOWS fatigue cracking included the application of a multiple constrained-layer damping treatment referred to as the "1980 Damping Treatment". The treatment was applied externally over bay L1 of the skin (see Figure 6) because at the time, the fatigue cracks were considered to occur only in this outer spar-rib bay. It consisted of 3 constrained-layers each of which contained a 0.002" layer of ISD-112 VEM and a 0.005" layer of aluminum. Figure 11 illustrates the "1980 Damping Treatment". The "1980 Damping Treatment" was installed and flown on numerous operational F-15 aircraft but it proved to be unsuccessful in eliminating the UOWS fatigue cracks.

As previously mentioned, the Flight Dynamics Directorate developed two new damping treatments which were recommended to W-R ALC for F-15 fleet retrofit. The treatments consisted of an externally applied, field installable system and an internally applied, depot installable system. Figure 12 shows the recommended external treatment's multiple (4) constrained-layer configuration. Two different constrained-layers were used in the design. One consisted of a 0.002" layer of ISD-112 VEM which was constrained by 0.005" of aluminum and the other was made of a 0.002" layer of ISD-113 VEM also constrained by 0.005" of aluminum. Two each of these different constrained-layers were used to build-up the total of four constrained-layers in the external treatment design. The use of two VEMs broadened the effective temperature range relative to the "1980 Damping Treatment". The six outer most spar-rib bays were covered (R1, R2, R3, L1, L2, and L3) by the external treatment. Figure 13 is a photo of the external treatment installed on an F-15 wing.

The recommended internal treatment is summarized in Figure 14. Starting at the wing skin, there was a 0.004" layer of pressure sensitive adhesive (VEM). Next there was an 0.080" stand-off layer of syntactic foam configured to maintain high shear stiffness and low flexural stiffness. This was achieved by cutting a checker board pattern into the syntactic foam. Finally, three constrained-layers of damping material were placed on top of the stand-off layer. The first constrained-layer (from the bottom) consisted of 0.004" of VEM and 0.005" of aluminum. The other 2 constrained-layer each consisted of 0.002" of VEM and 0.005" of aluminum. For all layers the Hueston Industries F-440 VEM was used. The internal damping treatment was applied in the chemically milled pockets between the integral stiffeners for all 8 spar-rib bays shown in Figure 6. Additionally, there were viscoelastic links (VELs) placed between the caps of the integral stiffeners and the notches in the rib. The VELs were located in all rib notch locations. The VEL material was slightly tacky at room temperature. A VEL thickness of 0.50" was used to provide an interference fit. The purpose of the VEL was to provide a link (having both stiffness and damping) from the stiffener cap to ground (rib notch) thereby reducing stiffener rotation. Figure 15 shows the stand-off damping treatment applied to the internal surface of the wing skin. Figure 16 shows the VELs located in the rib notches.

The installation of the damping treatments was simple and straight forward. First the UOWS was cleaned to remove all oil and dirt. Next, the external damping treatment was pre-cut to fit between the fastener rows for each spar-rib bay. The treatment was cut to insure that access to the fasteners was not impaired. A small amount of split peel ply or release paper was removed from the bottom of the damping treatment, exposing the first layer of VEM. The damping treatment was then carefully centered onto the appropriate spar-rib bay. Finally, the procedure was to gradually remove the release paper from under the damping treatment while simultaneously adhering the treatment. Special care was necessary to minimize entrapped air bubbles. A small, flat plastic scraper was rubbed over the surface of the external treatment as it was applied to squeegee out as much air as possible. This step is illustrated in Figure 17. A nice feature of the external damping treatment was that small amounts of compound curvature could be accommodated without adversely affecting the quality of the application.

The internal stand-off treatment was applied in a similar manner except additional effort was required to avoid damaging the brittle stand-off layer. The pieces of internal damping treatment were much smaller than the external damping pieces and therefore air entrapment was not a problem. Hand pressure was sufficient to apply the internal treatment so the plastic scraper was not used. The VELs were provided with release paper on the surfaces which were to adhere to the skin stiffener and the rib notch. During installation, the release paper on the rib notch side is removed and the VEL is positioned in the rib notch. Just before installing the skin, the second release paper is removed. The thickness of the VEL was such that an interference fit resulted; however, the force required to install the UOWS tightly to the substructure was nominal and easily provided by advancing the fasteners.

Life Extension

A comparison between the response of the baseline UOWS and the UOWS with the external damping treatment installed is presented in Figure 18. The frequency response functions (FRFs) are the acceleration FRFs which were integrated twice to obtain the compliance (displacement) FRFs; the compliance FRFs were assumed to be proportional to strain. Figure 19 makes a similar comparison for the internal damping configuration. Notice the dramatic, beneficial reduction in response. The comparisons in this report were made on the basis of RMS stress rather than comparing peaks. Figure 20 presents the equation used to calculate a life extension factor. The ratio of the damped to the baseline response is raised to the proper exponential to give the life extension (ie, ratio of life). The RMS of the compliance FRF between 300 and 400 Hz was the basis of the calculation. Calculations made in this manner revealed that the UOWS with the "1980 Damping Treatment" would last 4 times as long as the baseline UOWS (bare UOWS), thus the life extension was a factor of 4. The life of the baseline UOWS is approximately 1250 hours, therefore the projected life with the 1980 Damping Treatment is 5000 hours. Obviously, this is an estimate; however, it does provide a measure of the damping treatment's performance. Similar estimates gave life extension factors for the new recommended external and internal treatments of 5 and 34, respectively. The internal treatment is considered the primary solution to resolve the UOWS high cycle fatigue cracking. This is because of the dramatic reduction in response achieved when it was installed. Its large life extension factor should offset a variety of uncertainties not accounted for by this investigation, such as precise temperature at which damage accumulates, the fact that RMS stresses were used instead of peak stresses, and potential changes in future operational usage.

CONCLUSIONS

The Fight Dynamics Directorate, at the request and sponsorship of Warner-Robins Air Logistic Center tested 13 candidate add-on damping treatments for the F-15 UOWS. Of those tested, two damping treatments were recommended for F-15 fleet retrofit. One treatment was an externally applied constrained-layer treatment and the other was an internally applied stand-off treatment with viscoelastic links in the rib notches. The external and internal treatments resulted in life extension factors of 5 and 34, respectively. Thermal aging and corrosion tests were performed on the damping treatments with no adverse effects noted. At this time, there is no evidence to indicate that the recommended damping treatments should not be used to alleviate the UOWS fatigue cracking. Three hundred F-15 aircraft have accumulated ten years of service experience with the "1980 Damping Treatment" and to the authors knowledge there have been no reports of concerns or adverse effects associated with add-on damping treatments. It is projected that retrofit of the F-15 fleet with UOWS containing the internal treatment will result in a net savings of $100M in maintenance and repair costs over the next 25 years. The recommended damping treatments are fully qualified for F-15 fleet retrofit and represent a viable, cost effective solution which will substantially improve the F-15 UOWS service life.

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Figure 1. F-15 Aircraft

F-15 WING STRUCTURE

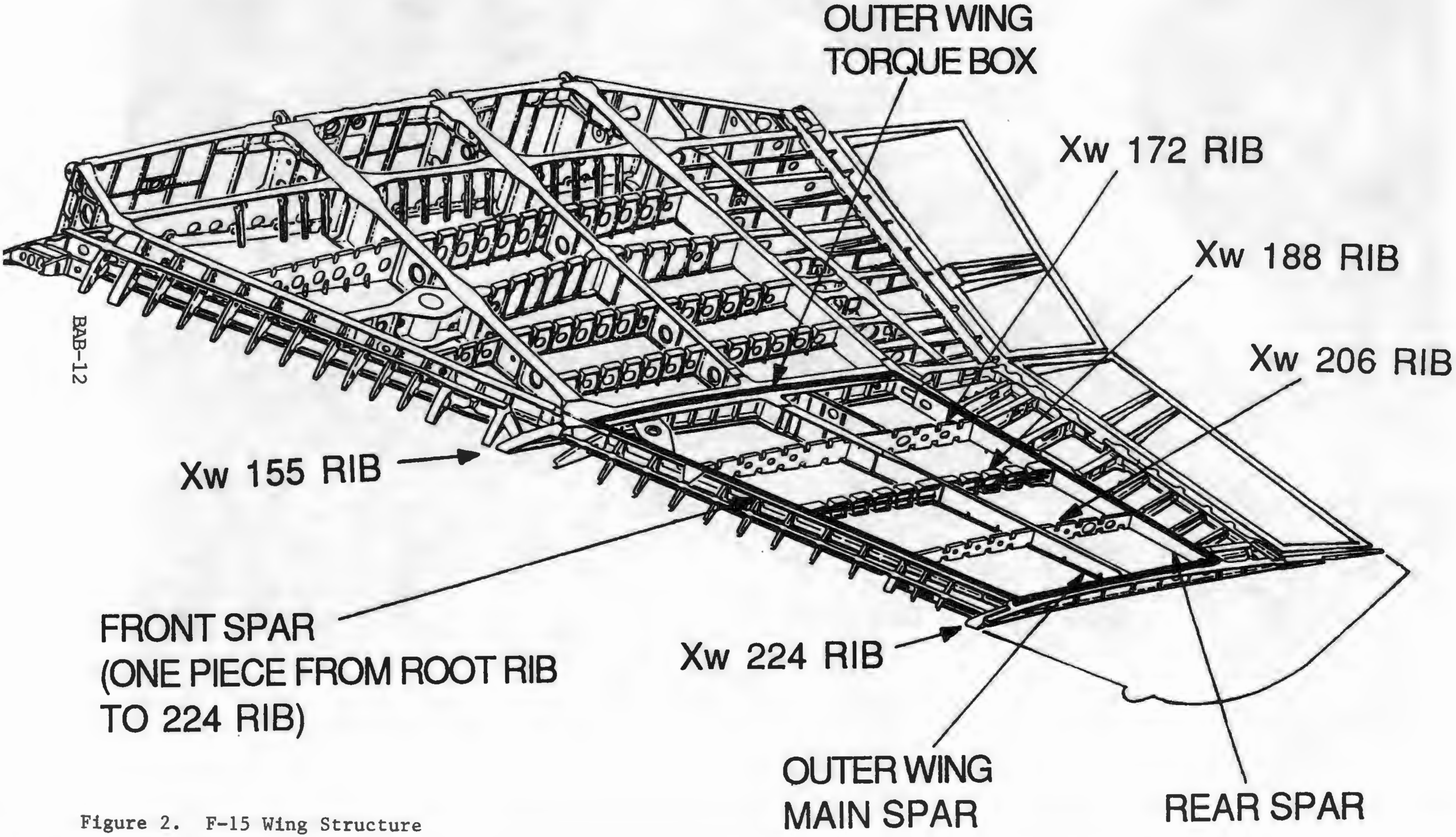

Figure 2. F-15 Wing Structure

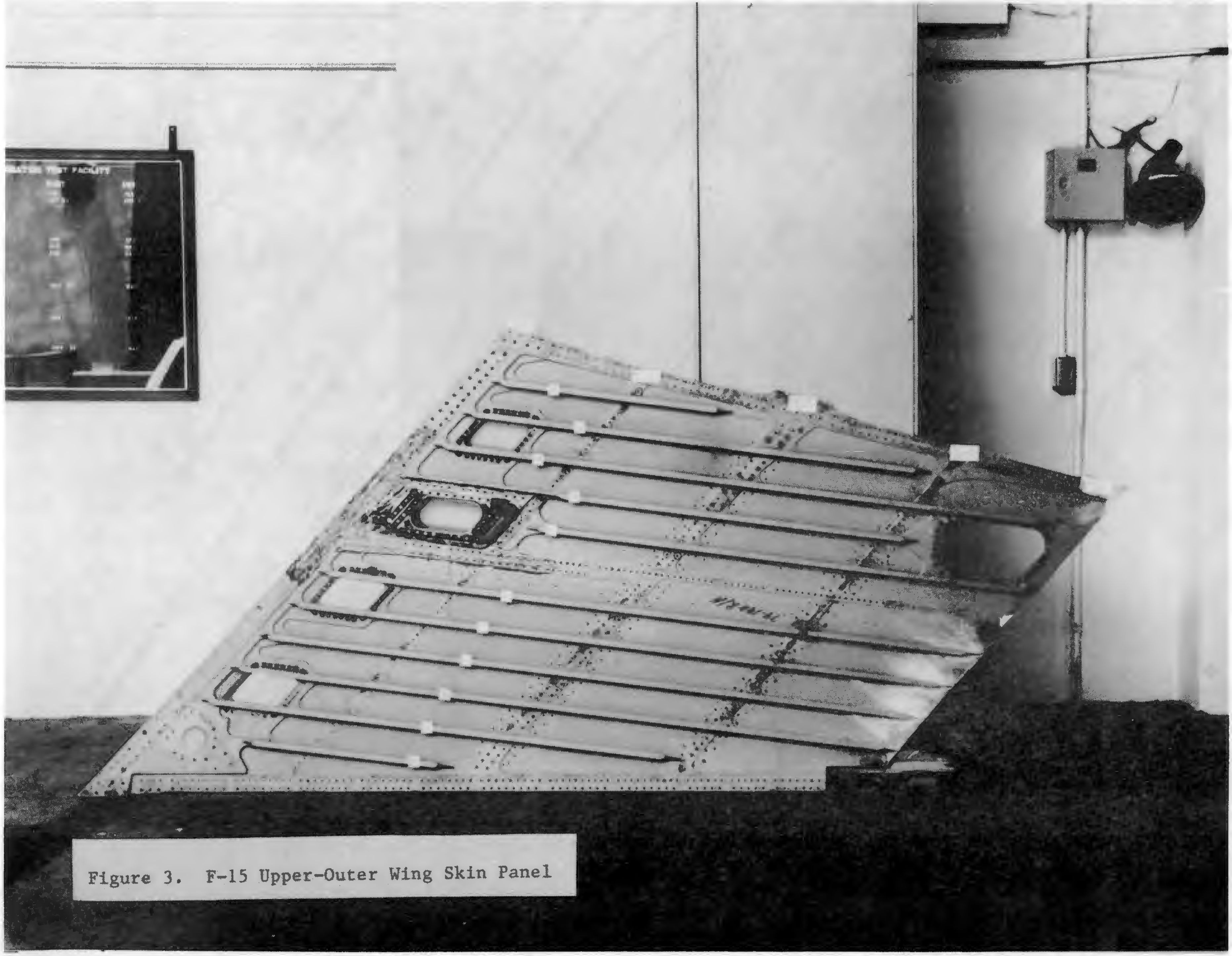

Figure 3. F-15 Upper-Outer Wing Skin Panel

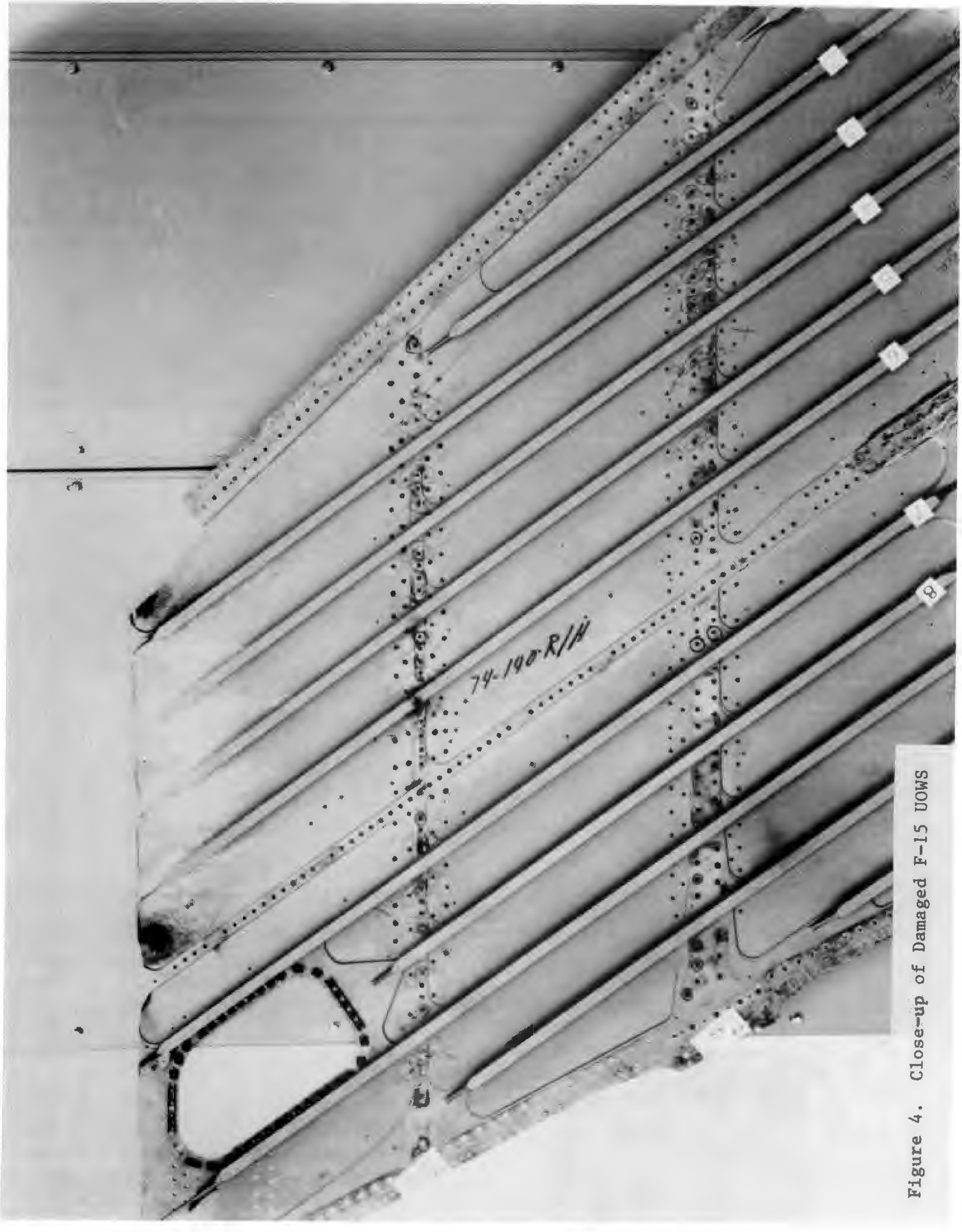

Figure 4. Close-up of Damaged F-15 UOWS

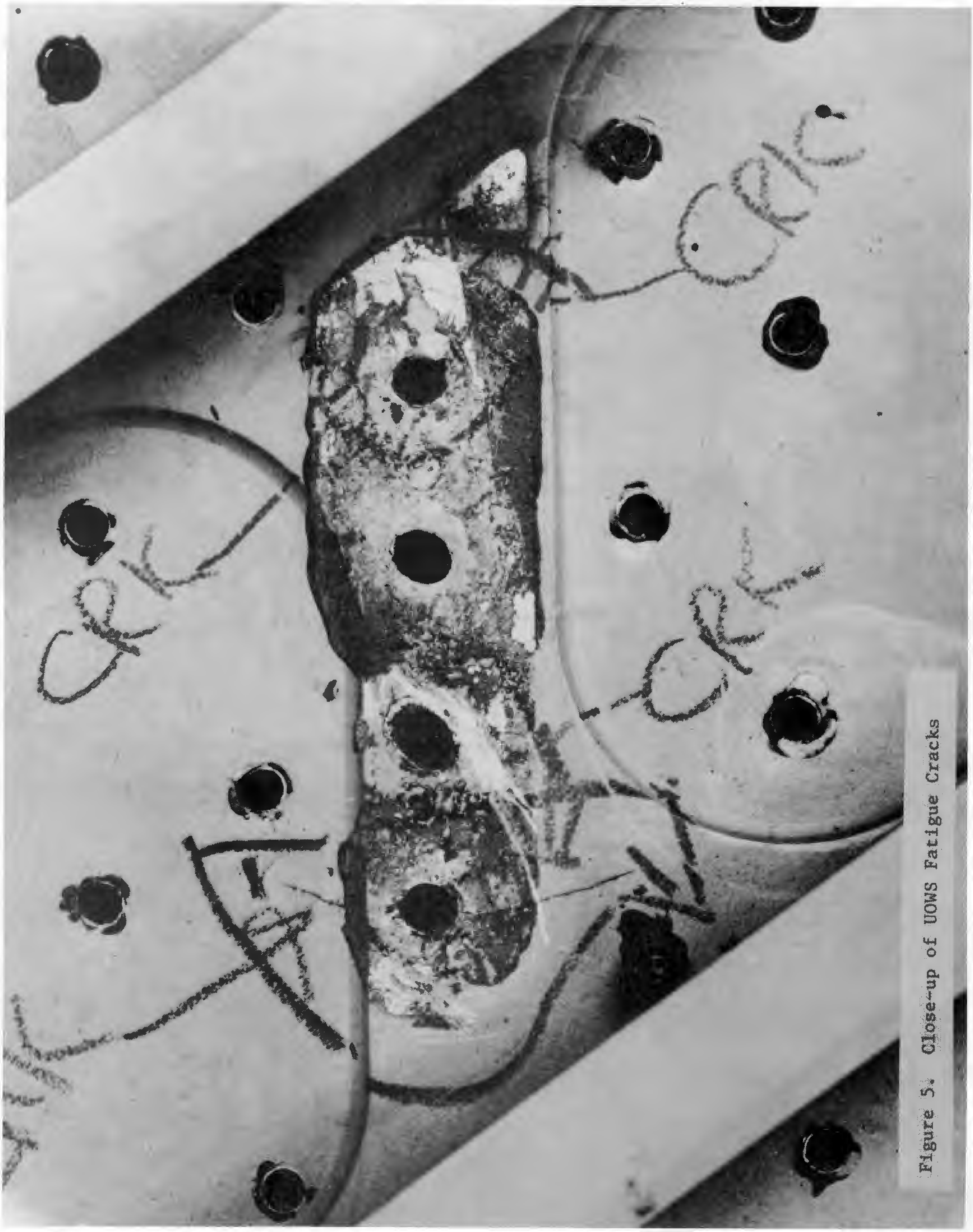

Figure 5. Close-up of UOWS Fatigue Cracks

SPAR-RIB BAY DESIGNATION

TOP VIEW OF LEFT WING

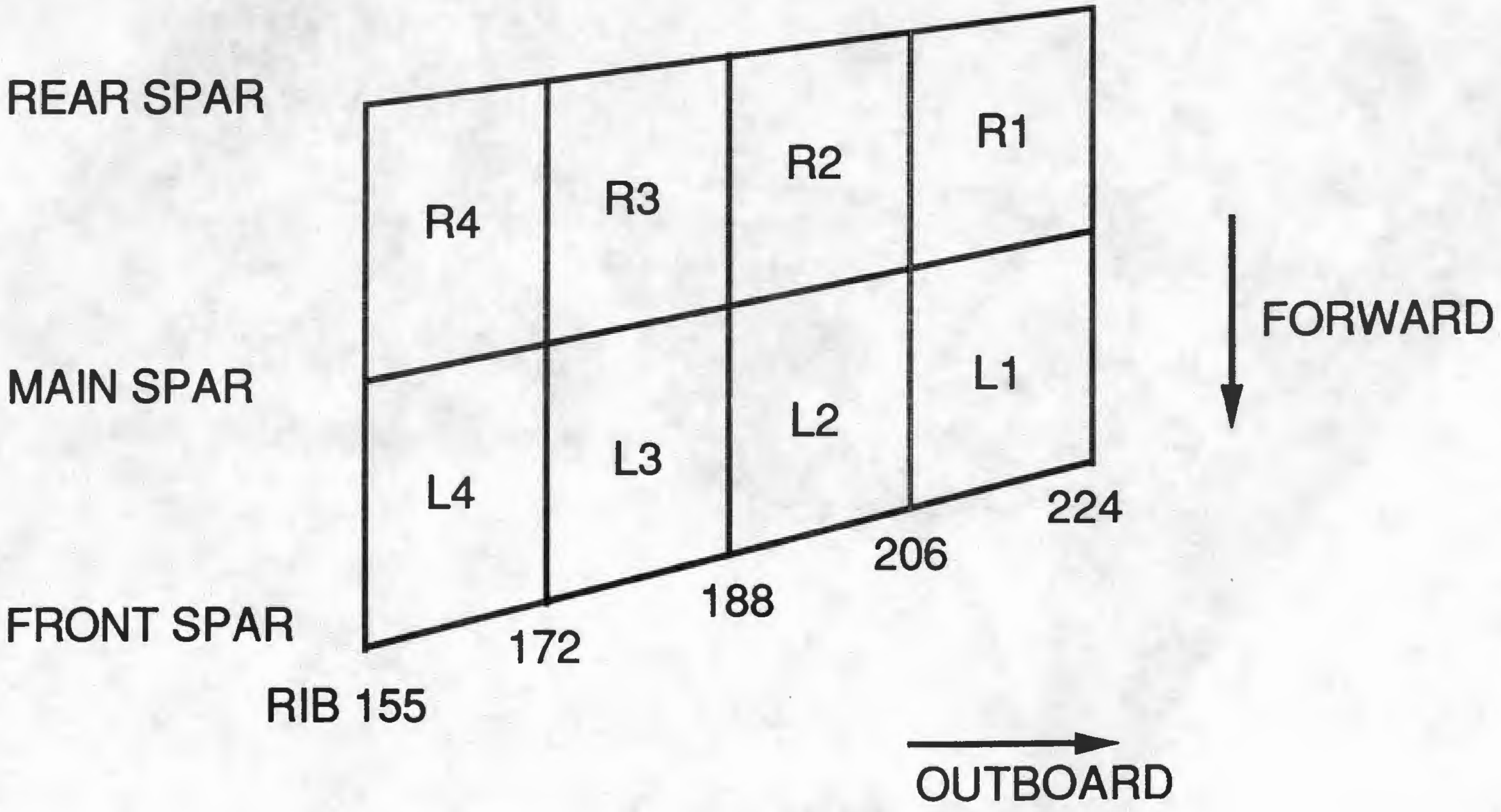

Figure 6. F-15 UOWS Spar-Rib Bay Designation

FLIGHT TEST INSTRUMENTATION FOR SEALENT EVALUATION

- L/H AND R/H WINGS INSTRUMENTED
- SEALENT BETWEEN SKIN AND RIBS & SPARS ON L/H OUTER WING
- NO SEALENT ON R/H WING

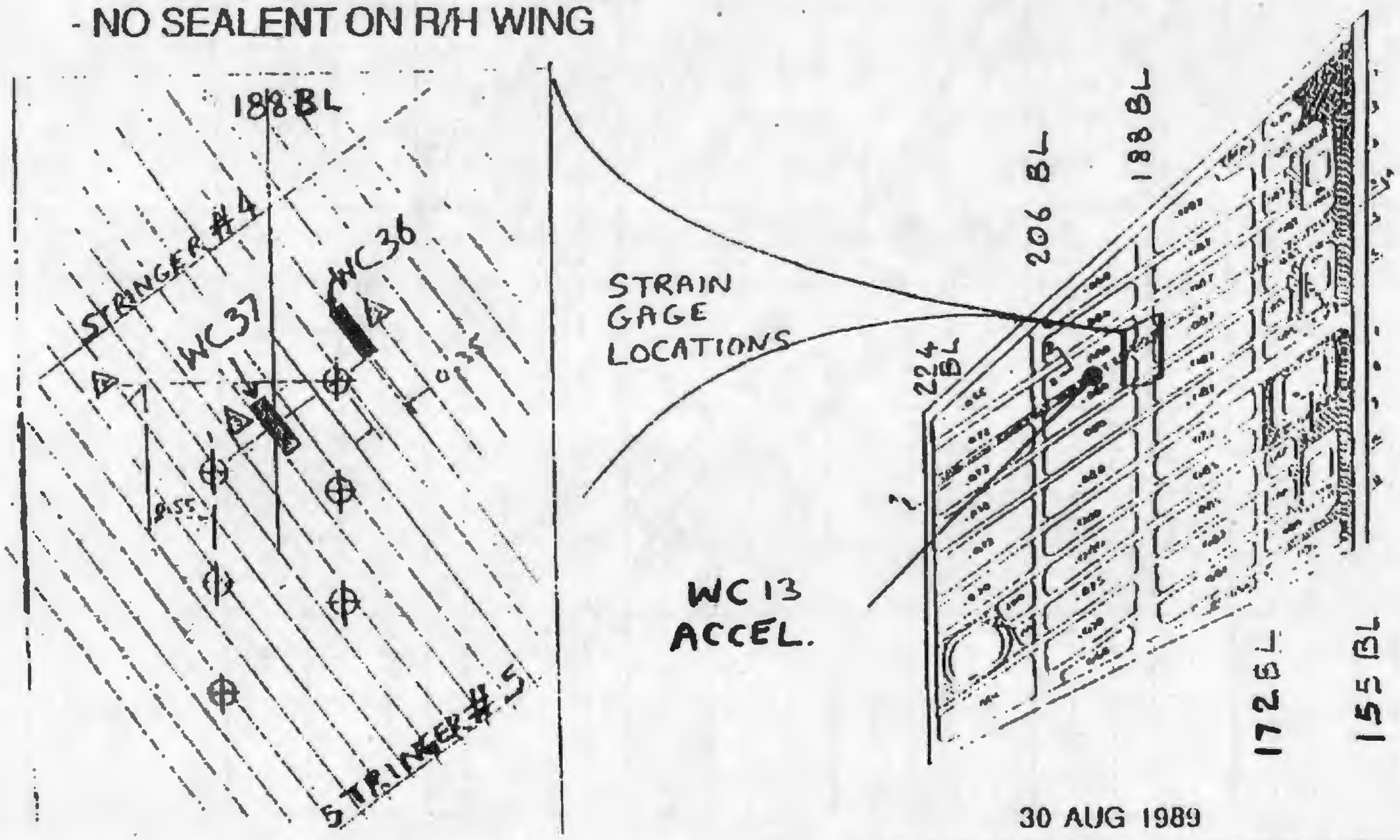

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Figure 7. Flight Test Instrumentation

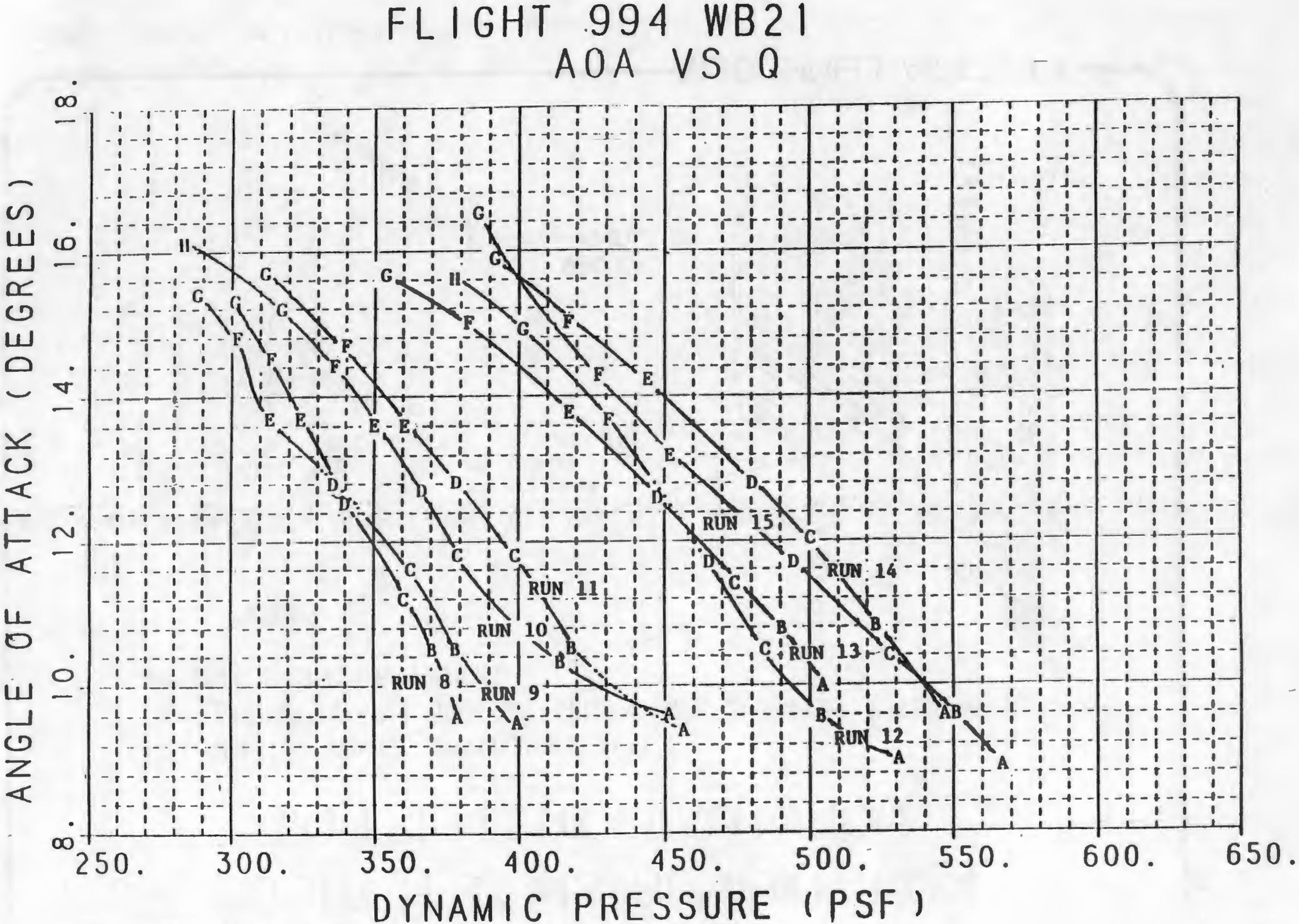


Figure 8. AOA vs Dynamic Pressure for F-15 Flight Conditions

F-15 UPPER OUTER WING SKIN LIFE EXTENSION

FLIGHT DATA PSD OF STRAIN GAGE

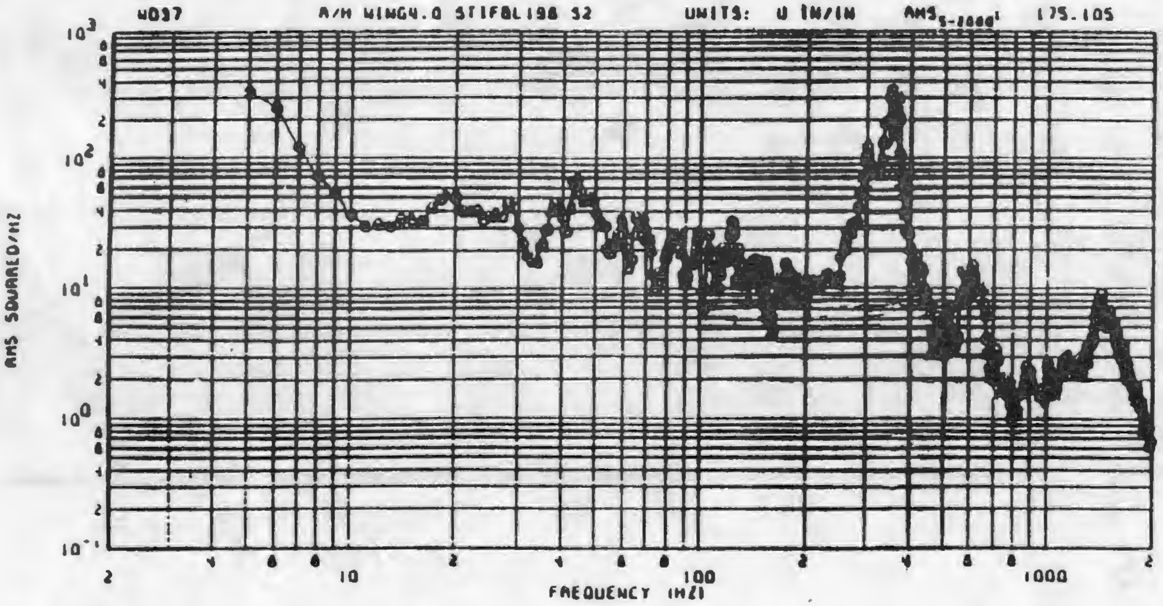


Figure 9. PSD of Strain Gage Flight Data

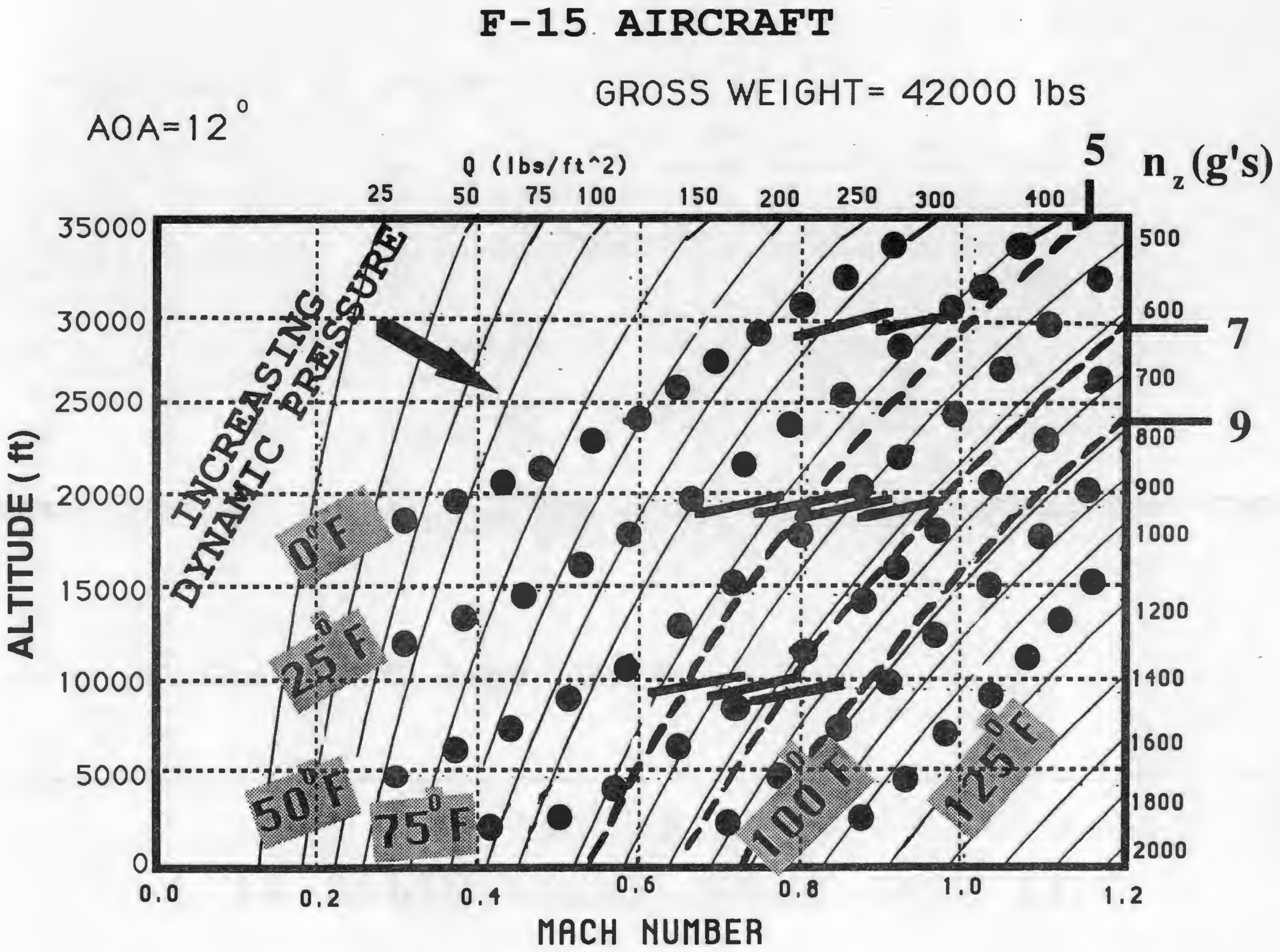


Figure 10. F-15 Flight Characteristics

F-15 UPPER OUTER WING SKIN

TEST CONFIGURATION 1

1980 DAMPING TREATMENT

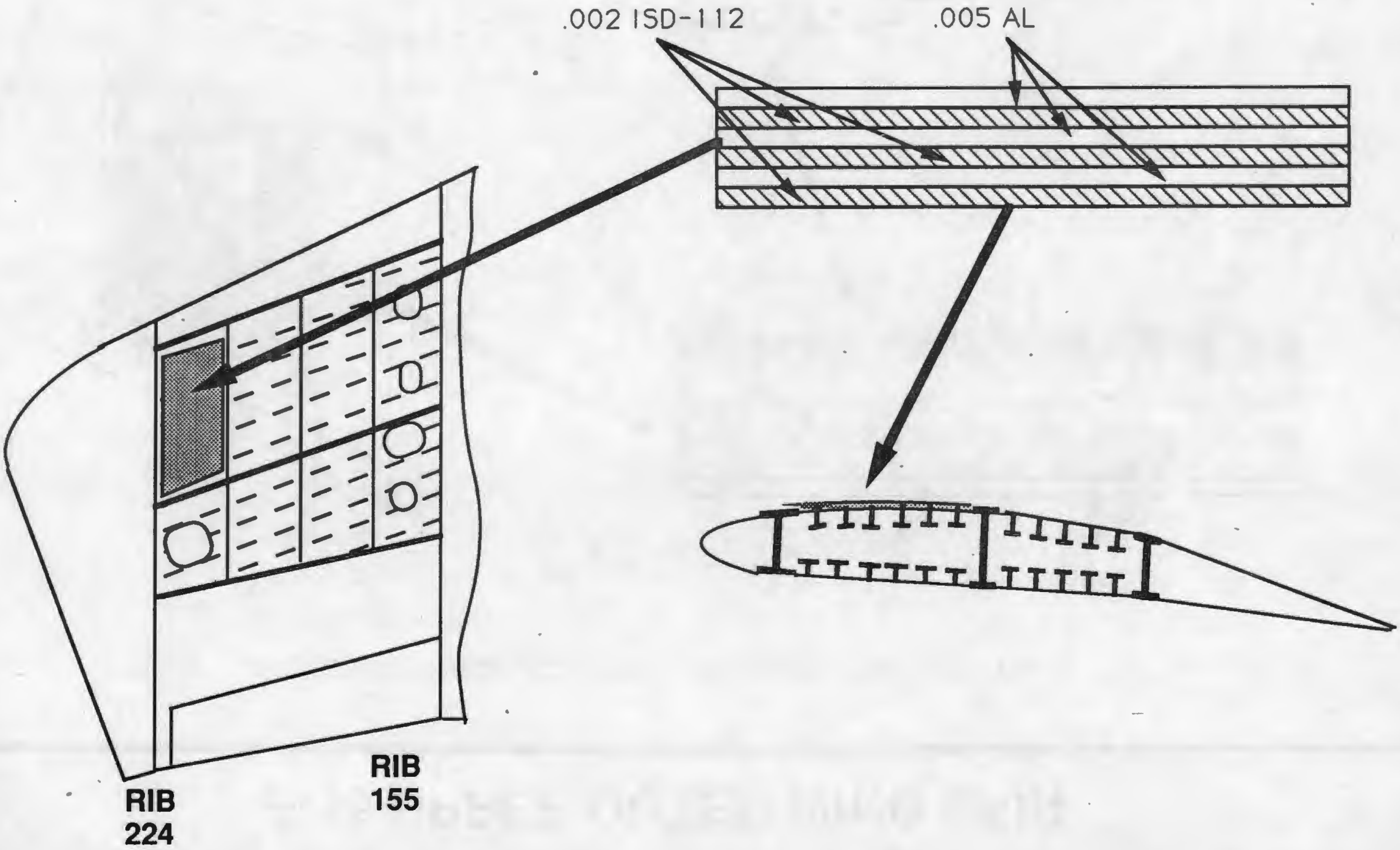


Figure 11. 1980 Damping Treatment

F-15 UPPER OUTER WING SKIN

RECOMMENDED EXTERNAL DAMPING TREATMENT

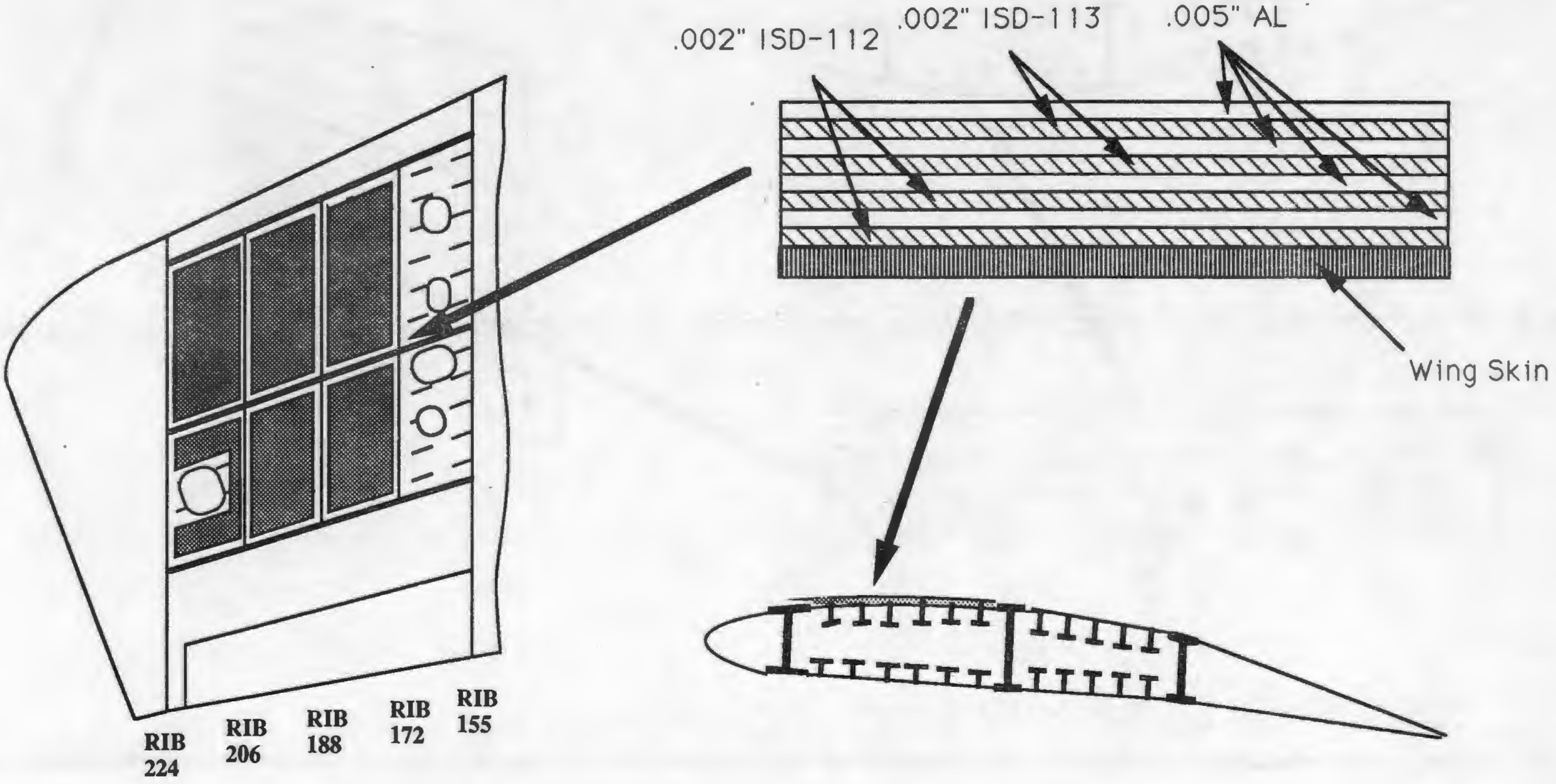
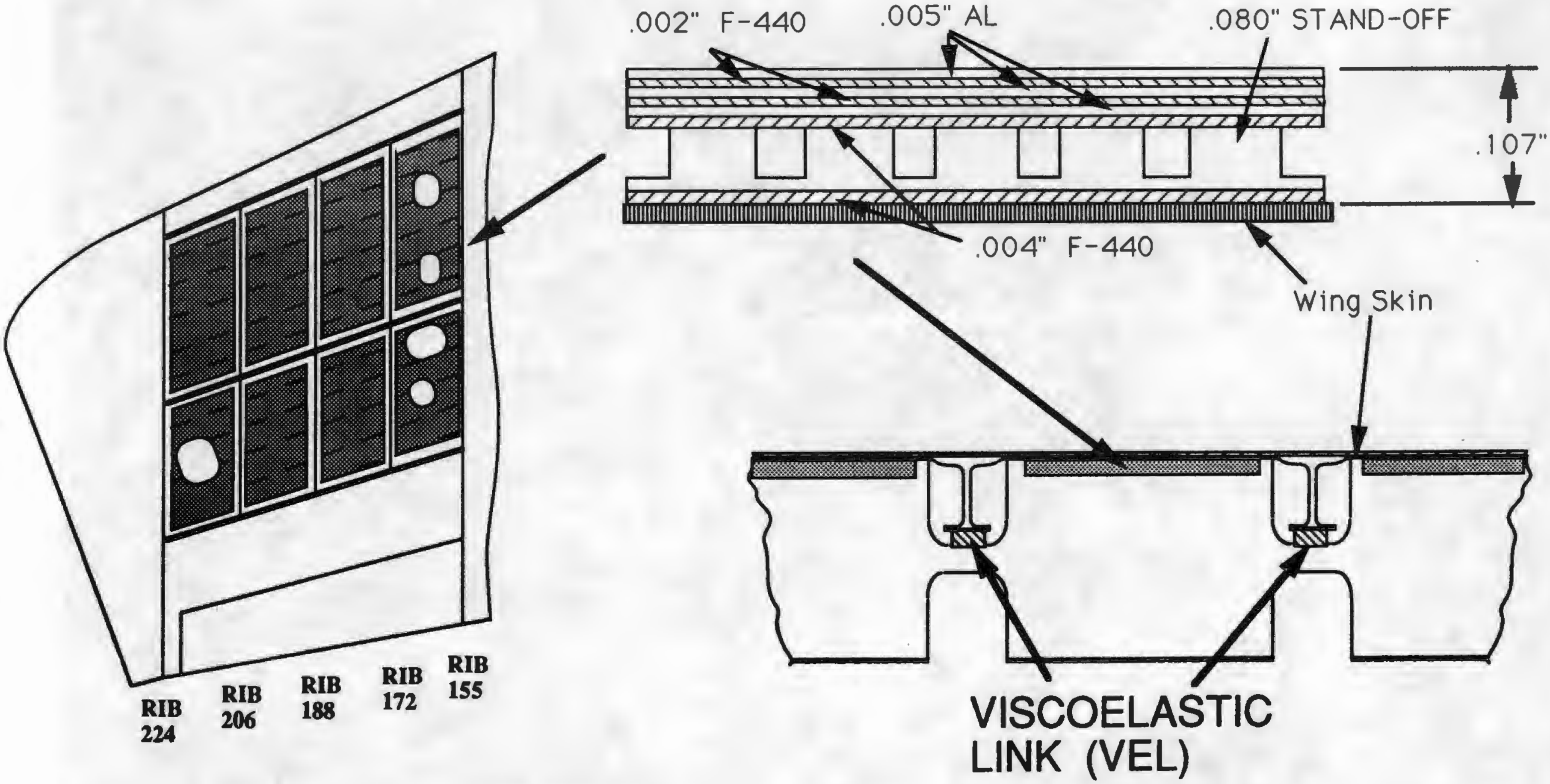


Figure 12. New External Damping Treatment

Figure 13. External Damping Treatment

F-15 UPPER OUTER WING SKIN

RECOMMENDED INTERNAL DAMPING TREATMENT



NOTE: DAMPING TREATMENT APPLIED TO INTERIOR SURFACE OF WING SKIN BETWEEN STIFFENERS.

NOTE: VEL APPLIED IN RIB NOTCH

Figure 14. New Internal Damping Treatment

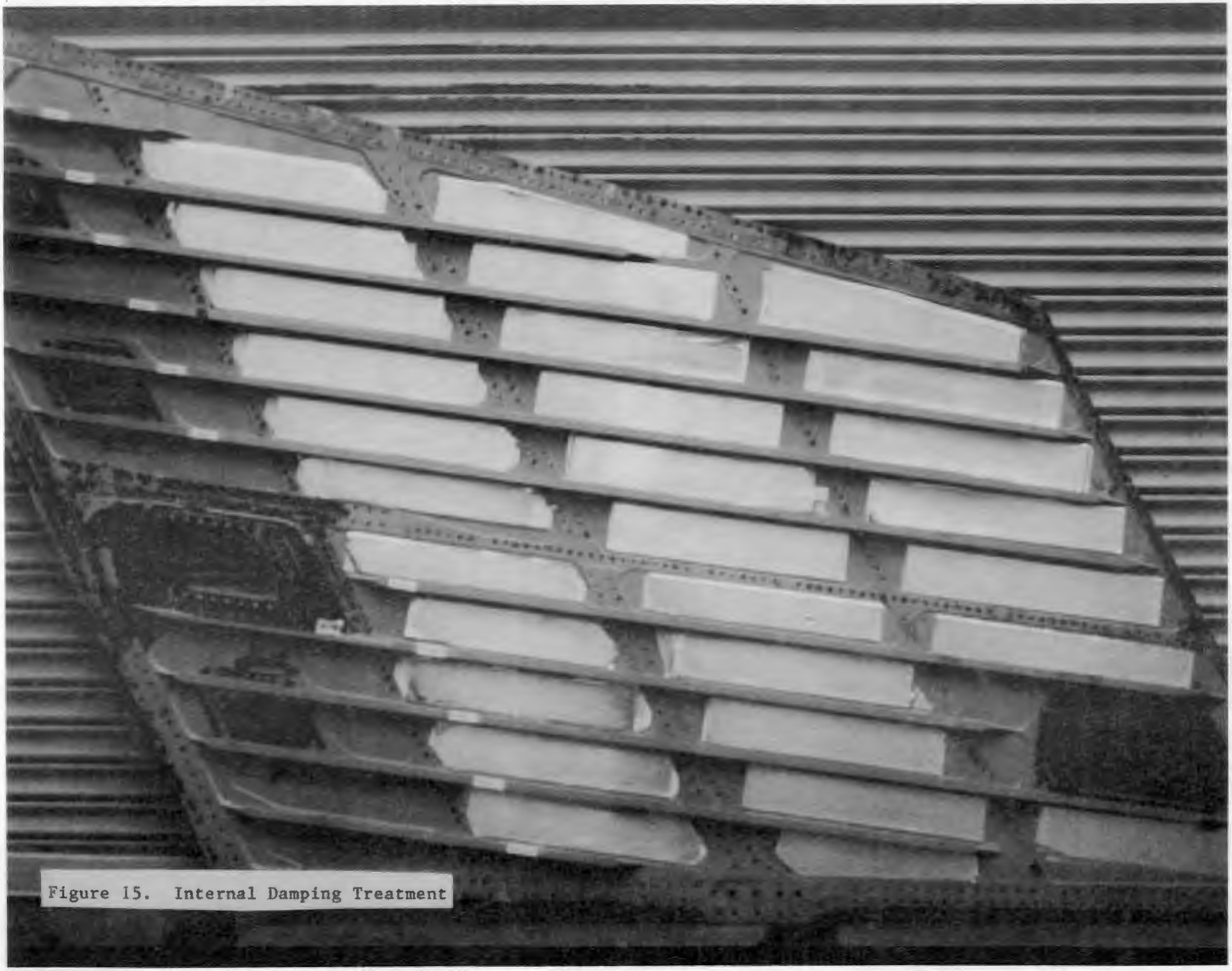


Figure 15. Internal Damping Treatment

Figure 16. Placement of VELs

Figure 17. External Treatment Installation

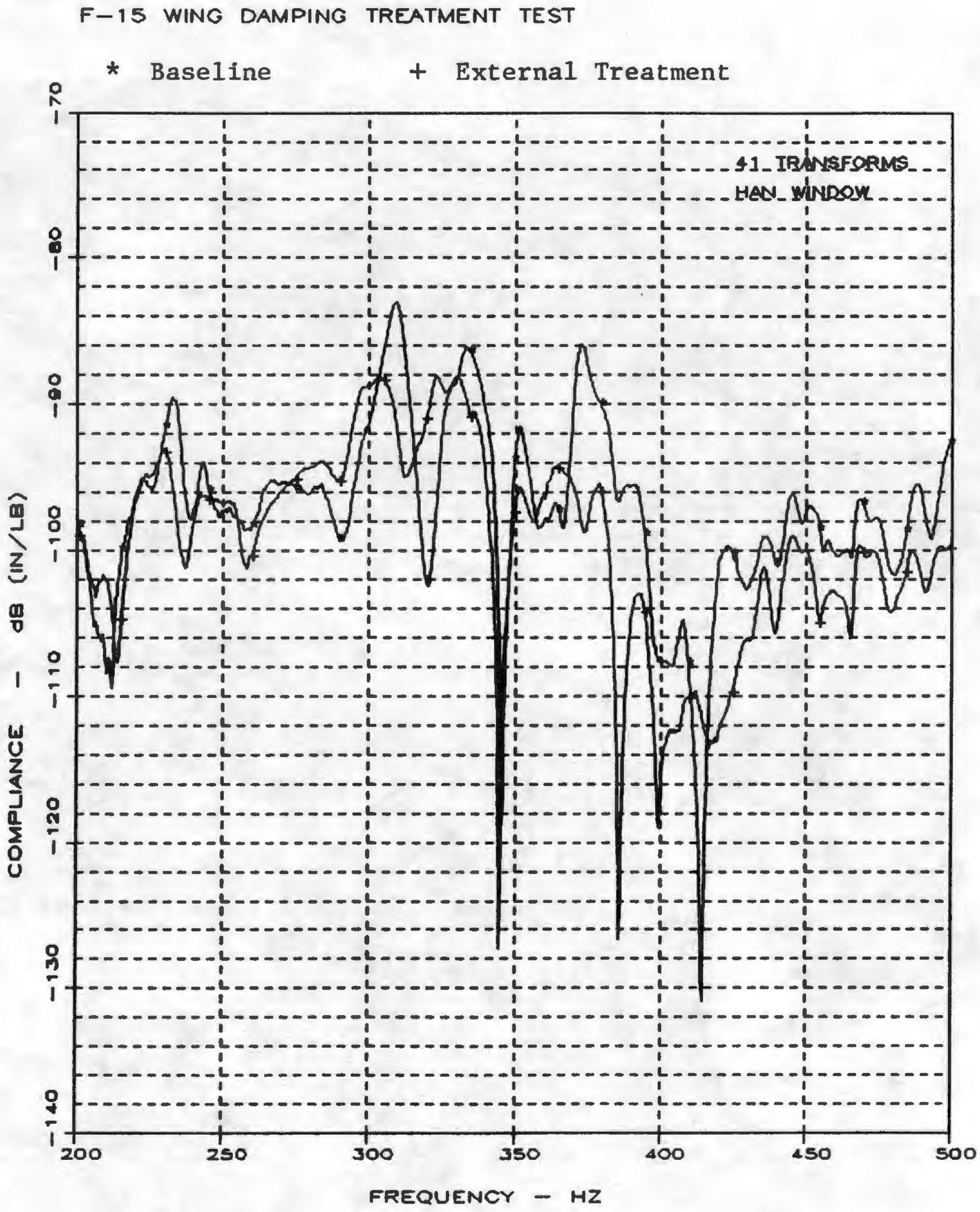


Figure 18. Comparison of Baseline UOWS and Externally Damped UOWS

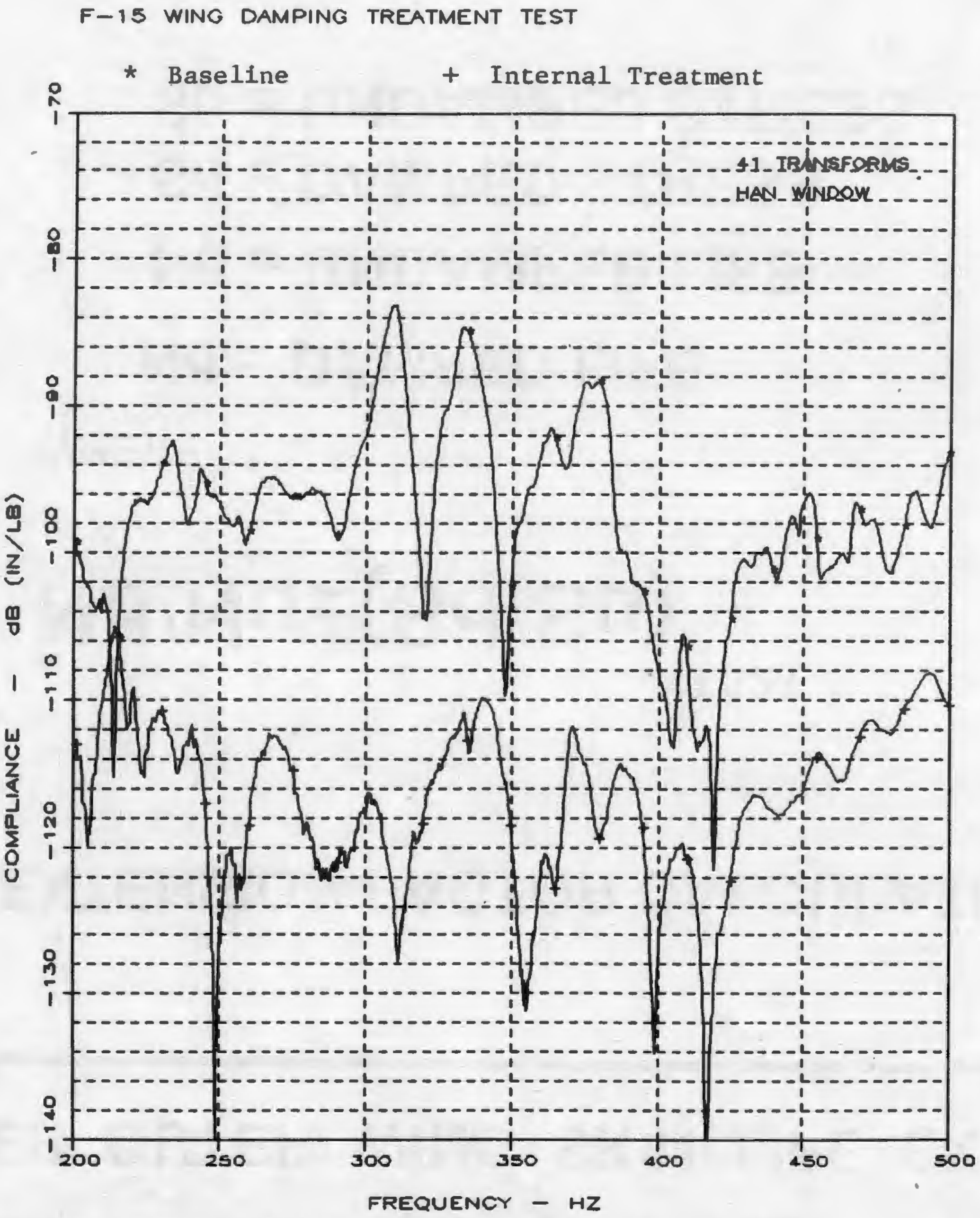


Figure 19. Comparison of Baseline UOWS and Internally Damped UOWS

F-15 UPPER OUTER WING SKIN LIFE EXTENSION

LIFE EXTENSION FACTOR CALCULATION

$$Nd/Nu=(Sd/Su)^{-3.323}$$

WHERE

Nd = DAMPED LIFE
Nu = UNDAMPED LIFE
Sd = DAMPED STRESS
Su = UNDAMPED STRESS

Figure 20. Equation for Life Extension Calculation