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STRUCTURAL MECHANICS RESEARCH AT THE LANGLEY RESEARCH CENTER

BY

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16. Abstract

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ABSTRACT

The contributions of NASA's Langley Research Center in areas of aerospace mechanics are traced from its NACA origins in 1917 to the present. Particular emphasis is given to the developments in structural mechanics technology since 1940. In addition a brief review of some current research topics is discussed as well as anticipated near-term research projects.

STRUCTURAL MECHANICS RESEARCH AT THE LANGLEY RESEARCH CENTER

WENDELL B. STEPHENS

STRUCTURAL MECHANICS RESEARCH AT THE LANGLEY RESEARCH CENTER

The subject of aerospace mechanics is quite broad and many important contributions have been made by Langley engineers and scientists ranging from the design of the NACA cowling in the late 1920's to the supercritical airfoil concept in the early 70's. This presentation however, will be directed toward developments in structural mechanics and consequently, the paper will focus on some of the major developments in the structural analysis and design of aircraft and spacecraft. Except for discussions of a peripheral nature, the contributions of Langley engineers and scientists in aeroelasticity, fluid mechanics, thermoelasticity and material behavior will be bypassed.

QUOTE ON AERONAUTICS

"I HAVE NOT THE SLIGHTEST FAITH IN THE FUTURE OF AERONAUTICS OTHER THAN AERIAL BALLOONING"

LORD KELVIN (C. 1900)

QUOTE ON AERONAUTICS

At the turn of the century many men of science thought that Lord Kelvin's attitude toward aeronautics was correct when he said "I have not the slightest faith in the future of aeronautics other than aerial ballooning." When NACA came into being in 1915 much of the skepticism of the earlier era was swept away with the stunning successes of the Wright Brothers in 1903 and a frenchman, Louis Bleriot, who in 1909 flew across the English channel. Bleriot's monoplane aircraft became a prototype of the industry for almost twenty years. In fact, with the mounting tensions in Europe prior to WWI the European progress was rapid. When the war erupted in 1914 it was reported that France had 1400 airplanes, Germany 1000, Russia 800, Great Britian 400, and the United States 23. Perhaps more important each of these countries had some form of national support for their aeronautics efforts and all had wind tunnels in operation.

NACA — NASA CHARTER

1915

. . . TO SUPERVISE AND DIRECT THE SCIENTIFIC STUDY OF THE PROBLEMS OF FLIGHT, WITH A VIEW TO THEIR PRACTICAL SOLUTION, AND TO DETERMINE THE PROBLEMS WHICH SHOULD BE EXPERIMENTALLY ATTACKED

1958

. . . AERONAUTICAL AND SPACE ACTIVITIES . . . SHALL BE CONDUCTED SO AS TO CONTRIBUTE . . . TO THE EXPANSION OF HUMAN KNOWLEDGE OF PHENONEMA IN THE ATMOSPHERE AND SPACE

NACA-NASA CHARTER

In 1915 President Wilson appointed 12 men to the National Advisory Committee on Aeronautics with the charter shown in the slide. Of these representatives from the government, military and academic institutions, 6 were members of the National Academy of Science. This balance between industrial practicality and academic foresight was maintained throughout NACA's existence. For 43 years dedicated and renowned members of this committee guided and directed NACA without pay.

In 1958, NACA became the nucleus of a new organization, the National Aeronautics and Space Administration, which was created to meet the new national challenge of what was called the "space race". The new organization was designed to coordinate in a rational manner the talents of the American scientific community.

FACTORS LEADING TO SUCCESS

- FACILITIES
- PEOPLE
- EXCELLENCE

FACTORS LEADING TO SUCCESS

It is important to understand that outstanding men of aeronautics and science were members of the advisory committee and that they gave enlightened leadership to its goals. The philosophy of these types of personalities guided NACA and later NASA to build facilities which would meet not only the state-of-the-art technology but which would anticipate the future directions of the technologies. Examples of this would include building a full-scale wind tunnel in 1931, a "full speed" (or so it was hoped) 800 km/hr wind tunnel in 1936, a blow down tunnel in the mid-thirties to study stream flows up to 1200 km/hr, the new NASA centers for research, the acoustic laboratory in the 70's, and this year the National Transonic tunnel. These facilities have created an atmosphere which has attracted many outstanding engineers and scientists and has helped the development of America's excellence in aerospace, in general, and more specifically excellence at NACA and NASA. This excellence is demonstrated by notable achievements. Collier awards for the outstanding contribution to aircraft development were won by NACA for the NACA cowling, deicing techniques, and breaking the sonic barrier. Other achievements include the development and use of test pilots, instrumentation for scientific study, the Whitcomb area-rule for reducing transonic drag on an aircraft, the early NACA airfoil and now the super-critical airfoil, the 1958 X-15 flight of M = 6.7, as well as the Gemini, Mercury, Apollo, Viking and space shuttle programs.

THE DEVELOPMENT OF STRUCTURAL MECHANICS AT NACA – NASA

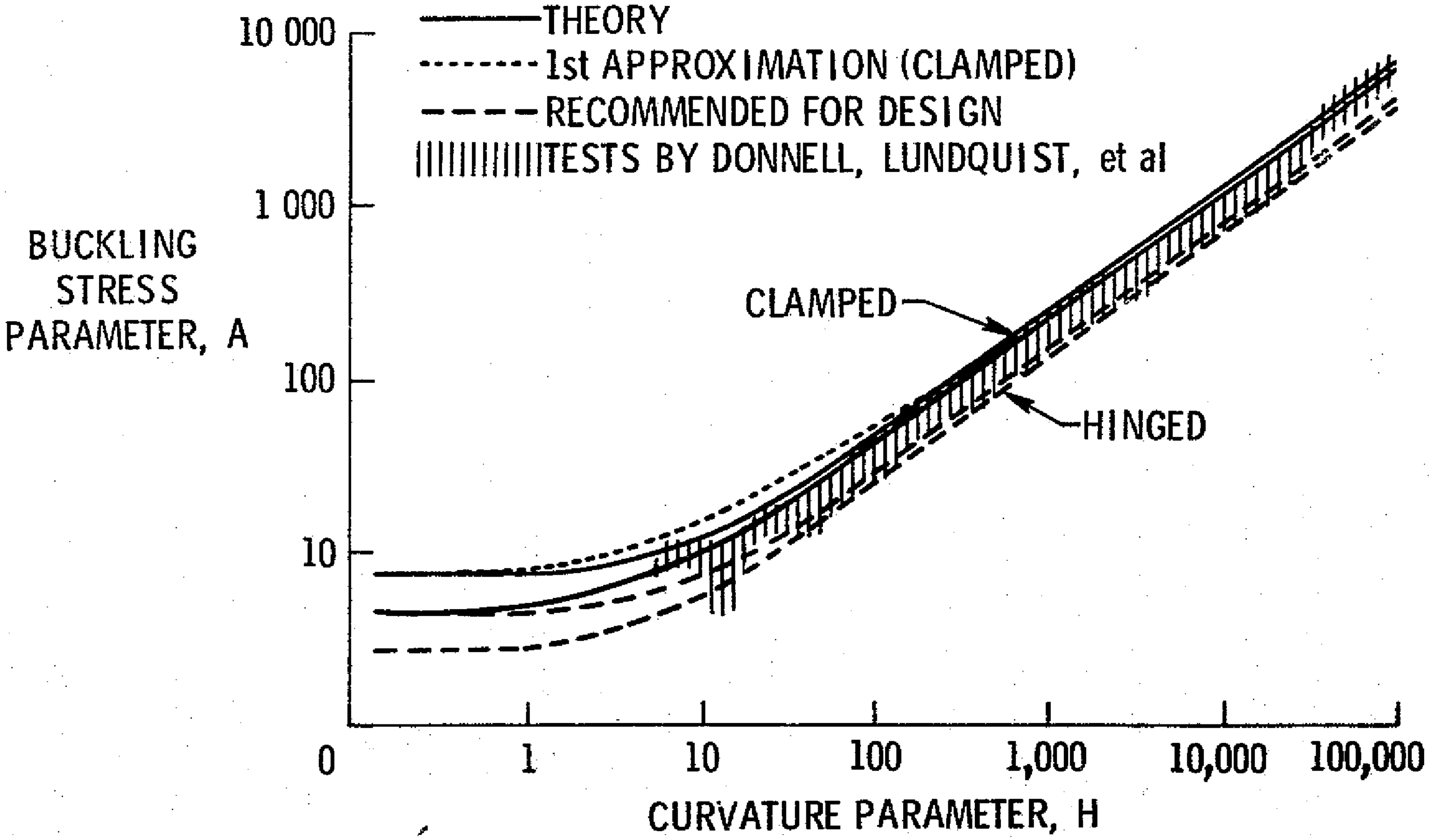
- THE PAST
  - THE BEGINNING YEARS, 1917 - 1939
  - THE WAR AND POST-WAR YEARS, 1939 - 1958
  - THE AEROSPACE YEARS, 1958 - PRESENT
- THE PRESENT
- THE FUTURE

THE DEVELOPMENT OF STRUCTURAL MECHANICS AT NACA-NASA

Some of the origin and philosophy of NACA and NASA has been covered in a very general manner. However, it is necessary now to outline more specifically how structural mechanics has contributed to the development of aircraft and spacecraft. These contributions have not been separated in time from the national consciousness. NACA came into being as a reaction to the war in Europe in 1915 with Langley selected as its Research Laboratory in 1917. It was not until the late 20's that significant contributions were made and those contributions were primarily the result of the wind tunnel and propulsion system research. During the early months of WWII the structures laboratory emerged at Langley and this was followed by Langley's "Golden Years of Structural Mechanics". This era was followed by the massive support of the space program. This latter period, represents a second golden era for structural mechanics. In retrospect the first period (1939-1958), at least at Langley, was characterized by broad experimental investigation which led to the development of sound theoretical and mathematical approaches. The second era was characterized by the emergence of computer automation and numerical techniques along with scale model and full-scale model testing of spacecraft for which there was no previous experience or criteria.

Also, a description of some of the current research thrusts at Langley will be presented which are followed by some anticipated programs and challenges of the future. In the past the World Wars and cold-war conflicts and pressures have led to vigorous support of aerospace research. Now one questions what will be the next impetus to research; environmental concerns could hamper this effort as in the case of the SST program or could give it new directions by demanding the development of the technology to harness solar energy through large orbiting space structures.

DONNELL (CAL TECH)—STABILITY OF THIN WALLED TUBES UNDER TORSION

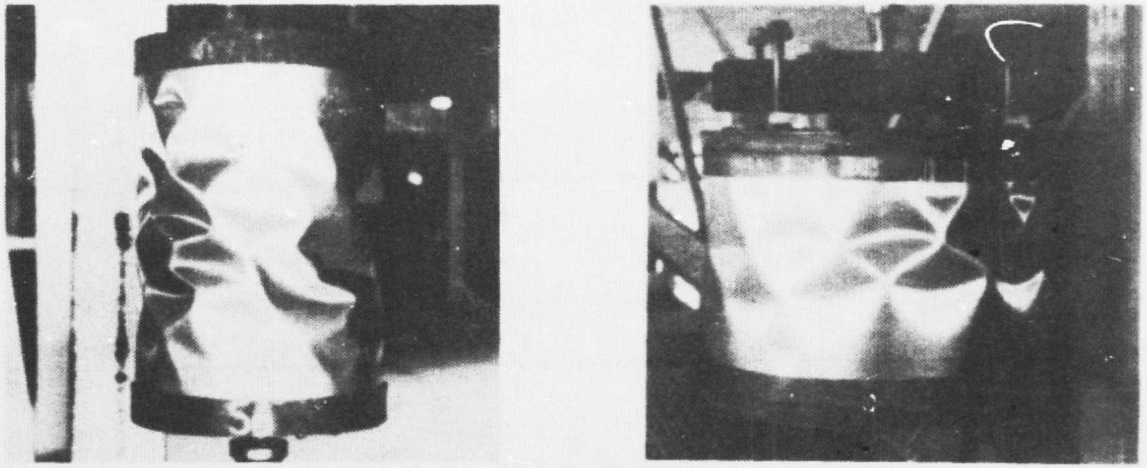


REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

DONNELL (CALTECH)-STABILITY OF THIN WALLED TUBES UNDER TORSION

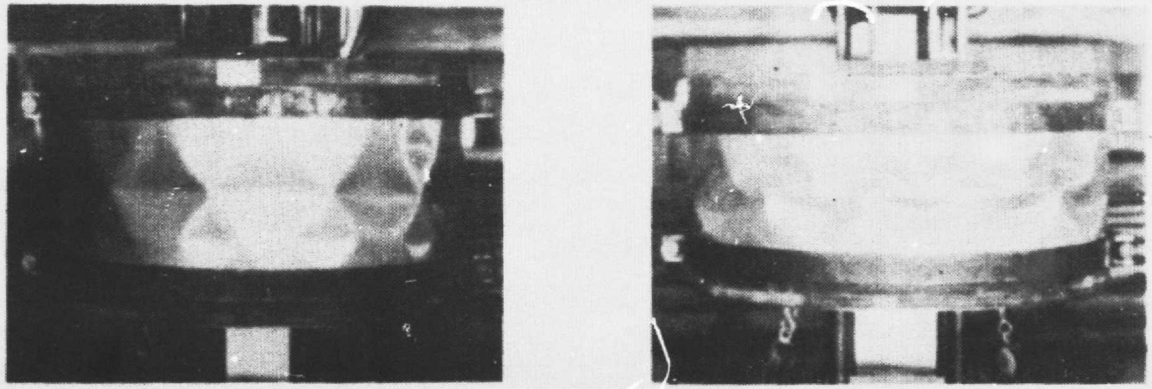
Structural mechanics as we know it today in the aerospace disciplines did not begin to emerge until the mid-30's. In 1934 Donnell, under contract to NACA, wrote one of the first landmark reports. This NACA TR included his now well known shell theory as well as the results of some 50 tests which he conducted. Here are his comparisons between theory and experiment in terms of the geometric parameter, H. A is a nondimensional measure of stress. The H, parameter is now generally known as the Batdorf Z parameter. The experimental results are shown in the shaded region some of which are attributed to NACA's Lundquist. The appearance of this paper in the mid-30's coincided with growing concerns in the aircraft industry about the structural response of airplanes at high speeds and with increased size.

LUNDQUIST, TESTS OF CYLINDERS IN COMPRESSION, 1933



(a) $r = 7.5$ in.; $\frac{l}{r} = 2.50$; $\frac{r}{t} = 646$

(b) $r = 15.0$ in.; $\frac{l}{r} = 1.00$; $\frac{r}{t} = 920$



(c) $r = 15.0$ in.; $\frac{l}{r} = 0.63$; $\frac{r}{t} = 1,415$

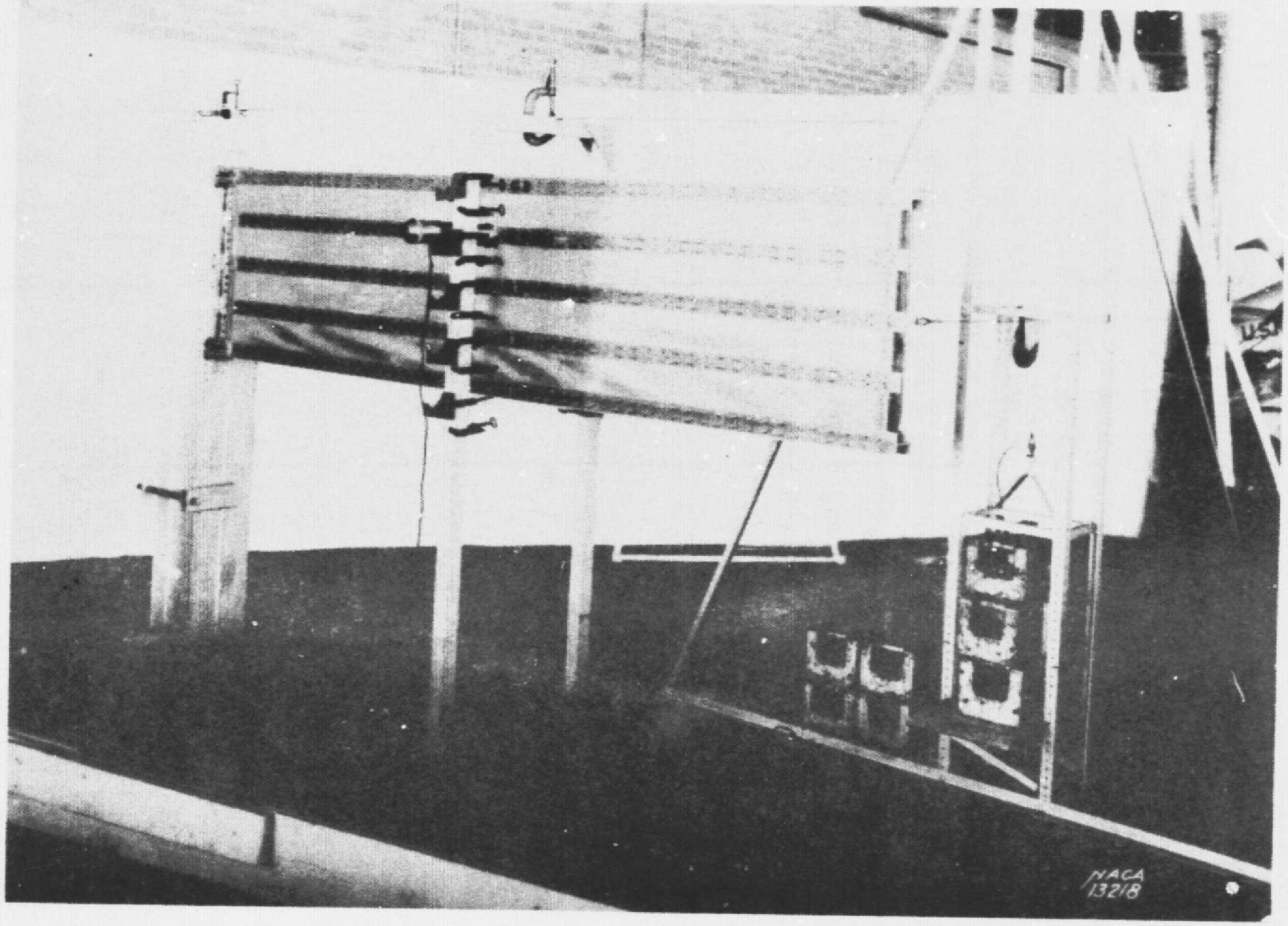
(d) $r = 15.0$ in.; $\frac{l}{r} = 0.50$; $\frac{r}{t} = 711$

LUNDQUIST, TESTS OF CYLINDERS IN COMPRESSION, 1933

Two outstanding NACA men in structural mechanics emerged in the 1930's. The first was Eugene Lundquist, who as early as 1933 addressed the problem of cylinder buckling and the correlation with theory. He also did considerable work in areas of elliptic cylinder buckling, calculating stresses in beam flanges and presented numerous papers on plate buckling phenomena. In reviewing some of his early work it is interesting that the compression loading was applied manually by adding weights to a cable-pulley system.

The work of Donnell and Lundquist was in response to an NACA observation in 1934 that "the coming of the internally braced monoplane was delayed for a number of years by the lack of a proper type of construction. In modern high speed airplanes the increased strength and stiffness required in the structure are obtained by use of stressed-skin construction."

KUHN, SHEAR DEFORMATION OF SEMIMONOCOQUE BEAMS, 193



KUHN, SHEAR DEFORMATION OF SEMIMONOGUE BEAM, 1937

In 1937 another NACA man in structural mechanics, Paul Kuhn, began contributing to the development of structural mechanics. His primary concern as shown in this 1937 photo of an early experimental study of shear deformation was in developing theories to describe shear flow, diagonal tension, and shear lag and later in his career he made important contribution in the area of fatigue phenomena. He wrote a textbook on "STRESSES IN AIRCRAFT AND SHELL STRUCTURES" which was published in 1956 and which became a standard at many universities. This photo again shows the state of the art in 1937. The concentrated load on the longitudinal straps is applied by means of manually applied weights and a Tuckerman optical strain gage is used to measure the strain.

In 1937 a new challenge to structural mechanics technology surfaced. An NACA report read, "The rapidly increasing size of aircraft structures is forcing designers to rely increasingly, for economic reasons, on mathematical stress analysis rather than on static tests. It is well known that the classic methods of analysis are not always sufficiently accurate and efforts are being made to correct these methods." To meet this challenge in 1937 a NACA reorganization recognized "AIRCRAFT STRUCTURES" as one of the 6 major technical committees and structural mechanics at Langley had come of age. Its leaders would be Lundquist and Kuhn.

THE ENGINEERING LABORATORIES OF THE WAR AND POST—WAR YEARS

1939	STRUCTURES RESEARCH LABORATORY
	16-FT. HIGH-SPEED TUNNEL
	STABILITY TUNNEL
	AMES RESEARCH CENTER
1940	LEWIS RESEARCH CENTER
	LOW TURBULENCE PRESSURE TUNNEL
1943	INTEGRATED APPROACH TO TRANSONIC FLIGHT AND JET PROPULSION
	LOW DRAG AIRFOIL FOR TRANSONIC SPEEDS
	SWEPTBACK WING
1945	WALLOPS ISLAND (PARD), PILOTLESS AIRCRAFT RESEARCH DIVISION
1947	EDWARDS FLIGHT RESEARCH CENTER

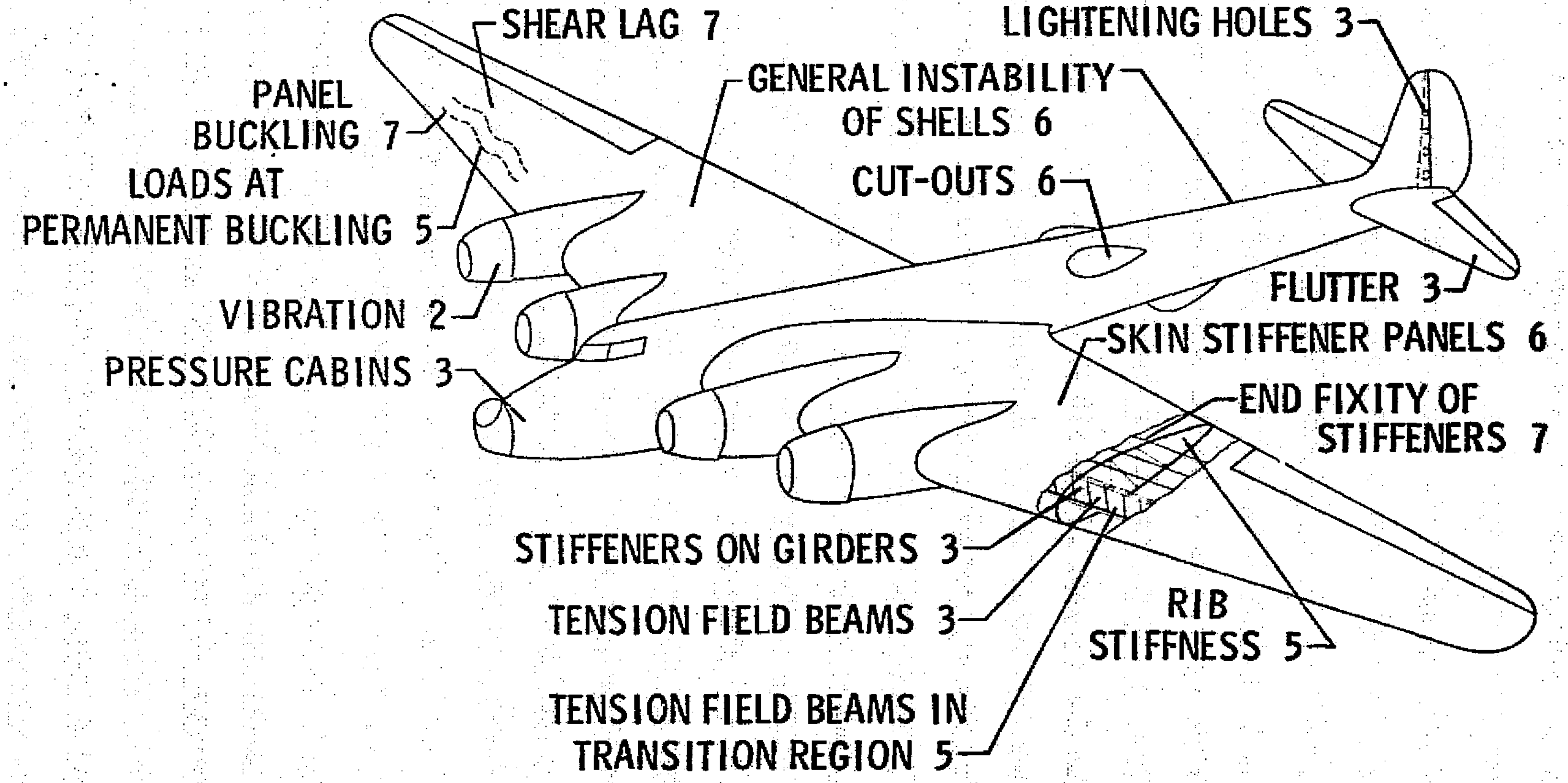
THE ENGINEERING LABORATORIES OF THE WAR AND POST-WAR YEARS

In 1939 the pressures of the second world war led to a vigorous expansion of NACA. Up to this time Langley had been the only NACA Laboratory. In 1939 NACA had about 523 employees less than half of whom (204) were technical people. As late as Oct., 1940 only 10 men were working on airplane structures. At the war's end Langley had about 3200 of NACA's 6800 employees. During these years many of the key people at Langley were transferred, of course, to staff the new centers. But the story in structures revolved around Lundquist, the Division Chief and Kuhn, the assistant Division Chief. By the end of the war the staff included many outstanding people some of whom are now in industry and at Universities. Briefly, some of the more easily recognizable names include Roger Anderson, Samuel Batdorf, Bernard Budiansky, Norris Dow, John Duberg, John Hedgepeth, Richard Heldenfels, John Houbolt, Joseph Kotanchik, Edwin Kruszewski, Charles Libove, Roger Peters, James Peterson, Richard Pride, Lyell Sanders, Paul Seide, and Manuel Stein.

By confining this presentation to Structural Mechanics I bypass many important contributions in related areas such as the aeroelasticity research by Theodorsen and the flutter work by Garrick, who is this year's Von Karman lecturer. Also as shown on this slide for 1943 is the plan which was devised to combine the jet propulsion research with supersonic flight. This project culminated on Oct. 14, 1947 at Edward Flight Research Center in the flight of the X-1 research plane through the sonic barrier. John Stack at Langley along with 2 others won the Collier Trophy for his contribution in the conception of the program. I will also mention in passing that in 1951 Richard Whitcomb developed the area-rule principle or "Coke-Bottle" shaped fuselage to reduce drag at transonic speeds thereby improving performance as much as 25% with seemingly subtle configuration changes. He followed this in the early 70's with the development of the supercritical airfoil which was still another outstanding technical achievement.

SUGGESTED STRUCTURAL RESEARCH PROGRAM

REDUCTION OF TEST DATA TO STANDARD 5



FUTURE DEVELOPMENTS: PLASTICS 6, LOW DENSITY MATERIALS 5

SUGGESTED STRUCTURAL RESEARCH PROGRAM

This slide represents the results of a survey taken among aircraft companies in 1940 to determine the areas which they felt needed further research. The numbers indicate the number of companies requesting that further research be devoted to a particular problem area. At the beginning of the war there was little theoretical background in the problem areas shown here, no design charts or criteria, little experimental data and practically no experience to guide the designer's judgement. By the end of the war each of the research areas had been studied at least experimentally and some had been reduced to a firm theoretical foundation.

CHANGES IN AIRCRAFT DESIGN

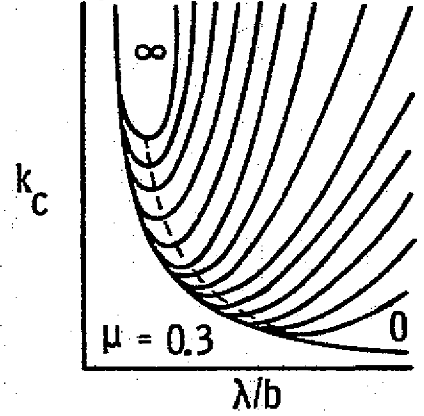
- LARGER AIRCRAFT
- HIGHER SPEEDS
- HIGH AND LOW ASPECT WINGS
- SWEPT AND UNSWEPT WING
- THIN WING - THICK SKIN
- SEMIMONOCOQUE CONSTRUCTION
- STRUCTURAL LIFETIME ANALYSIS
- MORE FLEXIBLE AIRCRAFT

CHANGES IN AIRCRAFT DESIGN

During the period from 1940 to 1958 dramatic changes took place in aircraft structures. The aircraft flew higher, faster and further and the loads on the structure increased sharply. Aerodynamicists had shown that considerable gains could be realized with thin wings. This meant that the airfoil skins would have to be thicker and carry a substantial amount of the load. Also, analysis was made more difficult by the use of low aspect ratio wings or delta wings. No longer would simplified approaches tending to beam or plate theory be used but deflection techniques using beam-and plate-like elements had to be developed. The fuselage was semimonocoque and the influence of cutouts on the load carrying capability needed to be assessed. Fatigue, aging and thermal effects in the fifties were problems that constantly needed attention. The aircraft structures in WWII and afterward were more flexible than the smaller structure from prior years and the design therefore much more difficult.

TECHNICAL HIGHLIGHTS FROM 1940–1948

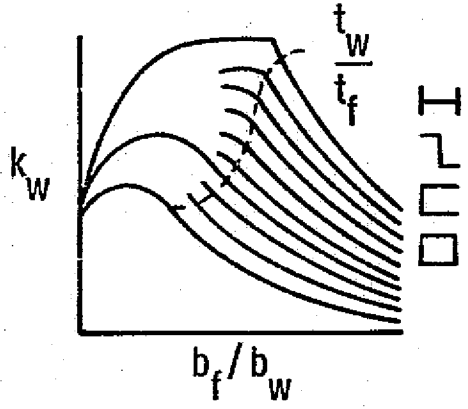
PLATE BUCKLING, LUNDQUIST & STOWELL, 1942



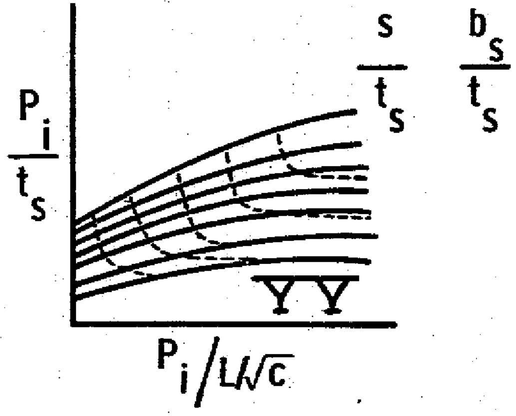
CYLINDER & PANEL BUCKLING, BATDORF, SCHILDCROUT, STEIN, 1943

$$D\nabla^4 w + \frac{Et}{r^2}\nabla^{-4}\frac{\partial^4 w}{\partial x^4} + \sigma_x t\frac{\partial^2 w}{\partial x^2} = 0$$

EDGE RESTRAINT, KROLL, FISHER, HEIMERL, 1944



PANEL DESIGN CHART, DOW, HICKMAN, 1948



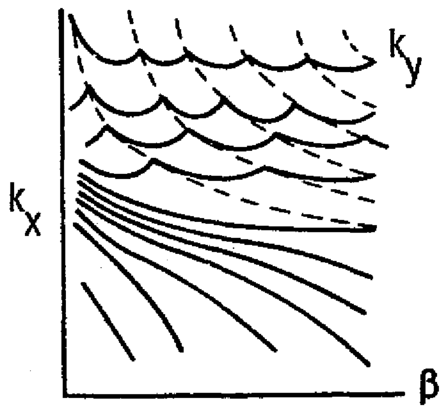
TECHNICAL HIGHLIGHTS FROM 1940-1948

The next 3 slides show the evolution of aircraft research and some rather randomly selected highlights from the vast amount of work done during those years. The first slide shows some of the early plate buckling studies by Lundquist and Stowell. The work was greatly extended by Batdorf a few years later when he modified the Donnell shell equations using the inverse operator. With this 4th order equation and by assuming the harmonic wave number varied continuously he, along with Stein and Schildcrout, was able to solve a large number of plate, curved panel and cylinder problems under various load contions. The minimum weight design charts of Dow and Hickman represented a major effort during this period.

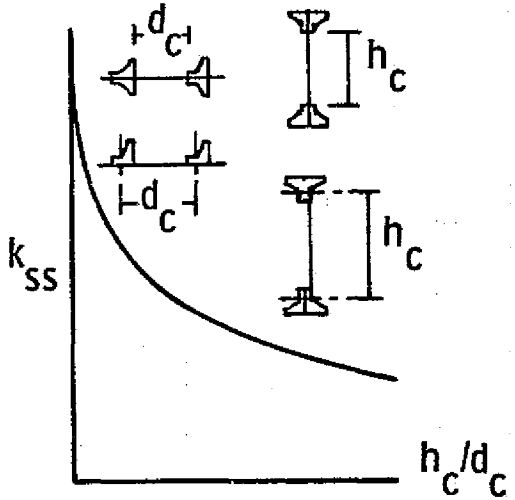
Design studies such as the ones on the bottom half of the slide represented Langley's largest effort during the war years. In many cases the design charts were based on experimental data. The experimental programs were broad enough to cover the full range of design requirements. The data were reduced to design charts which would lead to rational and rapid optimum designs for a variety of stiffener configurations. As an example of a design study, the hat-stiffened panel was first used in the B-36 long range bomber. Since there were no data available for this stiffener, about 700 hat-stiffened panels were tested at Langley for this bomber program alone and the results transmitted daily to the Consolidated Aircraft Co. Smaller similar programs were conducted with other aircraft companies.

TECHNICAL HIGHLIGHTS FROM 1945–1955

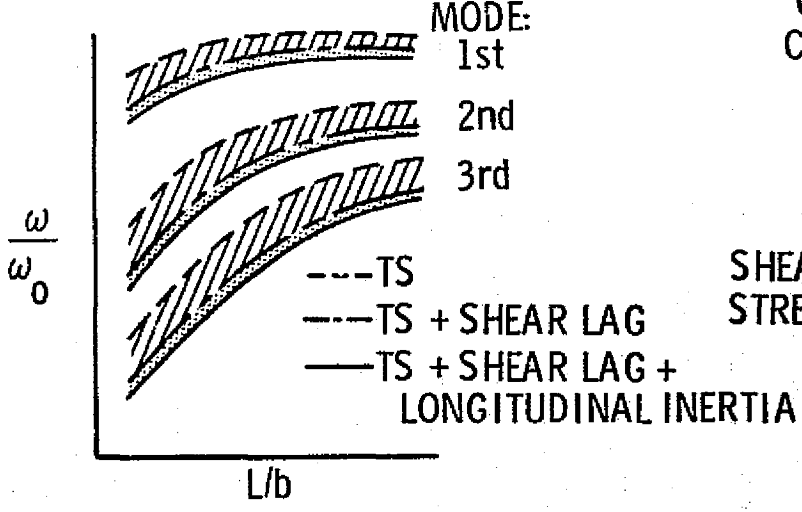
PLATE BUCKLING, LIBOVE, STEIN, 1946



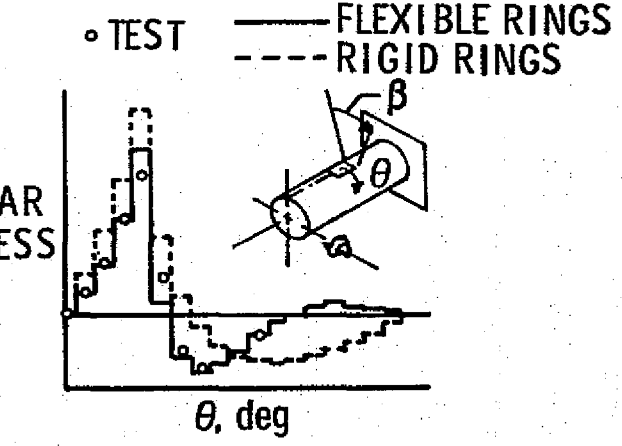
DIAGONAL TENSION, KUHN, 1952



TUBULAR BEAM VIBRATION, BUDIANSKY, KRUSZEWSKI, 1952



CUTOUTS IN SEMIMONOCOQUE CYLINDERS, McCOMB, LOW, 1955

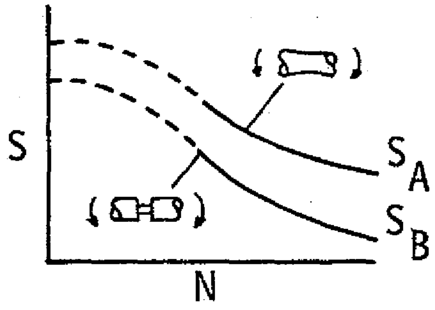


TECHNICAL HIGHLIGHTS FROM 1945-1955

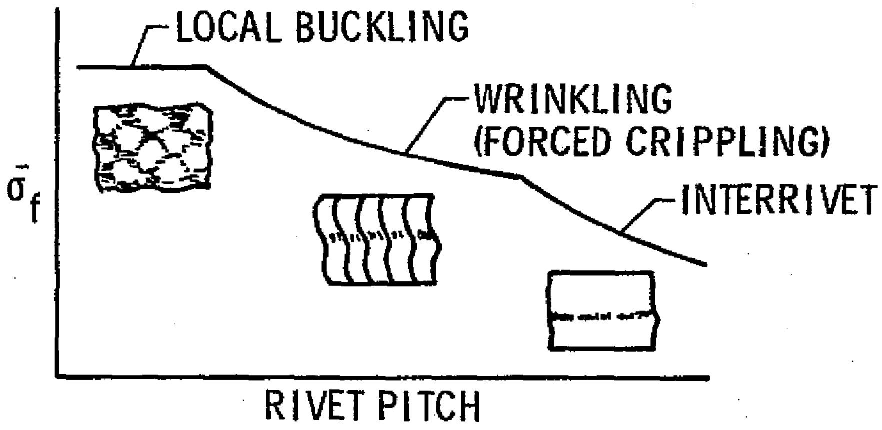
Advances in theory were particularly rapid this period. Analysis of combined loads on plates and shell-like structures were studied by Stein and Libove. Kuhn along with Peterson and Levin summarized his theories on diagonal tension, shear lag and cutouts in shell structure. Budiansky and Kruszewski analytically determined the effects of transverse shear, shear lag and longitudinal inertia on beam vibrations. About this time Batdorf and Budiansky formulated their "slip theory" for plasticity and Stowell and Duberg had made major contributions to the understanding of plastic column buckling. McComb was later cited by Argyris as formulating some of the initial concepts for curved element analysis in his semimonoque cylinder studies.

TECHNICAL HIGHLIGHTS FROM 1952–1958

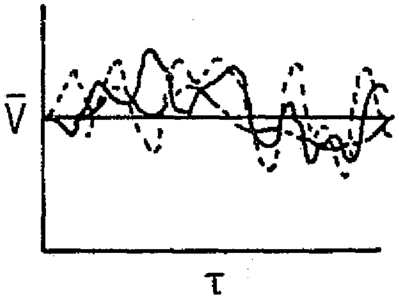
FATIGUE, KUHN, HARDRATH, 1952



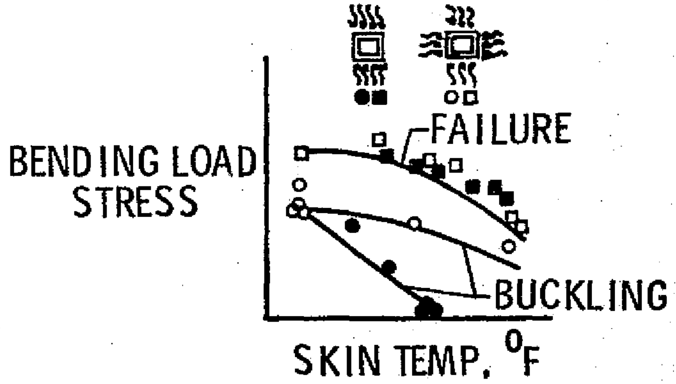
PANEL TESTS, SEMONIAN, PETERSON, 1956



TRANSIENT RESPONSE BEAMS, LEONARD, 1958

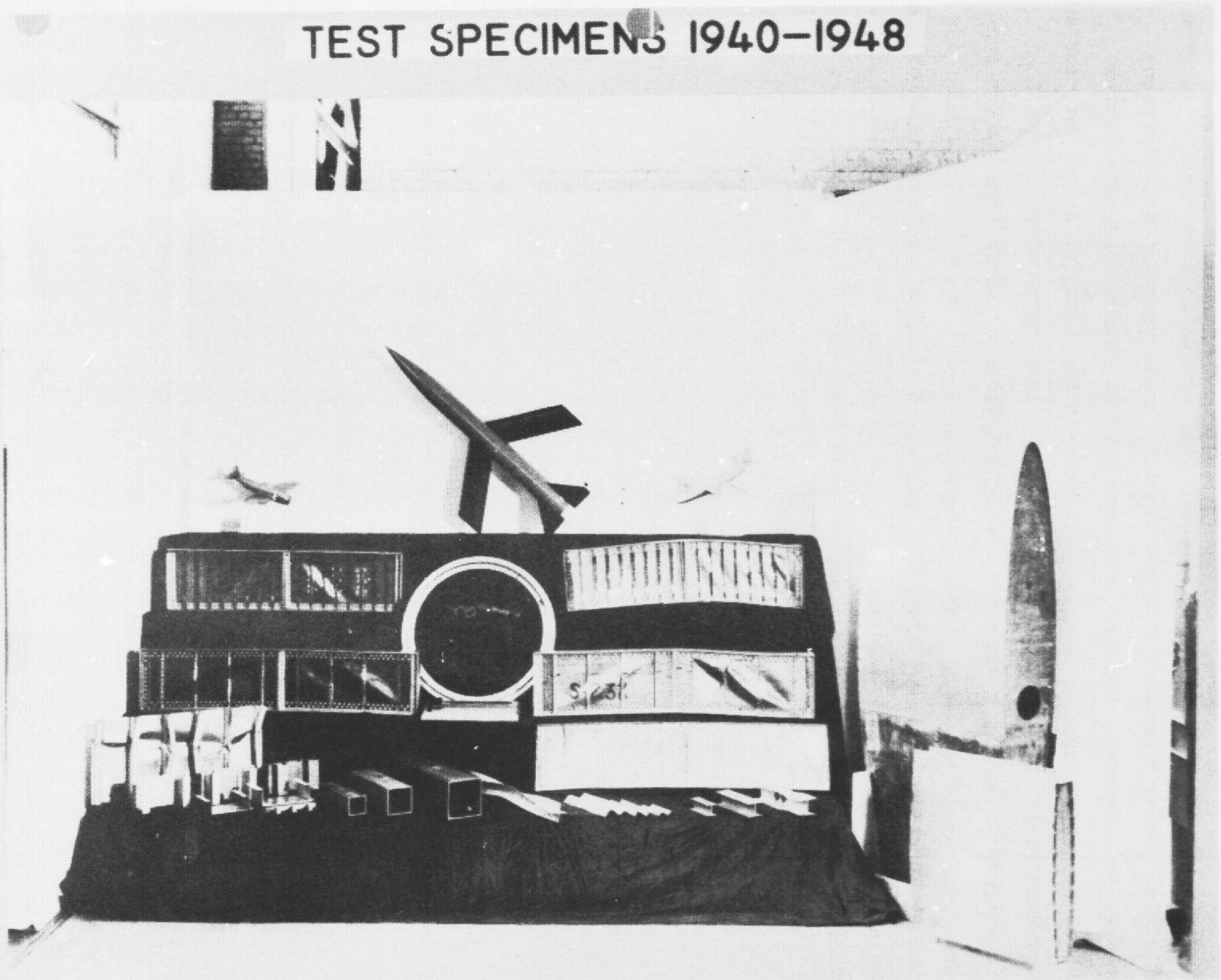


THERMAL BUCKLING, HELDENFELS, 1958



TECHNICAL HIGHLIGHTS FROM 1952-1958

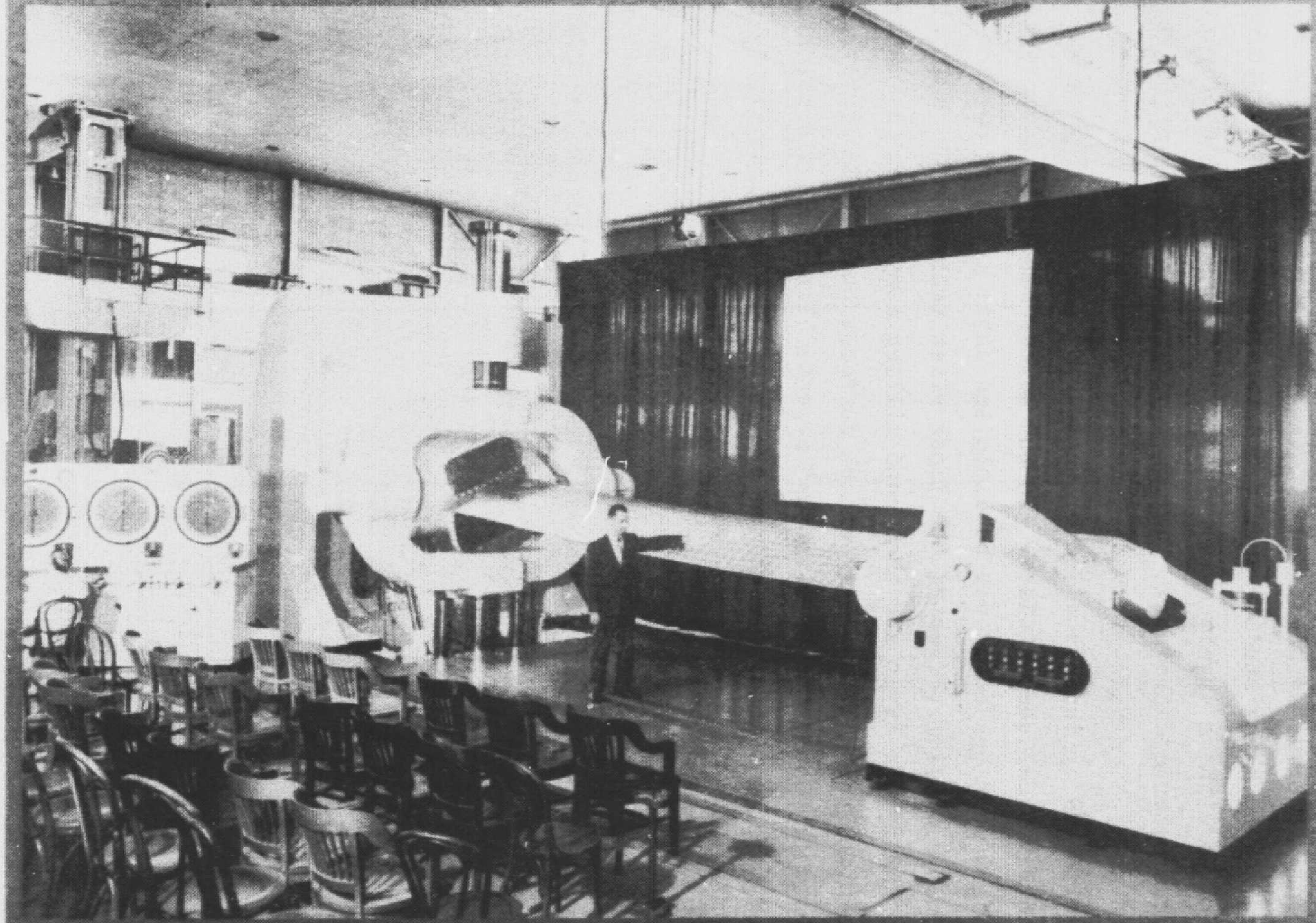
New areas of specialization in structural mechanics continued to surface in the 1950's. Among them were fatigue studies, crack propagation, transient response, and thermoelasticity. Kuhn and Hardrath summarized some of the significant experiments in fatigue phenomena in the early 50's and Peterson and Semonian had performed a series of panel test experiments which showed the various types of buckling that can occur in typical aircraft fabrication processes. By the late 50's problems in spacecraft and supersonic aircraft were demanding attention. Leonard and his colleagues studied a variety of problems associated with transient response, panel flutter, and vibration phenomena. Heldenfels conducted some of the early tests relating to high temperature buckling of wing-like structures.


TEST SPECIMENS 1940–1948
S-231

TEST SPECIMENS 1940-1948

This photograph was taken in 1948 and shows some samples of the extensive experimental work of the war years. Most of the larger specimens deal with the diagonal tension and shear lag studies. The cruciform, Z and square tube were for buckling studies attributed to Stowell, Heimerl, Libove and Lundquist where these specimens were analyzed as a collection of plate elements with various edge constraints. The model of the swept wing aircraft is from experimental studies made of swept wing stiffness. The ring symbolizes some of the stiffened cylinder studies of the period and the wing box was used in the flush rivet fastener studies. In the latter case, the advantages of laminar flow surfaces could not be exploited until the wing surface could be made smooth. Langley perfected the flush rivet technique which involved counter sinking the rivet and then hand milling away the excess material. This technique produced not only smooth surfaces but tighter rivets and a structure which could better withstand repeated loads and vibrations. The rib stiffened panel was used in combined pressure and shear load tests.

NACA COMBINED LOAD TESTING MACHINE



NACA COMBINED LOAD TESTING MACHINE

This photograph shows a wing panel being prepared for a test on the NACA combined load testing machine. The machine was in various stages of construction from 1941 to 1949. This machine can apply and measure loads or moments in all 6 degrees of freedom. The early development of the laboratory was credited to Lundquist's assistant, Joseph Kotanchik, who along with Dow and Peters designed major portions of the unique combined load testing machine. Prior to the completion of the combined loads machine a million pound machine was installed in 1941 with some smaller universal testing machines.

Other test equipment was added in this period also. Langley had built a 2900 foot hydrodynamic tank in 1931 to study seaplane landing behavior. A second 2100 foot tank was added in 1942 to study the dynamics of land planes ditching at sea. In the late 1940's a landing loads track was built. With this facility the landing gear of any aircraft could be tested with the same dynamic loads which would occur in actual landing. By the mid-fifties, arc jet heating facilities were added for the testing and study of thermal protection systems. In 1957 the 9 × 6-ft Thermal Structures Tunnel was added and structural components could be subjected to elevated temperature and aerodynamic pressures. Foland and Heldenfels conducted some outstanding tests in high temperature behavior. In addition radiant heating facilities were conceived and constructed at Langley for some of the first significant tests in that area.

These facilities were expanded somewhat during the space era. Notably the dynamics laboratory was added for the testing of scale model vehicles. Finally in 1972 the Aircraft Noise Reduction Laboratory was added in response to concerns involving noise pollution from aircraft.

In addition to the test facility development Langley engineers became leaders in developing test techniques and equipment. They were forerunners in the development of electrical strain gages and made improvements to the microformer gages. Langley engineers enhanced the development of radiant heating applications and led in the development of arc jets for use in reentry heating simulation. They also led in automating the calculation of principal strains from rosette strains.

AREAS OF RESEARCH DURING THE NACA YEARS

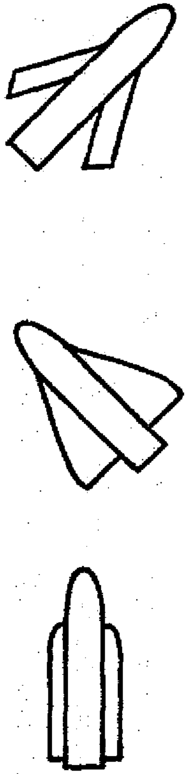
- FUNDAMENTAL SHELL THEORY
- EXTENSIVE EXPERIMENTATION
- DESIGN CHARTS AND HANDBOOKS
- FABRICATION
- FATIGUE, CREEP, STRESS CORROSION
- STRESS CONCENTRATION
- PLASTICITY
- ENERGY METHODS
- STABILITY AND POST-BUCKLING
- VIBRATIONS AND DYNAMICS
- FLUTTER ANALYSIS
- THERMAL EFFECTS
- LANDING GEAR TESTS
- DITCHING OF AIRCRAFT
- MATERIALS

AREAS OF RESEARCH DURING THE NACA YEARS

This review is too brief to cover in any detail the vast contributions which were made in this period. The categories shown here indicate some of the research thrusts of the latter NACA years.

STRUCTURAL MECHANICS RESEARCH CHALLENGES

1958 - PRESENT



- HIGHER LOADS
- SUPERSONIC SPEEDS
- ELEVATED TEMPERATURES
- LOW ASPECT RATIO WING
- THIN WING
- CORRUGATED STRUCTURES
- SANDWICH PANEL
- COMPOSITES
- FLEXIBLE STRUCTURES
- MATED STRUCTURES
- CONCEPTUAL DESIGN
- MULTIDISCIPLINE ANALYSIS
- HYPERVELOCITY IMPACT

STRUCTURAL MECHANICS RESEARCH CHALLENGES, 1958-PRESENT

If the NACA golden era was characterized by giving birth to sound theory with vast experimental support, the NASA era can be categorized as introducing and advancing the computer automation of the theory. At the same time this period can be credited with developing scale model testing techniques for a wide variety of load conditions. Scale model studies were not new to aeronautics to be sure, but the use of scale models in structural mechanics had received little attention prior to the need to get an early assessment of parameters governing space vehicle design.

The problems of this era were thermoelasticity, multiple mode analysis, and developing light stiff panels of corrugated, sandwich or composite construction. In order to launch the huge vehicles into space, there was literally an explosion of interest into every phase of structural flexibility associated with the long slender spacecraft which were subjected to large thrust loads, entry pressures and temperatures.

STRUCTURAL MECHANICS CONTRIBUTIONS

1958 - PRESENT

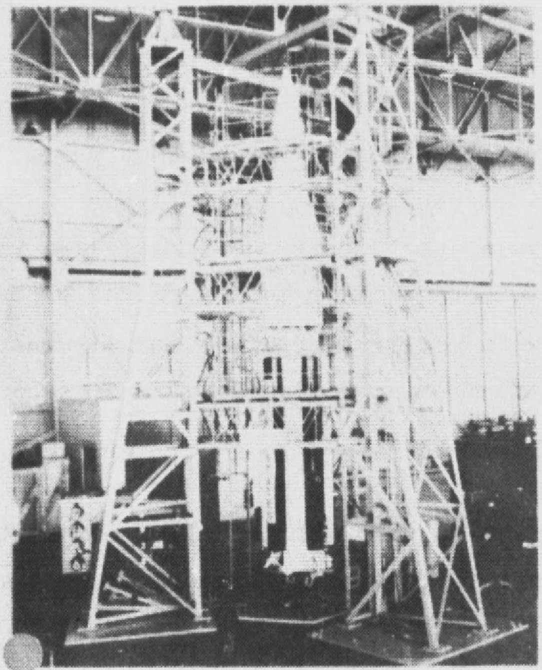
- ANALYSIS OF THERMAL PROTECTION SYSTEMS
- ADVANCED SHELL STUDIES
  - LINEAR AND NONLINEAR THEORY
  - EFFECT OF ECCENTRIC STIFFENING
  - WALL CONSTRUCTIONS
  - LARGE SCALE SHELL TESTING
  - SCALE MODEL TESTS
- AUTOMATION AND NUMERICAL APPROACHES

STRUCTURAL MECHANICS CONTRIBUTIONS

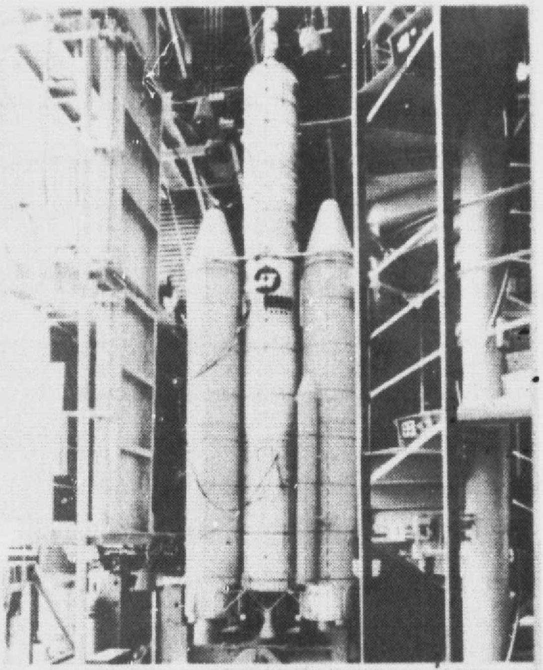
At this point in Langley's history a fundamental change took place in the way business was conducted - NASA was a large organization requiring vast skills. The identity of Langley contributions in this period is much more difficult since virtually every aerospace research organization in the country was affected in some way by the space exploration effort. During this period Langley grew to over 4300 employees and NASA to roughly 34,000 employees located at a dozen major research centers around the country. Universities and research organizations throughout the country poured their best efforts into solving the difficult problems encountered with modern spacecraft and aircraft. During this era it was not unusual to hear of other countries complaining about the "brain drain" and sociologists discussing the fluid motion of people employed in the aerospace industry.

With this broad view of Langley's interaction with the technical community in mind and looking back at the Langley's activity, several things stand out as notable accomplishments. One, a mechanics researcher of the first rank, John Houbolt, became a leader in orbital mechanics. He had previously contributed to advances in the study of whirl flutter, transient response and other areas of dynamic behavior. His foresight, however, in developing lunar trajectory and landing schemes became one of the outstanding stories of the space race and contributed directly to its success. Another development spurred by the Langley structural mechanics and materials research was the vast testing of thermal protection systems, (TPS) and the successful formulation of analysis techniques for estimating the degree of ablation during reentry. The area most associated with Langley however, is the development of shell theory and its correlation with experimental data. The publication of Sanders linear shell theory in 1959, the outstanding experimental studies and the support for the computer automation of various shell and finite element codes both in-house and under contract are the basis of Langley's reputation in this area.

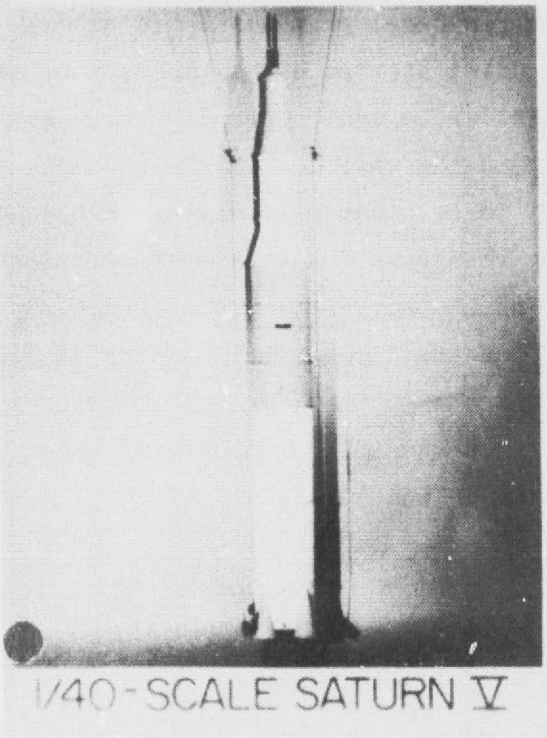
DYNAMIC SCALE MODELS



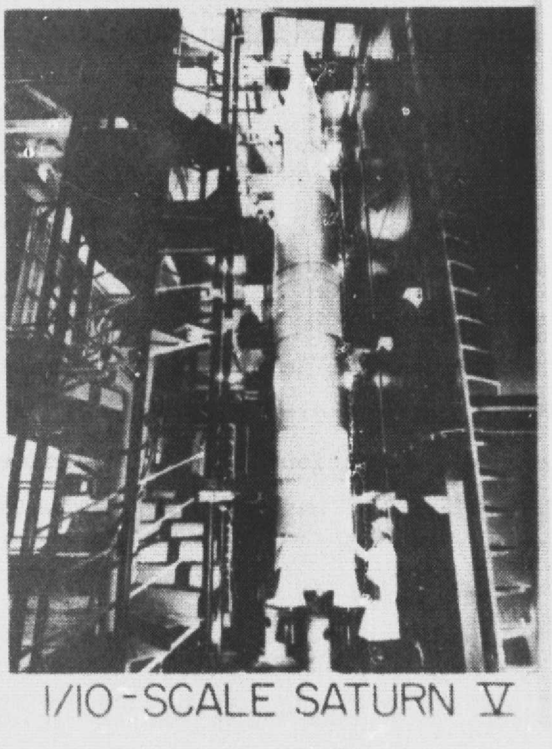
1/5-SCALE SATURN I



1/5-SCALE TITAN III



1/40-SCALE SATURN V



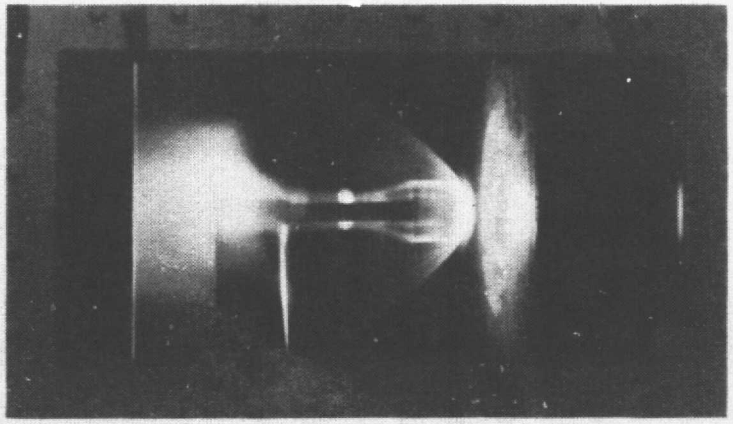
1/10-SCALE SATURN V

DYNAMIC SCALE MODELS

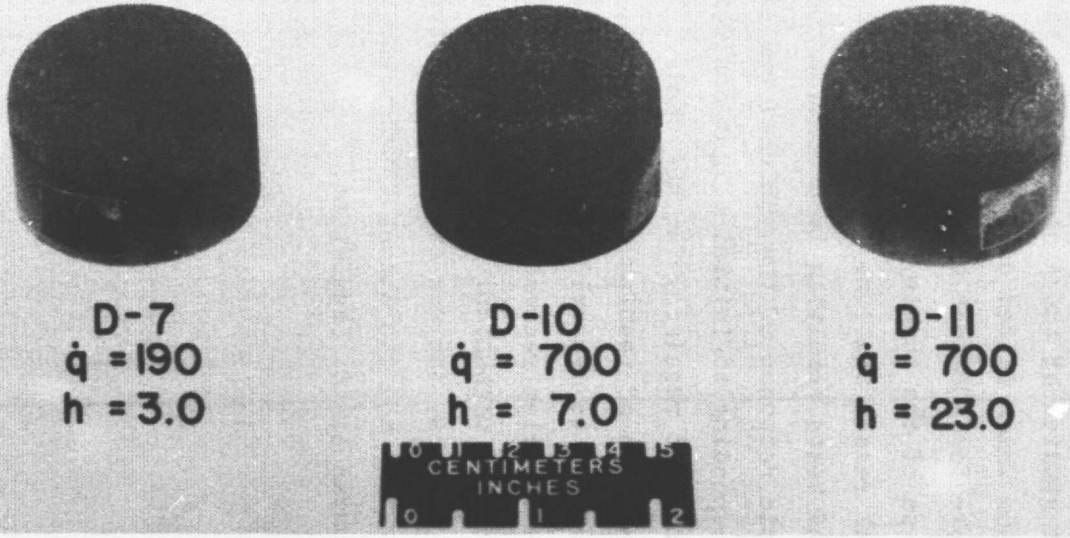
Other challenging problems faced structural engineers also. Shown here are some of the scale model launch vehicles which were tested in Langley's dynamics laboratory. The Saturn I was the launch vehicle used in early earth orbit studies of the Apollo program and the Saturn-V was used to launch Apollos which landed on the moon. The Titan represents a mated military vehicle for ICBM use which NASA studied at the request of the Air Force. The success of the Langley tests and analysis of the Titan vehicle were the fundamental reason that the Air Force could accept the vehicle without full-scale ground tests resulting in a considerable cost savings to the government. The dynamic response of the vehicles was of prime interest with responses corresponding to initial flight conditions at lift-off, maximum dynamic pressure and burnout requiring further study. In addition to building instrumentation and methods of testing these vehicles, non-existent analysis tools had to be formulated to determine the frequencies of the scale and full scale structures. These vehicles represent some of the first efforts to use scale models in structural mechanics. Although aerodynamicists had long used scale models in wind tunnels, the use of models in structural mechanics is a fairly recent innovation and its use at Langley was pioneered by G. Brooks, H. Morgan, H. Runyan and S. Leadbetter.

THERMAL PROTECTION SYSTEM DEVELOPMENT

ARC JET HEATING



TYPICAL SPECIMENS



D-7
$\dot{q} = 190$
$h = 3.0$

D-10
$\dot{q} = 700$
$h = 7.0$

D-11
$\dot{q} = 700$
$h = 23.0$

THERMAL PROTECTION SYSTEM DEVELOPMENT

Thermal protection systems evolved into a new area of specialization during this period. Arc jet facilities were built and literally hundreds of samples tested. Shown here is an arc-jet facility in operation and some samples after charring. The question was, however, could these small-scale tests be used to gage large scale flight behavior? The debate ran throughout the industry as to how much ablation material would be required. Langley analysts devised an approach similar to that used in transient response analysis and were able to estimate accurately the amount of energy absorbed at various heating rates. Much of this early work was due to the efforts of Kotanchik, W. Brooks and Levin. It is important to recall also that the density of TPS material decreased rapidly during these years of research. For Mercury the density was approximately 1600 kg/m^3, for Gemini 960 kg/m^3 and for Apollo 480 kg/m^3. For Space Shuttle the density has been reduced to 144 kg/m^3 and the system is reusable. In fact, the weight savings are even more dramatic than the densities indicate since the TPS thickness requirements have also decreased.

SANDERS LINEAR SHELL THEORY

- VIRTUAL WORK APPROACH ASSUMING EQUILIBRIUM

$$\iint\left\{\left(\frac{\partial\alpha_2 N_{11}}{\partial\xi_1}+\frac{\partial\alpha_1 N_{21}}{\partial\xi_2}+\frac{\partial\alpha_1}{\partial\xi_2}N_{12}-\frac{\partial\alpha_2}{\partial\xi_1}N_{22}+\frac{\alpha_1\alpha_2}{R_1}Q_1\right)\delta U_1+\left(\frac{\partial\alpha_2 N_{12}}{\partial\xi_1}+\frac{\partial\alpha_1 N_{22}}{\partial\xi_2}+\frac{\partial\alpha_2}{\partial\xi_1}N_{21}-\frac{\partial\alpha_1}{\partial\xi_2}N_{11}+\frac{\alpha_1\alpha_2}{R_2}Q_2\right)\delta U_2\right.$$

$$+\left[\frac{\partial\alpha_2 Q_1}{\partial\xi_1}+\frac{\partial\alpha_1 Q_2}{\partial\xi_2}-\alpha_1\alpha_2\left(\frac{N_{11}}{R_1}+\frac{N_{22}}{R_2}\right)\right]\delta W+\left(\frac{\partial\alpha_2 M_{11}}{\partial\xi_1}+\frac{\partial\alpha_1 M_{21}}{\partial\xi_2}+\frac{\partial\alpha_1}{\partial\xi_2}M_{12}-\frac{\partial\alpha_2}{\partial\xi_1}M_{22}-\alpha_1\alpha_2 Q_1\right)\delta\Phi_1$$

$$\left.+\left(\frac{\partial\alpha_2 M_{12}}{\partial\xi_1}+\frac{\partial\alpha_1 M_{22}}{\partial\xi_2}+\frac{\partial\alpha_2}{\partial\xi_1}M_{21}-\frac{\partial\alpha_1}{\partial\xi_2}M_{11}-\alpha_1\alpha_2 Q_2\right)\delta\Phi_2+\alpha_1\alpha_2\left(N_{12}-N_{21}+\frac{M_{12}}{R_1}-\frac{M_{21}}{R_2}\right)\delta\Phi_n\right\}d\xi_1 d\xi_2=0$$

- STRAIN EXPRESSIONS INDEPENDENT OF Z

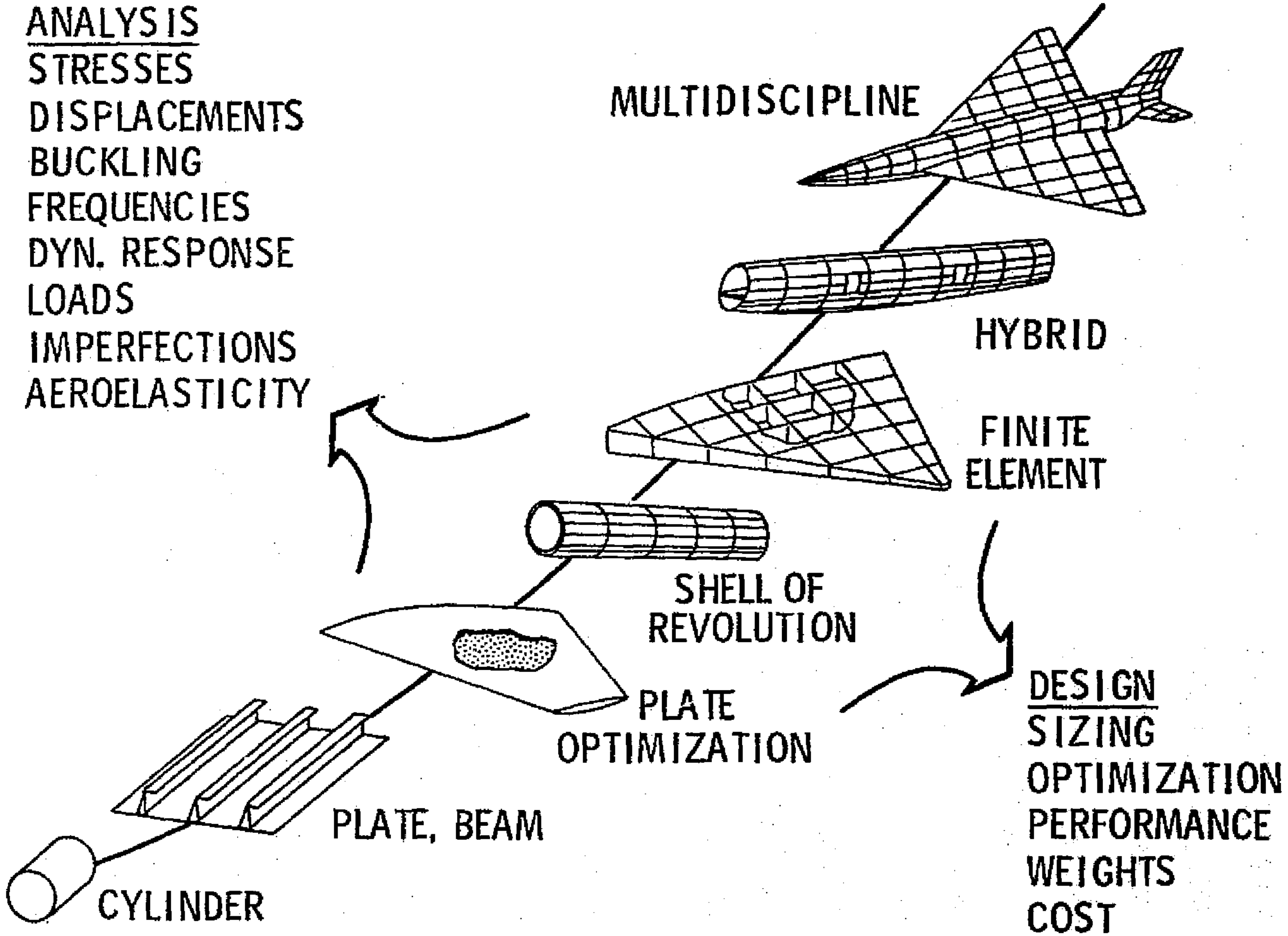
$$\varepsilon_{11}=\frac{1}{\alpha_1}\frac{\partial U_1}{\partial\xi_1}+\frac{1}{\alpha_1\alpha_2}\frac{\partial\alpha_1}{\partial\xi_2}U_2+\frac{W}{R_1}\qquad k_{11}=\frac{1}{\alpha_1}\frac{\partial\Phi_1}{\partial\xi_1}+\frac{1}{\alpha_1\alpha_2}\frac{\partial\alpha_1}{\partial\xi_2}\Phi_2$$

- RIGID BODY MOTIONS FREE OF STRAIN

SANDERS LINEAR SHELL THEORY

Central to Langley's specialization however were the developments in shell analysis and testing. One outstanding contribution was the publication of Sanders Linear shell theory in 1959. Sanders theory was not the only one available to be sure but there were several significant features in his approach. First, instead deriving equilibrium expressions he assumed them correct and used an energy approach to derive the strain expressions. He found that with his theory Love's 1st approximation was satisfied and rigid body motions were free of strains. His theory became one of the standards of the profession. After leaving NASA he further refined his shell theory to include geometric nonlinearilities. The theory was not based on a descent from 3-dimensional equation of elasticity but was developed as a 2-dimensional one and as such, is independent of approximations through the thickness. Later with the development of computers during this period rapid gains could be made in analysis of highly optimized and complex structures.

STRUCTURAL ANALYSIS AND DESIGN



ANALYSIS

- STRESSES
- DISPLACEMENTS
- BUCKLING
- FREQUENCIES
- DYN. RESPONSE
- LOADS
- IMPERFECTIONS
- AEROELASTICITY

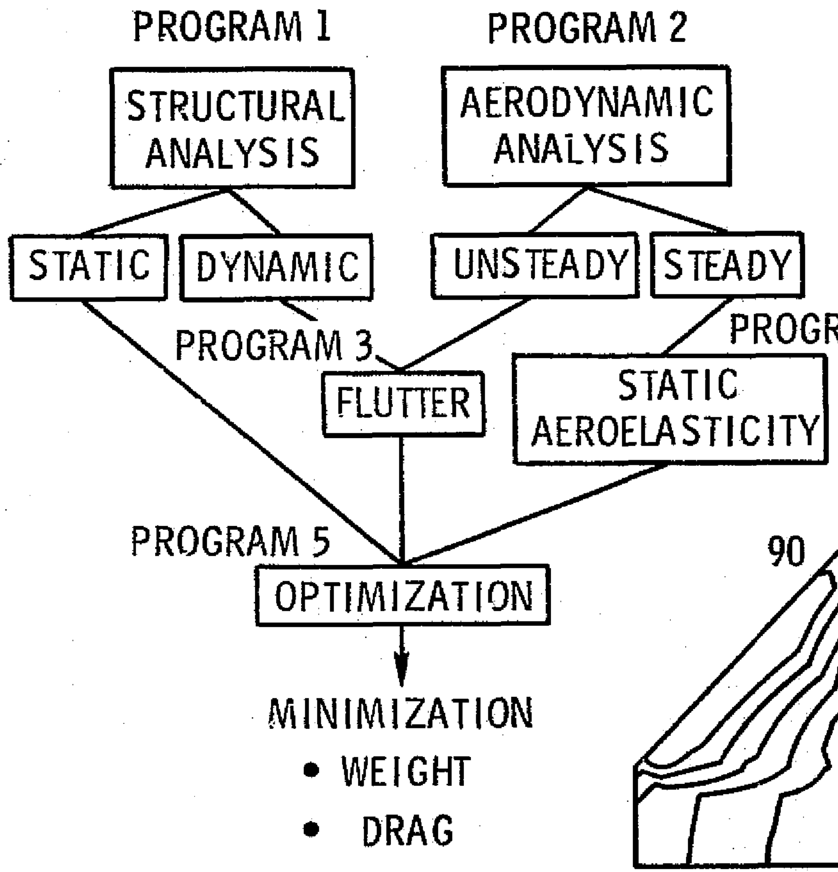
DESIGN

- SIZING
- OPTIMIZATION
- PERFORMANCE
- WEIGHTS
- COST

STRUCTURAL ANALYSIS AND DESIGN

With the advances of theory and computer hardware a new expertise began to emerge, that of developing computer software. In just a few years this expertise itself has undergone great change. Initially, the codes were of a modest scale involving simple plate or shell configurations and practically every organization produced its own code. The engineering profession quickly realized the value of these codes and began using them as more than just an analysis tool. They were exploited in the design process allowing the engineer to consider a large number of trial designs before selecting an optimum design; this usually meant a minimum weight design in aerospace applications. As the numerical techniques and computer hardware progressed several codes began to emerge which were sponsored by an agency or company and which had a large community of users. Typical codes from industry and government are the shell of revolution programs such as SRA, BOSOR, and SALORS and the finite element analysis programs such as NASTRAN, SPAR and FLEXSTAB. These programs were quite general in concept and virtually entire components of aircraft or structural networks can be modelled. For the most part, these codes are treated by the user as "black boxes" and are fairly monolithic in structure. That is, the user does not make notable changes to program but rather contracts the sponsor to make these changes. Further, the user does not interact with the execution logic but accepts a preprogrammed rigid format or option as a choice. Recent trends seem to be tending to an interactive mode of operation, wherein the user may program complex input loadings, geometry or stiffening into the code; or, more importantly, where the user may develop a unique flow chart for his calculations through decomposed or modular codes such as SPAR and STAGS. This is important, particularly in the areas where iterative approaches are needed such as in nonlinear analysis, design studies, or in eigenvalue studies. Finally, the state-of-the-art seems to be developing toward allowing the user to involve several major codes and engineering specialities to a design or analysis. Ideally, the file manipulation between these codes is standardized and automated. A recent example of this approach is shown in the next slide.

DESIGN OPTIMIZATION TECHNOLOGY



PROGRAM 1

STRUCTURAL ANALYSIS

STATIC

DYNAMIC

PROGRAM 2

AERODYNAMIC ANALYSIS

UNSTEADY

STEADY

PROGRAM 3

FLUTTER

PROGRAM 4

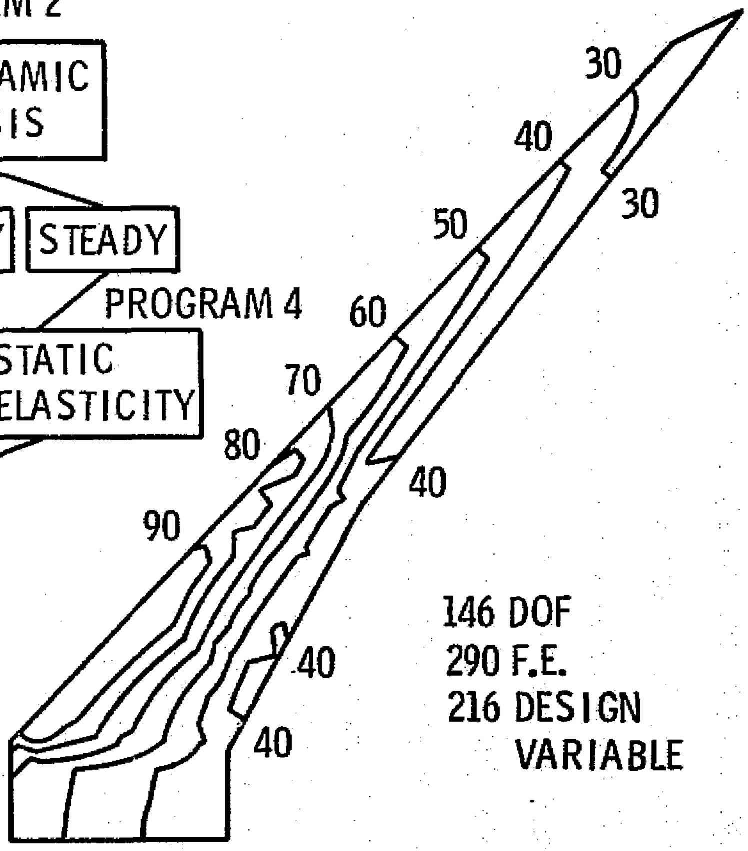
STATIC AEROELASTICITY

PROGRAM 5

OPTIMIZATION

MINIMIZATION

- WEIGHT
- DRAG



146 DOF
290 F.E.
216 DESIGN
VARIABLE

DESIGN OPTIMIZATION TECHNOLOGY

This slide represents some recent advanced study of mathematical programming techniques by J. Starnes and R. Haftka. The scope of the problem is large enough so that designers can no longer specialize in a limited area of structural mechanics but must have a working understanding of aeroelasticity, dynamics, statics and stability. Here the wing structure is to be optimally designed with respect to thickness, strength, and flutter constraints. The structure itself can be modelled with 290 finite elements and 146 degrees of freedom. The important contribution is that a large number of design constraints can also be included without unduely impacting run times. The logic for the automation of this design effort is shown in the flow chart where a multi-program approach was used. The key feature of the approach is that the designer is able to tailor his approach to a particular design effort without repetitious modelling or time consuming manual file manipulation. A little later we will take a look at a 5-year effort Langley is sponsoring to further automate this process.

COMPUTER TECHNOLOGY

"TEN OF TODAY'S (1952) LARGE COMPUTERS WILL SUPPLY ALL OF THE COMPUTING NEEDS THIS COUNTRY WILL EVER HAVE."

T. J. WATSON, Sr.
PRESIDENT, IBM

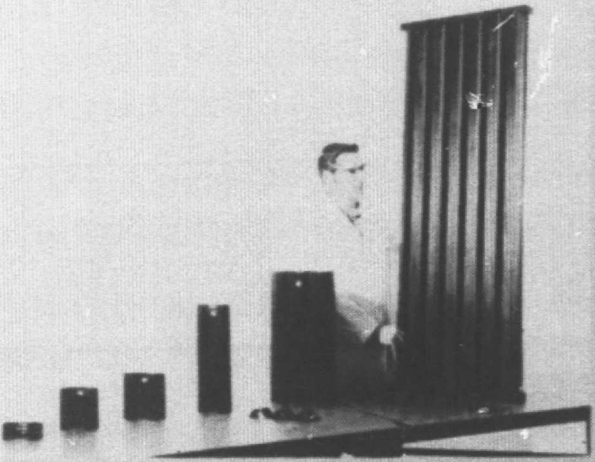
COMPUTER TECHNOLOGY

In view of the rapid growth of computer hardware and advances in computer software it is useful to take a look backward at this area to see where we were and aspired to be and find how far we have exceeded the expectation.

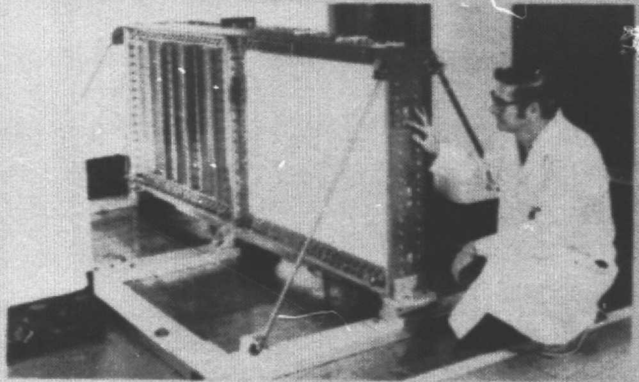
In 1952 the president of a major computer development corporation could foresee only modest gains in computer usage when he said "Ten of today's large computers will supply all of the computing needs this country will ever have".

With the previous slide on mathematical programming I highlighted some current research at Langley. I would like to continue to review a few of our current thrusts.

MINIMUM WEIGHT GRAPHITE EPOXY PANELS

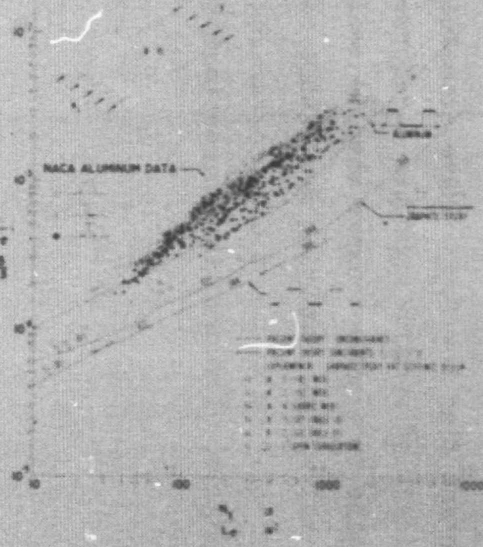


COMPRESSION PANELS



SHEAR WEB

STRUCTURAL EFFICIENCY OF COMPRESSION PANELS

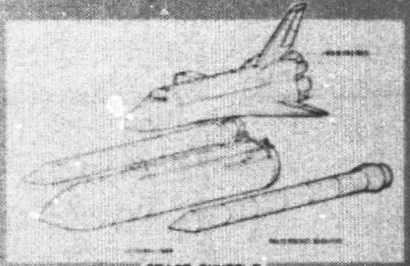


MINIMUM WEIGHT GRAPHITE EPOXY PANELS

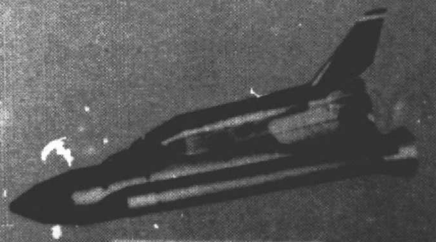
Reminiscent of the stressed-skin panel work of the war years is the current study of composite panels by J. Williams and M. Mikulas. Here is shown a weight versus strength plot for compression panels. The sea of data in the upper portion of the graph represents the earlier NACA studies with aluminum panels for stiffeners with a variety of cross-sections and the resulting design envelope. The lower curves show the theoretical prediction of the current study with the composite panels. These panels reduce the weight by a factor of 2 or more depending on the open or closed corrugation of the configuration. A significant feature of this study is that the testing is much more selective taking advantage of the advances in theory. A similar study will be conducted for shear panels. Updated test techniques include automatic and simultaneous data reduction as well as the use of photography and Moire fringe patterns. These techniques enhance the accuracy of the tests.

TYPICAL 1/8-SCALE MODEL MATED TEST RESULTS

- MODAL DENSITY HIGH
- DAMPING LOW
- LOCAL DEFORMATION CRITICAL

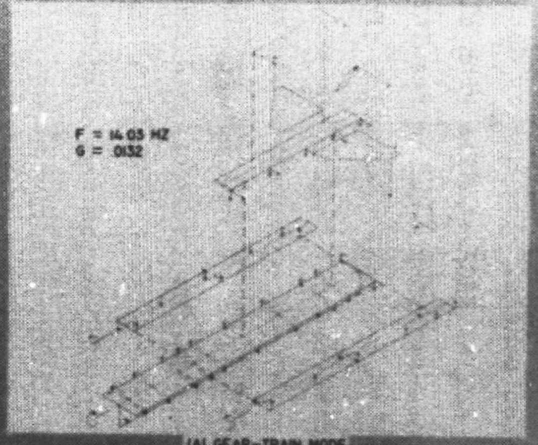


SPACE SHUTTLE

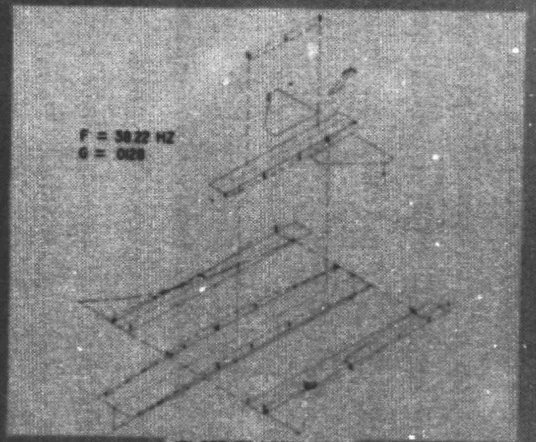


1/8-SCALE SHUTTLE MODEL

FREQUENCY



(A) GEAR-TRAIN MODE



(B) SRB/ET LOCAL YAW

TYPICAL 1/8-SCALE MODEL MATED TEST RESULTS

Much of Langley's work remains in the area of vehicle analysis as shown by this space shuttle study. Here the free vibrations of the mated orbiter-solid rocket booster - external tank structure is shown with a lift-off fuel load. This study involves of a number of people in structural dynamics under the direction of S. Leadbetter and L. Pinson. This configuration has a high modal density. In the modes shown, the response can be either general involving all the components or fairly localized as shown in the lower figure. The structural damping coefficients were also determined. Vehicle studies invariably challenge and extend the state-of-the-art in both the experimental and analytical areas, as well as provide the needed vehicle support.

STRUCTURAL DYNAMICS AND AEROELASTICITY STUDIES

- BUFFET
- FLUTTER
- NOISE
- POGO
- SLOSH
- PANEL
- THERMAL EFFECTS
- WHIRL

NASA LANGLEY CRASH SAFETY PROGRAM

In recent years a three-pronged effort has begun to upgrade the reliability of technology associated with crash safety design. The program involves full-scale crash simulation testing, non-linear crash impact analysis and crash safety design concepts. The full-scale testing is being conducted at Langley's Impact Dynamics Research Facility. The analysis effort involves both material and geometric nonlinearities as well as transient response analysis. The conceptual effort focuses on maintaining the occupant survivable volume and adding energy absorption devices through improved flooring and seat restraint systems.

ADVANCED NUMERICAL SOLUTIONS

- FIELD METHOD

  2 POINT B. V. P. $\Longrightarrow$ INITIAL PT B. V. P.

- TRIGONOMETRIC DIFFERENCES

$$f(X) = a_0 + a_1 X + a_2 X^2 + \ldots$$

$$f' = \frac{f_{i+1/2} - f_{i-1/2}}{\Delta X}$$

$$f(X) = a_0 + a_1 \sin \frac{\pi X}{\lambda} + a_2 \cos \frac{\pi X}{\lambda}$$

$$f' = \frac{f_{i+1/2} - f_{i-1/2}}{\frac{2\lambda}{\pi} \sin \frac{\pi \Delta X}{2\lambda}}$$

- MIXED METHODS

  FORCES & DISPLACEMENTS
  SUBSTRUCTURING

- HYBRID

  FINITE ELEMENTS & FINITE DIFFERENCES

ADVANCED NUMERICAL SOLUTIONS

In numerical analysis several research areas are being pursued both in-house and under contract to NASA. The field method of analysis is being developed under contract by G. A. Cohen for a shell-of-revolution code. The procedure involves converting a set of 2-point boundary value equations into two sets of nonlinear initial point equations corresponding to forward and backward sweeps. A set of field functions is used to make this transformation. The resulting code using this approach will be free of numerical round off problems and the integration scheme automated to the extent that convergence will be assured. Preliminary studies show the method is more efficient than conventional integration schemes and will attain the desired accuracy on 32-bit word machines without requiring double precision operations.

Another area of numerical approximation being pursued is the use of trigonometric differences as opposed to the conventional differences based on polynomial expansions. A recent study by M. Stein and J. Housner at Langley showed that converged solutions can be obtained with dramatically coarser grids by using trigonometric difference expressions. Since a large class of problems in mechanics involve sinusoidal or trigonometric series solution forms this approach may be an attractive option in many finite difference codes.

A similar procedure is being studied by B. O. Almroth at Lockheed under contract to Langley. In the Lockheed 2-dimensional STAGS code Almroth is formulating a scheme whereby the user may select a function in a manner similar to a Rayleigh-Ritz procedure to represent the structural behavior in one direction while retaining the conventional difference scheme in the other direction. Since problems in computer storage or run times compound rapidly in 2 dimensional codes, this approach will provide an economic alternative to the user. A further feature under development in the STAGS code is that major structural shell components such as the fuselage can be analyzed using finite differences and take advantage of the accuracy of shell theory while finite elements can be used to model complex geometries and networks attached to the shell structure.

Another area of numerical analysis receiving attention involves the research of A. Noor, who has studied formulations in finite differences and finite elements which include both force vectors and displacement vectors as independent unknowns rather than just displacements as in the usual matrix procedure based on the displacement approach. He has found that these mixed methods give much more rapid convergence. The disadvantage has been that the stiffness matrix is no longer positive definite. His recent work in formulating and automating substructuring techniques for this class of problems, however, show that this drawback can be efficiently eliminated.

FUTURE RESEARCH THRUSTS

- COMPUTER AIDED DESIGN
- FUEL EFFICIENT AIRCRAFT
- LARGE AREA SPACE STRUCTURES

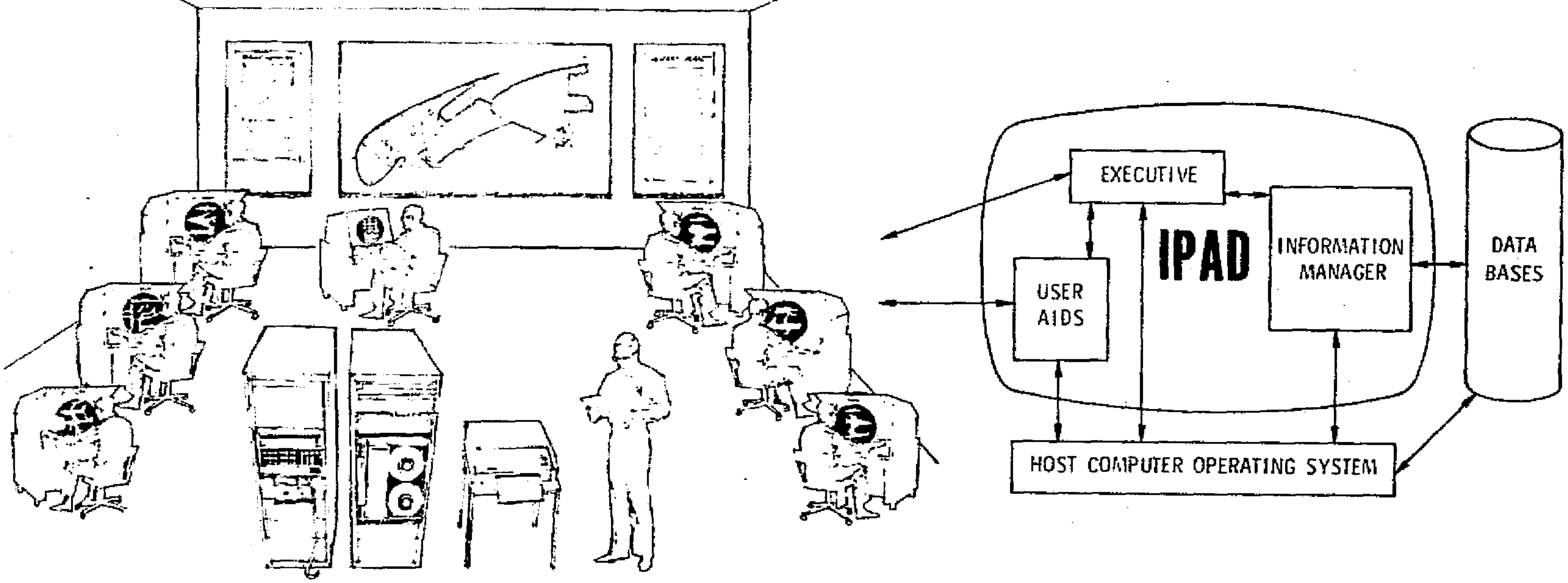
FUTURE RESEARCH THRUSTS

This has been a brief summary of some current research areas, but what about the future thrusts in research? Besides continuing and broadening the research indicated in previous slides three areas are coming to our attention. An executive system for automating the design process for an aircraft by including all the related analysis disciplines is currently under development. Another topic includes the design, erection and use of very large structures in space. For the types of problems in current plans these structures may cover areas larger than a square kilometer. Another topic which is attracting considerable attention is the fuel efficient aircraft. A goal has been established to double the current fuel efficiency of our larger aircraft.

COMPUTER AIDED DESIGN SYSTEM FOR THE AEROSPACE INDUSTRY

ENGINEERING STAFF

COMPUTER SOFTWARE

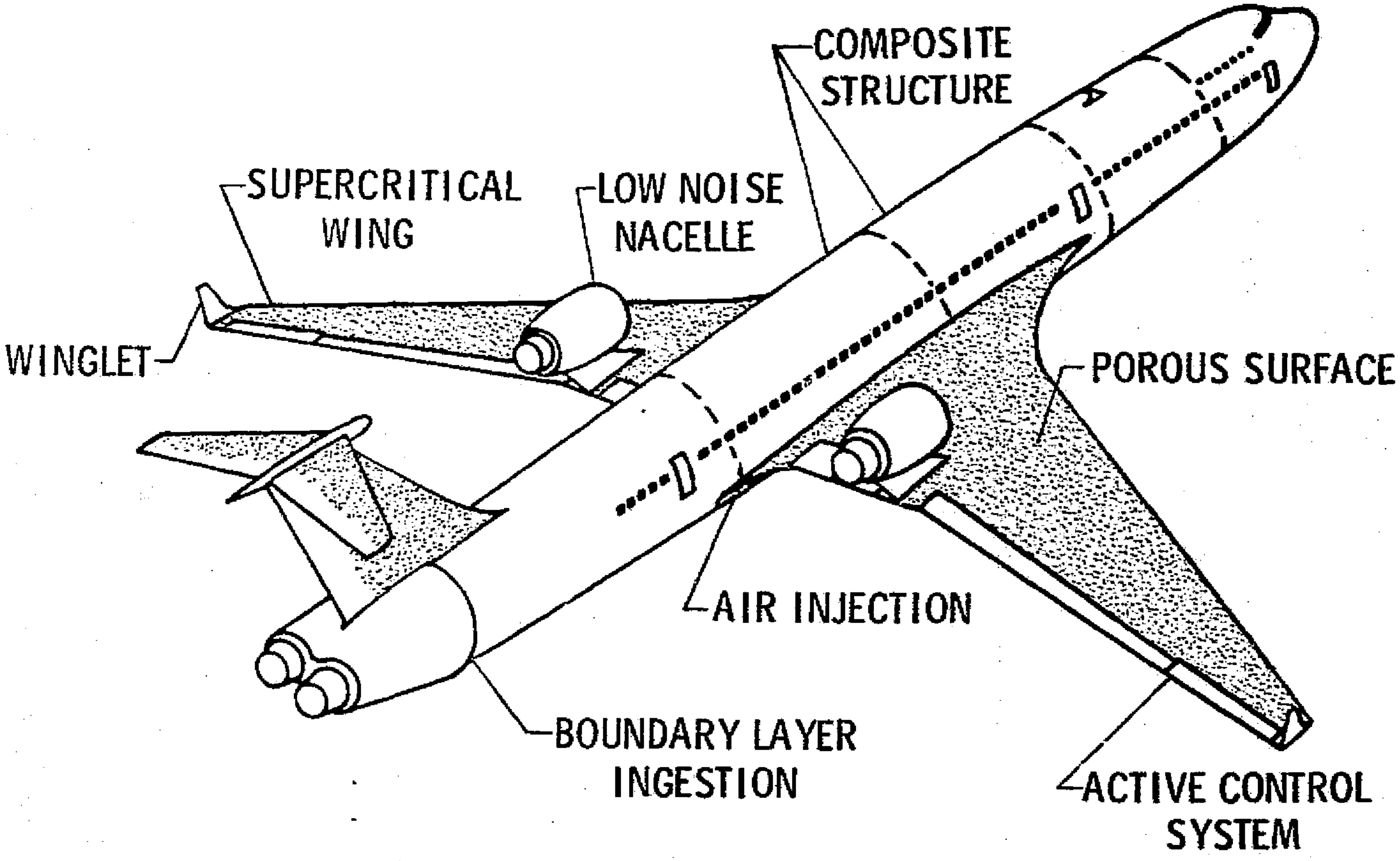


- 5 YEAR DEVELOPMENT PLAN
- INCREMENTALLY RELEASED ON 2 DIFFERENT COMPUTERS
- HEAVY INDUSTRY INVOLVEMENT

COMPUTER AIDED DESIGN SYSTEM FOR THE AEROSPACE INDUSTRY

This slide depicts a futuristic design process and some of the requirements are many years away from being met. This project is being managed by R. E. Fulton and the prime contractor is Boeing Commercial Aircraft Company and the principal investigator is R. E. Miller. A five year development plan to build the IPAD computer-aided design software for industry to provide company wide access to design data and computer codes is just beginning. The slide illustrates the hypothetical engineering staff and the various software elements which make up the IPAD system on the right. The three major software components of IPAD include the executive, the information manager, and the user aids. The executive controls the process and serves as the principal interface to the user. The user aids includes graphic software for plotting CRT use. The key capability in the IPAD system is the information management capability to handle a wide variety of data such as programs or data which are included in the data base. The IPAD software is to rest on and take advantage of the host computer operating system. The development includes incremental release on two different computers and incorporates heavy user involvement in its definition, design, and software checkout. Its goal is to be the prototype for industry for the future.

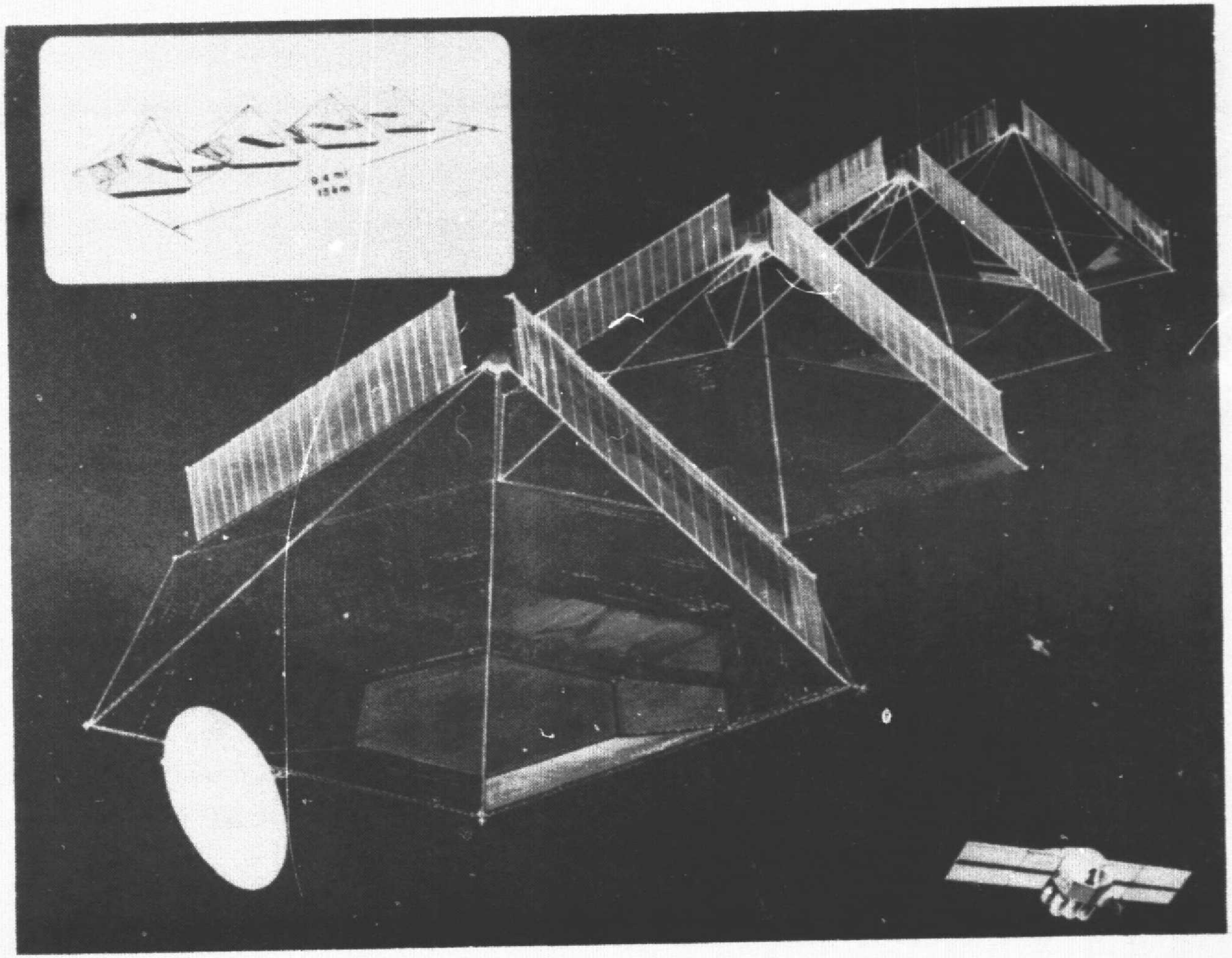
FUEL EFFICIENT AIRCRAFT



FUEL EFFICIENT AIRCRAFT

A number of options such as those indicated in the slide are being investigated to increase aircraft fuel efficiency. Of those which affect the structural behavior of the aircraft, the most emphasis is given to lightweight composite materials. Many components now are being fabricated for aircraft and it is anticipated that soon major components such as wing structures and the fuselage of in-service aircraft will be constructed of composite materials. In terms of structural response this material opens a vast new area requiring theoretical and experimental support. For NASA, Langley has the prime responsibility for composite structures development. Active controls will be used to direct wing response and allow for a smaller wing surface areas. The lift-drag ratio will be increased by porous or slotted wing structures. The supercritical airfoil has already been shown to decrease drag in transonic regions. The ingestion chambers and remaining features are included here only for completeness. They indicate the type studies being pursued to meet the overall goal of doubling aircraft fuel efficiency within a 10 year period.

LARGE AREA SPACE STRUCTURES



LARGE AREA SPACE STRUCTURES

As the space shuttle nears completion a new kind of space technology is beginning to emerge. That is, the assembly of structures in space for some prescribed mission. The concept shown here is that of a large solar collector which transmits energy to earth. Such structures must be of a very large size to be effective; for example the 15 km length depicted here. This structure must respond to a set of active controls. Such a structure faces many design constraints. First, it must be transportable in the space shuttle and erectable in space. This structure for a square kilometer will require on the order of 100,000 elements and approximately 14 shuttle missions for material transportation. The questions arise as to how it will be analyzed or tested. The conventional process of using automated analysis is severely impacted when attempting to analyze large area structures due to the large number of degrees of freedom. The answer seems to be to develop a macro or megamechanics approach where truss-works can be analyzed as layered plate-like structures using appropriate definitions for stiffnesses. Actually, the problem of setting up a reasonable earth-based test schemes may be the most difficult task in this long range project. Preliminary planning for this project has been under the direction of Dr. Kruszewski.

CONCLUDING REMARKS

- GOVERNMENT, INDUSTRY AND ACADEMIC SUPPORT HAS RESULTED IN:
  - NUMEROUS THEORETICAL CONTRIBUTIONS
  - FUNDAMENTAL UNDERSTANDING THROUGH EXTENSIVE EXPERIMENTAL PROGRAMS
  - CRITERIA TO GOVERN DESIGN OF BASIC STRUCTURAL COMPONENTS
  - RAPID ADVANCES IN COMPUTER SOFTWARE

CONCLUDING REMARKS

In attempting to scope Langley's past, present and future the combination of government, industry and academic support has resulted in numerous contributions to the theoretical understanding of mechanics. Well conceived experimental programs, thorough analysis and consistent theoretical approaches have combined to enhance the state of the art in each period. These studies have led to the formulation of widely accepted design criteria to guide the aerospace industry. Perhaps, equally important is the host of experimental techniques, automated design and analysis tools available to speed the process to a successful conclusion and at the same time achieve a level of structural detail and sophistication with a speed and accuracy never before imagined.